ABSTRACTS FOR THE WORKSHOP ON COSMOGENIC NUCLIDE PRODUCTION RATES

Vienna, Austria

July 25-26, 1989

Sponsored by

Lunar and Planetary Institute
San Jose State University
University of Vienna

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PREFACE

This volume contains abstracts that have been accepted by the Program Committee for presentation at the Workshop on Cosmogenic Nuclide Production Rates. The Program Committee consisted of Peter A. J. Englert, San Jose State University; Robert C. Reedy, Los Alamos National Laboratory; and Rolf Michel, Technical University Hannover.

Logistics and administrative support were provided by the Projects Office staff at the Lunar and Planetary Institute. This abstract volume was prepared by the Publications Services Department staff at the Lunar and Planetary Institute.

PREFACE

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CONTENTS

ISOTOPE PRODUCTION IN CHONDRITES BY COSMIC RAYS : EXPERIMENTAL DEPTH PROFILES AND MODEL CALCULATIONS; N.Bhandari, Physical Research Laboratory, Navrangpura, Ahmedabad, India.

About 20 radioisotopes, ranging in half life from a few hours to billions of years, produced in cosmic ray interactions with meteoritic material have been studied in chondrites. Deviation of their observed activity from the expected levels, based on the present galactic cosmic ray [GCR] flux could possibly be due to (i) time variation in GCR flux (ii) spatial variation of GCR intensity in the orbital space of the meteoroid (iii) variation in modulation of GCR by the sun-spots and other solar activity cycles or (iv) complex exposure and fragmentation history of the meteoroid. Whereas reasonably precise measurements are now being made in meteorites using high resolution gamma ray counting and Accelerator Mass spectrometry, there remains large uncertainty in predicting the production rates as none of the models developed for this purpose have the desired accuracy [see (1)]. To obtain production rates as accurately as possible we have used an experimental approach (2) which is briefly as follows. We first select chondrites, on the basis of a combined study of track density profiles, neon isotope concentration and (^{22}Ne/^{21}Ne), which have simple one stage exposure history (3) and determine their preatmospheric size and shape. The track production rate is the most sensitive parameter to obtain shielding depth. The observed activity profiles of some chosen radioisotope in such meteorites, together with excitation function of the isotope can yield an "effective" energy spectrum of nucleons (4) as a function of depth in the meteorite of a given size, as is done in Reedy-Arnold model (5) for the moon.

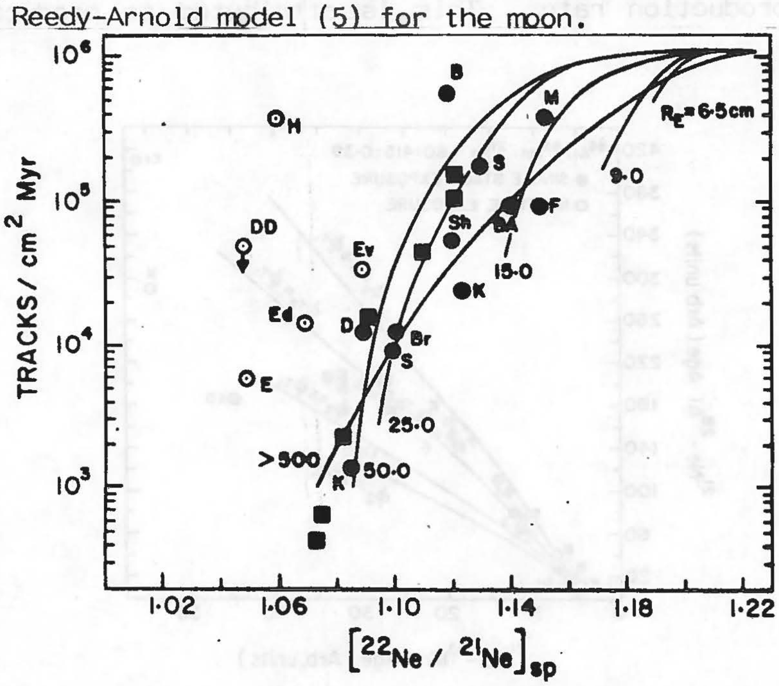

Fig. 1 Calculated track production rate vs $[^{22}Ne/^{21}Ne]_{sp}$ correlation curves for meteorites of various radii, R_E having simple exposure history. For data points and symbols see (8). ■ are Knyahinya data from (6).

Two criteria have been developed to identify chondrites with simple exposure history: one based on the correlation diagram of track production rate and spallation neon isotope ratio $^{22}Ne/^{21}Ne$ (Fig.1). The other is based on concordance of ^{26}Al-^{21}Ne exposure age with ^{53}Mn-^{21}Ne exposure age (Fig.2). Seven meteorites Madhipura (L), Udaipur (H), Bansur (L5), St. Severin (LL), Keyes (L6), Knyahinya (L5) and Dhajala (H3) where depth profiles of some radionuclides eg. ^{26}Al, ^{10}Be or ^{53}Mn have been measured [2,6,7,8] qualify these criteria; these meteorites cover preatmospheric radius, R_E, of 6 to 50 cms. Several other meteorites which have simple exposure history have been identified (8). The data points for meteorites inferred to have simple exposure history from Fig.1 lie on constant cosmic ray flux curve in Fig.2 and suggest that the "average" GCR flux has not varied over the past 5 million years.

The observed depth profiles of radioisotopes in these meteorites provide a simple way of understanding size and depth dependence of the production function. Some systematics emerge from these profiles :

(1) The isotope depth profile in small (R_E<15cm) meteorites is nearly flat

(2) The isotope production rate increases with depth for meteorites (15<R_E <30cm)

(3) The central production rate increases with size for chondrites (6<R_E <30cm) as shown in Fig.3

(4) For larger meteorites (R_E>30cm) the production rate decreases with size and depth of >15cm.

In some cases the surface samples show significantly high track density and isotope production rate. This is attributed to production by solar cosmic rays.

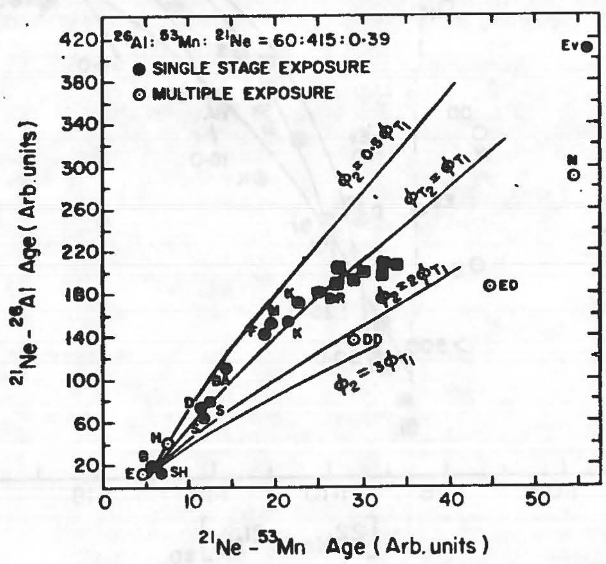

Fig. 2 Calculated ^{26}Al-^{21}Ne age vs ^{53}Mn-^{21}Ne age (arbitrary units) concordance curves for constant ($\phi_{T2}=\phi_{T1}$) and variable GCR flux. For symbols see (8). ■ are Knyahwya data from (6).

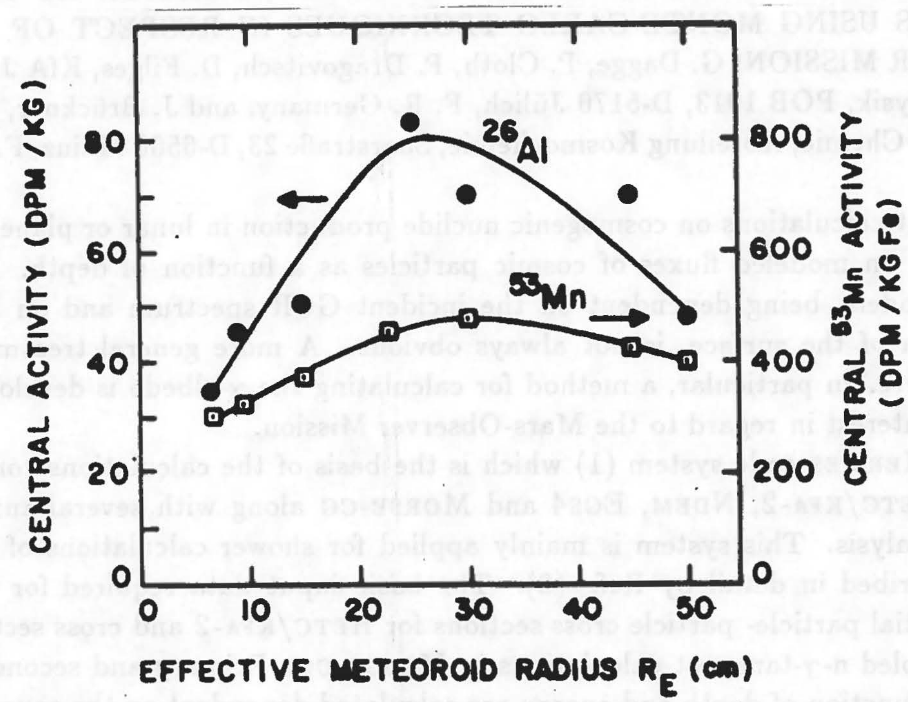

Fig. 3 The production rate of ^{26}Al and ^{53}Mn near the centre of meteoroids of different radii. For data points see (2,3,6,7,8).

We here use the depth profile of ^{26}Al or ^{53}Mn in our model [2,3] to obtain the energy spectra of nucleons within meteorites of different sizes. The predictions of this model for other isotopes eg. ^{21}Ne ^{22}Ne, ^{22}Na are then compared with the observed profiles. The model satisfactorily reproduces the observed ratio of $^{22}Na/^{26}Al$ and $^{22}Ne/^{21}Ne$. Limitations and merits of this model will be discussed.

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STUDIES OF THE COSMIC RAY INDUCED γ-EMISSION AT PLANETARY SURFACES USING MONTE-CARLO TECHNIQUES IN RESPECT OF THE MARS OBSERVER MISSION; G. Dagge, P. Cloth, P. Dragovitsch, D. Filges, KfA Jülich,Institut für Kernphysik, POB 1913, D-5170 Jülich, F. R. Germany, and J. Brückner, Max-Planck-Institut für Chemie, Abteilung Kosmochemie, Saarstraße 23, D-6500 Mainz, F. R. Germany

Recent calculations on cosmogenic nuclide production in lunar or planetary surfaces were based on modeled fluxes of cosmic particles as a function of depth. The validity of these models, being dependent on the incident GCR spectrum and on the chemical composition of the surface, is not always obvious. A more general treatment shall be pesented here. In particular, a method for calculating the γ-albedo is developed which is of special interest in regard to the Mars-Observer Mission.

The HERMES code system (1) which is the basis of the calculations consists of four modules HETC/KFA-2, NDEM, EGS4 and MORSE-CG along with several auxiliary codes for data analysis. This system is mainly applied for shower calculations of calorimeters and is described in detail by Ref. (2). The basic input data required for this method are differential particle- particle cross sections for HETC/KFA-2 and cross section libraries for the coupled n-γ-tansport calculations in MORSE-CG. Primary and secondary particle fluxes as a function of depth and energy are calculated dependent on the source spectrum, material and geometry of the target using analog Monte-Carlo methods. These results can be folded with any available reaction cross section to obtain the production rates of interest.

As a test case for Mars, a 2π-GCR irradiation of the lunar surface was simulated. The GCR spectrum was taken as the mean energy distribution from solar maximum 1969 and solar minimum 1965. A Regolith soil of density $\rho = 1.5$ g/cm^3 and a chemical composition given in Table I was chosen. An effective simulation of a 2π-irradiation on an infinitely large planetary surface was performed by substituting this geometry by a large but not infinite disk of appropriate thickness. A point source was positioned above the center of this disk.

Table I: Chemical composition of lunar soil.

elem.	O	Mg	Al	Si	Ca	Ti	Fe	trace elem.
[g/g]	0.406	0.049	0.064	0.209	0.099	0.042	0.130	$66.9\,10^{-06}$

The total primary and secondary particle fluxes resulting from HETC/KFA-2 and MORSE-CG calculations are presented in Fig. 1 together with the total γ-flux (not including decay of naturally occurring radionuclides). By folding the neutron flux with the $^{10}B(n,\alpha)^7Li$ reaction cross sections the corresponding reaction rates are obtained and can be compared with the results of the LNPE-experiment (3,4,5). As can be seen in Fig. 2, the agreement between experiment and simulation is excellent, assuming a total GCR flux (4π) of 3.0 p/sec cm^2 as a realistic value for a solar maximum 1969. $^{235}U(n,f)$ rates could be reproduced as well. In contrast to the calculations of Lingenfelter (6) the obtained Cd ratio as a function of depth was in good agreement with the experimental data.

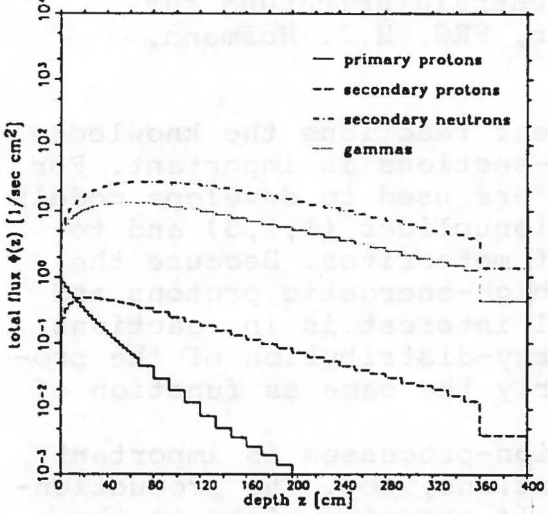

FIG. 1 Total particle and γ- fluxes as a function of depth in lunar surface, normalized to the primary flux $\Phi_{GCR}(2\pi) = 1.0/\mathrm{sec\,cm}^2$

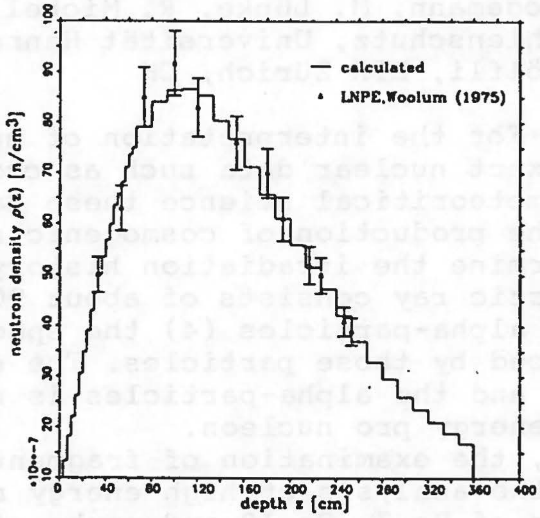

FIG. 2 Calculated $^{10}B(n,\alpha)^7Li$ reaction rates as a function of depth in lunar surface compared to experimental results from Ref. (5).

For calculations concerning Mars (or any other planetary surface) some minor changes of the setup have to be made. In this case, an atmosphere has to be taken into account and the water content of the soil implies differences in the thermal neutron spectrum. Including selected γ-ray lines in MORSE-CG calculations, parameter studies on variations in chemical composition and layered surface structures have to be performed.

The HERMES code system has proved to give a reliable description of particle fluxes in the lunar surface. Therefore, application of HERMES for the Mars Observer project seems very promising.

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CROSS-SECTIONS FOR LONG-LIVED RADIONUCLIDES FROM HIGH ENERGETIC CHARGED-PARTICLE-INDUCED REACTIONS; B. Dittrich, U. Herpers, Abteilung Nuklearchemie, Universität zu Köln, FRG, R. Bodemann, M. Lüpke, R. Michel, Zentraleinrichtung für Strahlenschutz, Universität Hannover, FRG, H.J. Hofmann, W. Wölfli, ETH Zürich, CH

For the interpretation of nuclear reactions the knowledge of exact nuclear data such as cross-sections is important. For the meteoritical science these data are used to develope models of the production of cosmogenic radionuclides (1,2,3) and to determine the irradiation history of meteorites. Because the galactic ray consists of about 90% high-energetic protons and 10 % alpha-particles (4) the special interest is in reactions induced by those particles. The energy-distribution of the protons and the alpha-particles is nearly the same as function of the energy pro nucleon.
Also, the examination of fragmentation-processes is important for the analysis of high energy reactions, too. The production-rates of Be-7, Be-10 and maybe of C-14 can give hints to the mechanimsm of the processes on nuclear level.
In the last years we did several irradiation experiments with high-energy-protons to study the transition from spallation to the fragmentation reactions. The irradiations were done with 600, 800, 1200 and 2600 MeV protons (tab.1).

Tab. 1: Irradiation experiments carried out

Energy(MeV)	600	800	1200	2600
Accelerator	CERN CH	LANL USA	LNS F	LNS F
Date	22.11. 1984	22.7. 1988	17.12. 1987	15.3. 1988
Time (1000s)	45.7	22.4	39.6	43.1
Flux(*10^{10} ps^{-1})	1.97	8.67	6.99	2.33

After the gamma-spectrometric measurements (5) chemical separations were done to get samples for the accelerator mass spectrometry. For the target elements oxygen in form of quartz, magnesium, aluminum, silicon, manganese, iron, cobalt and nickel separation techniques were developed. The chemical methods used give separates for all long-lived radionuclides which are important for the meteoritical science from only one target.
After solving the target with carrier for the nuclides of interest in a suitable solvens several separations by precipitation and ion-exchange were done. The measurement of the Be-10 were done at the ETH Zürich in co-operation with the group of Prof. W. Wölfli. The technique of the accelerator mass spectrometry is described in detail elsewhere (6).
The cross-sections of Be-7 and Be-10 at 600 MeV as a function of the mass number of the target is given in figure 1. For Be-7 the plateau in the region of 2-3 mb with variations above the target mass of 40 is explainable by fragmentation, whereas the cross-

sections of Be-10 under the same conditions show a decreasing tendency up to nickel The explanation of this structure cannot be found in a simple spallation model.

Up to now we determined the cross-sections of the Be-7 production in the same target-material at higher energies (fig. 2). One can see the increasing of the fragmentation-plateau up to 10 mb with increasing energies and the dissapearance of the differences between the small and high target masses. But there are still variations in the mass dependence of the cross-sections of the Be-7 production. It is necessary to take these variations into account by developing a model of fragmentation.

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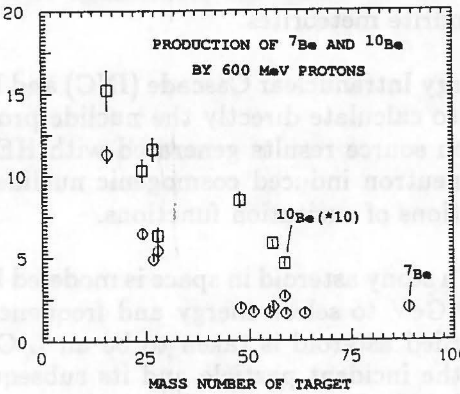

Fig. 1: 600 MeV cross-section of the production of Be-7 and Be-10 as a function of the mass of the target material.

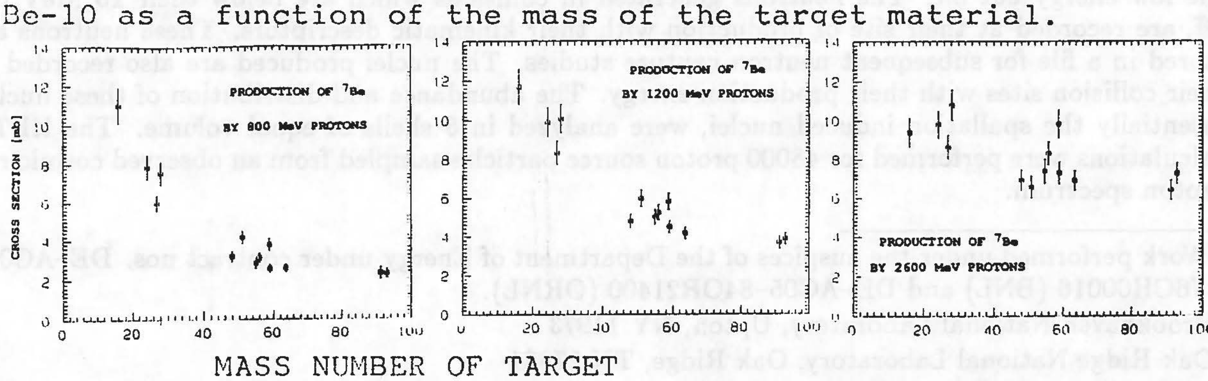

Fig.2: Cross-sections of the production of Be-7 as function of the mass of the target material at 800, 1200 and 2600 MeV.

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INC MODEL CALCULATION OF COSMOGENIC NUCLIDE PRODUCTION IN STONY METEORITES*

M. Divadeenam,[1] T. A. Gabriel,[2] O. W. Lazareth,[1] M. S. Spergel,[3] and T. E. Ward[1]

Intranuclear Cascade Model Monte Carlo calculations of ^{26}Al and ^{53}Mn production due to cosmogenic proton induced spallation of a model meteorite composition similar to L Chondrite were made. The calculated predictions are consistent with the observed decay rates in L Chondrite stony meteorites. The calculated ^{26}Al production rate in a 1 m diameter meteorite is within 1/2 S.D. of the mean taken from 100 bulk determinations in L Chondrite samples compiled by Nishiizumi. Similarly the calculated average value for ^{53}Mn is consistent within one S.D. of the mean in the widely scattered ^{53}Mn data. The production rates of ^{12}C, ^{13}C, and ^{14}C are also predicted.

In our calculations, use is made of Monte Carlo techniques for identifying nuclear collisions and specific nuclear reactions as well as establishing the transport of the incident nucleon and its generated nucleons. It is thus possible to use an integrated calculational approach in predicting the cosmogenic nuclide production rate and depth dependence. Previous calculational approaches have examined the production of nuclides by separating the collision into spallation, neutron capture and fragmentation processes. The calculations use a transport type mechanism for predicting the depth dependence of the cosmic ray induced nuclides (i.e. cosmogenic nuclides). One of the problems in predicting the production of cosmogenic nuclides, as a function of depth in meteorites, has been the need to determine the numerous nucleon–nuclear cross sections and then the subsequent nuclide excitation rates. In the case of neutron capture induced nuclides these difficulties have led many authors [e.g. (1–6)] to utilize the similarity in the shape to the production of ^{3}H for predicting the production of neutrons. These tritium rates were normalized to neutron production observations either for the Moon or for Chondrite meteorites.

In particular, the High Energy Intranuclear Cascade (INC) and Internuclear Cascade Transport Code, HETC [e.g. (7)] is used to calculate directly the nuclide production rate due to spallation. It is planned to link the neutron source results generated with HETC to the low energy neutron transport code, MORSE. The neutron induced cosmogenic nuclide production will be calculated without the resort to extrapolations of excitation functions.

The isotropic irradiation of a stony asteroid in space is modeled by utilizing the observed cosmic ray proton spectrum up to 200 GeV to select energy and frequency via Monte Carlo techniques. The composition of the bombarded asteroid is taken to be an L Chondrite like composition [e.g. (8)]. The HETC code follows the incident particle and its subsequent descendent light particles ($A < 5$) until they are absorbed, exit the meteorite (presently set at 1 m diameter) or drop below the low energy cut off. The neutrons generated in collisions which are below their 15 MeV cut off, are recorded at their site of production with their kinematic descriptors. These neutrons are stored in a file for subsequent neutron capture studies. The nuclei produced are also recorded at their collision sites with their production energy. The abundance and distribution of these nuclei, essentially the spallation induced nuclei, were analyzed in 5 shells of equal volume. The HETC calculations were performed for 48000 proton source particles sampled from an observed cosmic ray proton spectrum.

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[1]Brookhaven National Laboratory, Upton, NY 11973
[2]Oak Ridge National Laboratory, Oak Ridge, TN 37831
[3]York College, CUNY, Jamaica, NY 11451

The analysis of the history events generated by HETC utilizes 4 outer shells down to a depth of 30 cm and the central sphere to yield the production rate of ^{26}Al at 3.1810×10^{-2} no. sec^{-1} cm^{-3} which is equivalent to 54 dpm/kg for the decay rate predicted. The predicted ^{53}Mn production rate is 2.91×10^{-2} no. sec^{-1} cm^{-3}. Here the decay rate is calculated using the accepted Bogou standard: kg (Fe +1/3Ni), to give 223 dpm/kg for the ^{53}Mn decay rate.

Depth dependent neutron source spectra were calculated for a 1 m diameter meteorite in order to calculate the neutron capture contribution to nuclide production. Spallation and neutron induced production of cosmogenic nuclides both have to be examined in detail for measured radiogenic nuclides. It is expected that the spallation contribution will dominate near the surface while neutron induced contributions will dominate deep within the meteorite. Since cosmogenic nuclide ratios are less sensitive to incident flux normalization, selected isotopic ratios will be examined to give insight into inherent properties of the meteorite, such as pre–atmospheric–exposure size. In the present work only the spallation reaction product nuclei production rates are presented.

Monte Carlo calculations of ^{26}Al and ^{53}Mn production in model meteorite composition similar to L Chondrite has yielded predictions which are consistent with the observed decay rates in L Chondrite stony meteorites [e.g. (9)]. The calculated ^{26}Al production rate (54 dpm/kg) in a 1 m diameter meteorite as seen in fig. 1, is within 1/2 S.D. of the mean (49 ± 11 dpm/kg) taken from 100 bulk determinations in L Chondrite samples compiled by Nishiizumi. Similarly calculated average value for ^{53}Mn (223 dpm/kg) is consistent (cf fig. 2) with one S.D. off the mean in the widely scattered ^{53}Mn data (362 ± 113 dpm/km) compiled by Nishiizumi.

An examination of the depth dependence of these nuclei are seen in figs. 3 and 4. According to the HETC predictions, there is a gradual rise in the rate of production for ^{26}Al up to a depth of about 8 cm, (or 25 g/cm^2) as seen in fig. 1 (bottom). The production rate as a function of depth shown for ^{53}Mn displays an "expected" behavior, rising as a function of depth shown in fig. 1 (top). In addition to the ^{26}Al and ^{53}Mn, spallation calculations have also been made for the cosmogenic nuclei ^{12}C, ^{13}C, and ^{14}C in the meteorite. Carbon isotope production is most unusual, since it is not expected it in this L chondrite meteorite, yet it is produced at low levels by the spallation reactions as seen in fig. 4. However, the production rate indicates some statistical deviation from the mean as a function of depth.

In conclusion, considering the success of the HETC calculations in general and the level of statistical confidence presently generated, it is felt that the calculations must be performed with larger number of cascade particles. It may well be that the physical requirement to sample the large range of energies (40 MeV to 200 GeV) seen in the galactic cosmic ray spectrum demands more cascade particles.

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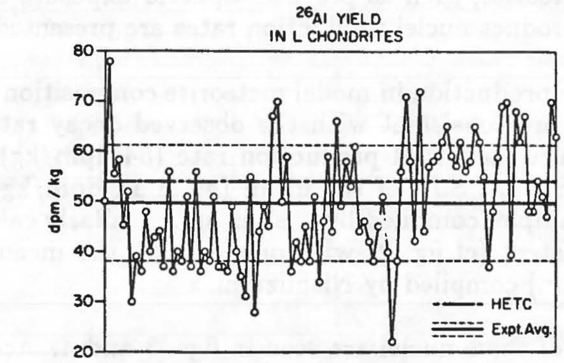

Fig. 1. ^{26}Al production rate: One hundred experimental data points taken from Nishiizumi's compilation are plotted to demonstrate the degree of fluctuation from the mean value (——). The HETC calculated mean value (——) over the meteorite volume is shown for comparison.

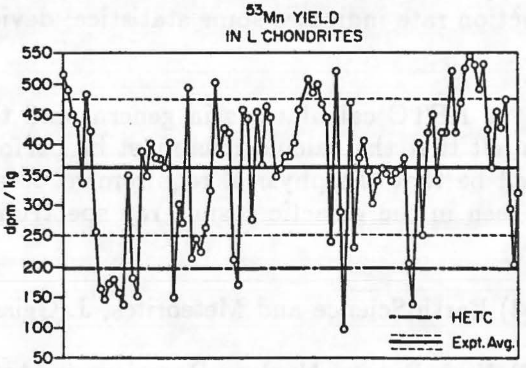

Fig. 2. ^{53}Mn production rate: One hundred experimental data points taken from Nishiizumi's compilation are plotted to demonstrate the degree of fluctuation from the mean value (——). The HETC calculated mean value (——) over the meteorite volume is shown for comparison.

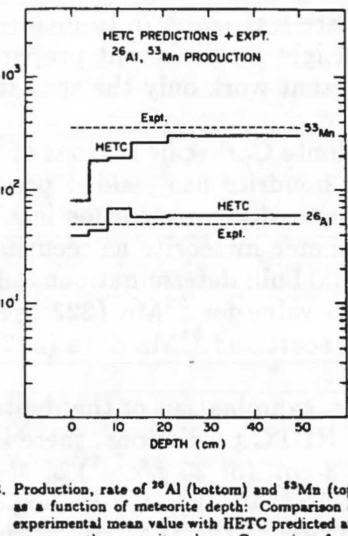

Fig. 3. Production, rate of ^{26}Al (bottom) and ^{53}Mn (top) as a function of meteorite depth: Comparison of experimental mean value with HETC predicted average over the meteorite volume. Conversion of production rate to dpm/kg units in the case of ^{53}Mn by making use of the Bogou standard.

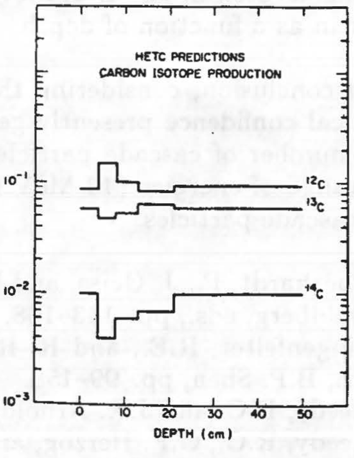

Fig. 4. HETC calculated spallation product production rates for carbon isotope ^{12}C, ^{13}C, and ^{14}C as a function of meteorite depth.

APPLICATIONS OF THE H E R M E S CODE SYSTEM IN METEORITICS

P. Dragovitsch, P.Cloth, G.Dagge, D.Filges (Institut für Kernphysik KFA Jülich, POB 1913, D-5170 Jülich), R.Michel (ZfS Universität Hannover, Am kleinem Felde 30, D-3000 Hannover-1)

A promising way to understand the effects of galactic cosmic ray particle radiation (GCR) in extraterrestrial matter is to simulate the complex irradiation of the respective body by suitable computer codes. By this method beside the observation of integral quantities (e.g. production of cosmogenic nuclides in meteorites) also detailed studies of the mechanisms of particle transport, interaction and production can be done in a wide range of irradiation conditions. In this context the extensive capabilities of the newly developed HERMES (1) code system offer themselves for an application in meteoritical research.

HERMES (High Energy Radiation Monte Carlo Elaborate System) is a system of off-line coupled Monte Carlo Codes which are needed to treat the different physics to be considered in the computer simulation of radiation transport and interaction problems. Additional HERMES offers comprehensive capabilities of Monte Carlo analysis and of merging the intermediate outcomes of partial programs into final results. The easy interchange of input/output data between the different modules is realized by an interfacing system using standardized data structures (Fig. 1). For all codes indentical terms of geometry description (Combinatorical Geometry, CG) are given, permitting the build up of particle cascades within very complex geometries and material configurations. The program modules of HERMES are able to simulate secondary particle histories induced by primary projectiles of any energy from thermal energies (e.g. neutrons) up to some 10 GeV. The particles being considered by the program are p, n, π^+, π^0, π^-, μ^+, μ^-, e^+, e^-, γ, and light-heavy ions to $A = 10$.

The mean physics modules of HERMES are HETC/KFA-2, MORSE-CG and EGS4. Beside some minor physic programs they are surrounded by a framework of modules treating for example the Monte Carlo analysis, the geometric setup, the command language or the graphical reproduction of the results.

In general the transport of an incoming high energy projectile (except el.-magn. rays) is performed by HETC/KFA-2. The code follows the history of the incindent particle to its first collision with a nucleus and implements the production of secondary particles using the intranuclear cascade-evaporation model (INCE) (1, and refs. therein). The outcoming secondary particles of the repective nuclear reaction are stored on temporal stack. Their history is followed one after the other until predefined cut-off energies are reached ore the geometry is left. Those particles and particles which cannot be handelt by the code, are written down on a submission file and can be used as input for other modules. Neutrons with energies below 15 MeV are submitted to MORSE which does a stochastic simulation of neutral particle transport (n, γ) The electromagnetic part of a shower is performed with EGS4 providing Monte Carlo simulation of the coupled transport of electrons and photons in the energy range between a few KeV to some TeV.

The properties of HERMES discussed above show its excellent suitability to simulate cosmic ray interactions with extraterrestrial matter. In the past HERMES was already used to calculate the setups of accelerator-experiments simulating the 4π-isotropic GCR-irradiation of meteoroids (2,3,4) with monoenergetic protons. The equivalence between the experimental and the calculational approach (5) allows the extension of the computer simulations to realistic GCR-irratiations of extraterrestrial bodies in space.

A series of Monte-Carlo simulations of the isotropic and homogeneous irradiation of H- and L-Chondrites with GCR-protons was performed in the recent year. The meteoroids were assumed to be spherical with radii variing between 5 and 65 cm. The differential energy-distribution of the incident GCR-protons was created from the average value of the GCR-fluxes of solar minimum 1965 and solar maximum 1969 to get a realistic source. Because of statistical reasons an analysis of residual nuclei produced inside the bodies has no sense the analysis of the Monte Carlo events was done in respect to primary and secondary protons and neutrons. The differential fluxes of these particles were registrated inside equidistant spherical shells of the meteoroids delivering depth dependend averaged fluxes. They are suitable as input data for folding algorithm (2 - 5) resulting in depth dependend production rates of cosmogenic nuclides.

The results of these physical computer simulations compared with the measurements of cosmogenic nuclides in meteorites for the first time give the chance to get concrete informations about the GCR-variations in time, intensity, energy-distribution and composition.

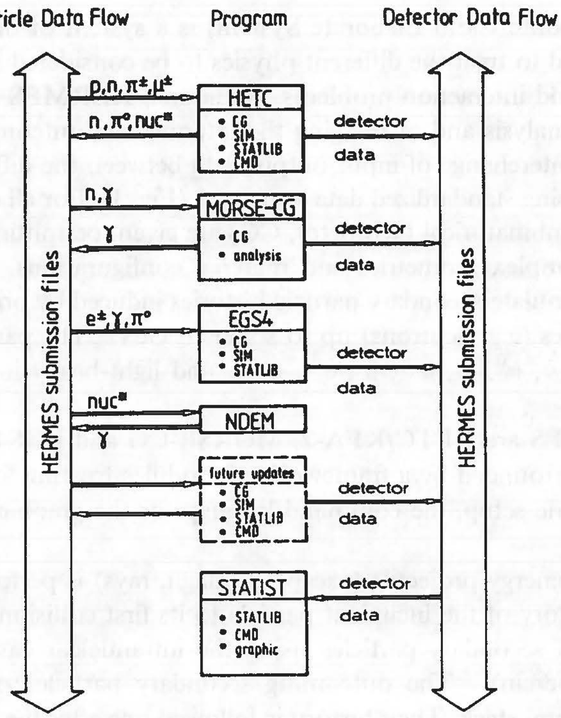

Fig.1: Organization scheme of the HERMES program system

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SIMULATION OF THE GCR IRRADIATION OF METEOROIDS: UNIFICATION OF EXPERIMENTAL AND THEORETICAL APPROACHES P. Dragovitsch (Institut für Kernphysik KFA Jülich, POB 1913, D-5170 Jülich) and the Cologne Collaboration (1)

By the interaction of galactic cosmic ray particles (GCR) a large variety of stable and radioactive nuclides is produced in meteoroids. The observed abundances of these cosmogenic nuclides in meteorites provide a multitude of information on the irradiated matter as well as on the cosmic radiation itself. The interpretation of cosmogenic nuclides in terms of the irradiation history or of the temporal and spatial behavior of the GCR itself requires a precise and accurate modelling of the depth and size dependence of *all* nuclear interactions leading to the respective nuclide production. The approaches made in the past to uncover these mechanisms were not satisfactory, due to the lack of physical foundation of most calculational models and due to systematic experimental problems for nearly all simulation experiments. Therefore a collaboration (1) was initiated in 1983 to improve this situation. Two independent approaches - an experimental and a calculational - were made to study the transport and interaction phenomena of GCR in meteoroids.

A series of thick target irradiations of spherical meteoroid models with radii of 5, 15 and 25 cm with 600 MeV protons was performed at the CERN-synchrocyclotron. The artificial meteoroids were made out of diorite (R = 5cm) and gabbro (R = 15 and 25 cm) with a density of 3 g cm^{-3} approximating a chondritic compositon. A homogeneous 4π irradiation of the models was achieved by complete mechanical integration of the accelerator beam using a sophisticated irradiation machine. The depth dependent production of a wide range of radionuclides from target elements O, Mg, Al, Si, Ti, Fe, Co, Ni, Cu, Ba, Lu, and Au was measured. Furthermore, the production of He and Ne isotopes from Al, Mg, Si and from degassed meteoritic material was determined. Including data derived from thin target experiments the size dependence of nuclide production for radii from 0 to 75 g cm^{-2} was investigated. For a detailed description see references (2) and (3) and the references therein.

The theoretical approach was to calculate the spectra of primary protons and of secondary protons and neutrons in the artificial meteoroids by computer simulation of the experimental setups. For this the HERMES code system (4) was engaged. HERMES is a system of Monte Carlo computer codes solving the physical problems of radiation transport and interactions within matter. A detailed description of the codes and the performance of the calculations is given by references (4) and (5).

Already the experimental depth profiles of nuclide production showed a wide variety of shapes depending both on the sizes of the meteoroid models and on the individual reaction channels possible for the respective nuclide. The strongest size dependence was observed for ^{60}Co from Co with center production rates increasing by a factor of 100 for radii between 5 cm and 25 cm. For other low energy products an increase up to a factor of 3.5 was typically observed. For products requiring extremy high incident energies a decrease of center production was seen up to a factor of 10. In between shapes having pronounced maxima (low energy products) and minima (high energy products), respectively, all transitional shapes could be observed (1).

The calculated fluxes of the secondary protons and neutrons strongly depend on depth and size of the meteoroid models. The differences between proton and neutron spectra are considerable both in their shape and in their magnitude. On the basis of thin-target excitation functions the outcoming spectra were integrated to theoretical production rates (1,2,3). These theoretical depth profiles allowed to distinguish the different contributions of primary and secondary protons and of neutrons and to unravel the individual production modes of cosmogenic nuclides in meteoroids. The agreement between theoretical and experimental depth profiles was a convincing validation of the suitability of the used computer codes in cosmic ray applications. Furthermore it shows that it is possible to model the production of residual nuclei in real meteoroids, provided that reliable excitation functions are given.

An extension of the theoretical approach to the simulation of the irradiation of H- and L-chondritic meteoroids in space with GCR-protons was done. For this the energy distribution of the incident protons was assumed to be the average value of the GCR-fluxes of solar minimum 1965 and solar maximum 1969.

The comparison of the resulting particle fluxes with those of the monoenergetic 600MeV case shows significant differences by an increase both of secondary proton and neutron fluxes simulating the realistic irradiation. The shapes of the particle spectra are quite different, too. The resulting depth dependent production rates and their relations to one other are comparable to those measured in meteorites. They indicate the necessity of studiing the influence of the spectral distributions of GCR protons as well as the influence of GCR-α-particles. These investigations are possible using the presented model. The connection of fluxes calculated by HERMES with reliable production cross sections promise to find out both the GRC-intensity and GCR-energy distribution in history as an *unequivocal* function of time.

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SIMULATION EXPERIMENTS FOR COSMOGENIC NUCLIDE PRODUCTION RATES;
Peter A.J. Englert, Department of Chemistry, San Jose State University, San Jose, CA 95192

The major problems of accurate prediction of cosmogenic nuclide production rates depend on the way how the complex physical processes that lead to their production are understood and incorporated into models. Cosmogenic nuclide production cross sections, especially for neutron induced nuclear reactions are not known for all incident particle energies. This is a significant problem, as secondary neutrons form the major cosmogenic nuclide producing component of the secondary particle cascade within a meteorite or a planetary surface exposed to cosmic radiation [e.g. 1]. Furthermore, the secondary particle cascade itself is a function of the primary cosmic ray particle flux, the energy and charge of the entering particles, the depth within the meteorite and planetary surface, and the composition of the target. The flux, composition and energy of the primary cosmic radiation is well known and understood. Consequently, the two areas of major concern are nuclear interaction cross sections in particular for neutrons, and the development of the secondary particle cascade as a function of shielding and chemical composition of the meteorite or planetary surface.

Though, a priori, the determination of numerous reaction cross sections for residual nuclei, nature, energy and angular distribution of exit particles, would seem to be the best way to solve all problems, it is immediately obvious that this is a long-term ambitious task. For proton and alpha-particle cross-section extensive tables have been established since about 1978 by Michel et al. [e.g. 2].

Simulation experiments are not equivalent to cross section experiments. In general, a few parameters are precisely known or controlled. A few, but by far not all effects of a controlled parameter change on the complex system are observed, in order to allow conclusions on the unobserved multitude of parameters. The result of a simulation experiment is therefore not a new physical parameter, but rather a step towards a better physical understanding of the phenomenon of interest or indication for changes of a model. The use of simulation experiments will therefore serve two aspects, the improvement and extension of our physical understanding of the complex phenomena as well as the validation of existing semiempirical models.

The different approaches of simulation experiments obtain their justification from the fact that no charged particle accelerator is able to produce particle beams with energy spectra even partially similar to that of the solar or galactic cosmic radiation. In addition, only one charged species can be produced at a time. In order to simulate the interaction of cosmic radiation with matter several experimental runs with different particle types and different energies would have to be made to approach the problem. On the other hand, complex neutron spectra, as they occur upon interaction of the galactic cosmic radiation inside matter are not too difficult to produce with monoenergetic charged particles from accelerators, but to determine their energy spectra and fluxes at a certain location within the irradiated matter is everything else but trivial; it is frequently not possible.

The first approach is based on the bombardment of thick targets: High energy charged particles bombard a target of defined dimensions to develop secondary particle fluxes as they may occur in realty. Elements or simple chemical compounds are exposed to different particle fields inside the target and subsequently analyzed for nuclear reaction products. A second approach consists in the generation of complex neutron beams of reasonably well known or measured energy spectra and flux. These spectra may represent those occurring under certain conditions in planetary surfaces or meteorites, and cosmogenic nuclide production rates can be determined for those conditions.

Research in the past was concerned with the production of residual stable and radioactive nuclides, many of which were short-lived and only partially useful in cosmogenic nuclide studies. A compilation of Thick Target experiments performed until 1984 can be found in [3]. Much progress has been made with thick target bombardments for cosmogenic nuclide studies in meteorites recently, i.e. after 1984. Two contributions of this workshop will discuss the CERN meteorite model irradiations series, model validation and application of the results to meteorites [4].

Only one additional thick target experiment has been performed and results relevant to cosmogenic nuclide research were obtained recently. This experiment was the exposure of a very thick rock target to 2.1 GeV protons and 800 MeV/nucleon alpha particles, in order to simulate the interaction of galactic cosmic radiation with matter. The effect of the projectile type on the build up of the low energy neutron component of the secondary cascade was analyzed [5]. It was shown that in case of alpha-particle impact the low energy neutron flux maximum occurred at shallower depths than in the case of the proton experiment. A ^{14}C depth profile along the beam axis was determined in the target rock material [6], and a ^{10}Be and ^{26}Al profile in aliquots of the same samples are in progress. The ^{14}C-contents follow the secondary cascade development as a function of depth as modeled for undisturbed lunar surface cores. The dependence of ^{14}C-production on the low energy component suggests strongly detailed studies of the depth dependent production of the isotope in meteorites and meteorite model irradiations. No extensive model calculations were done in this case.

Complex neutron spectra are obtained around beam stops of accelerators. If facilities are available to irradiate samples in these beam stop areas, simulation experiments with thin targets in these neutron fields are possible. The difficulty that arises immediately is the determination of the neutron spectra and fluxes. Under cosmogenic nuclide production conditions only threshold monitor reactions are applicable, and, consequently, energy spectra and to some extent also fluxes have a high degree of uncertainty.

Beam stop exposure experiments were continued and focussed especially neutron produced ^{10}Be, ^{14}C, and ^{26}Al in silicon dioxide as it is important for terrestrial applications [7,8]. Though absolute production rates cannot be determined in such experiments, production rate ratios obtained contain useful information.

Thick target bombardments have proven to be very sucessful simulation experiments useful for cosmogenic nuclide production rate studies. The difficulties of determining neutron fluxes and energy spectra in beam stop environments make experiments there less somewhat less useful.

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A MODEL FOR THE PRODUCTION OF COSMOGENIC NUCLIDES IN CHONDRITES

Th. Graf*, H. Baur, P. Signer. ETH-Zürich, Switzerland. *Pres. address: Univ. of Calif., San Diego.

The production rates of cosmic-ray produced nuclides depend on the chemical composition of a meteoroid, its size and shape and the shielding depths of the samples. In turn, the accuracy of exposure age estimates depends on the knowledge of the production rates. We developed a model to calculate the production rates of He, Ne, and Ar as well as of ^{10}Be, ^{26}Al, and ^{53}Mn in chondrites of any shape and size. This model is based on the production rate equation used by Signer and Nier [1] to model the distribution of the light noble gases in iron meteorites. The equation contains 2 free parameters for each nuclide which were fitted to the data of the L5 chondrite Knyahinya [2,3]. The validity of the model was then tested by comparing the predictions with experimental data on Keyes [4], St. Severin [5], and ALHA78084 [6]:

Fig. 1 shows predicted and measured ^{22}Ne/^{21}Ne ratios in the three test meteorites and in Knyahinya. The predictions are in excellent agreement with the experimental data. In fact, the deviations from the calculated depth profiles are comparable to the experimental uncertainties. Note, that agreement of the model predictions with ^{22}Ne/^{21}Ne ratios observed in St. Severin require the assumption of a nonspherical shape for this meteorite. We use an ellipsoidal shape with semi-axes of 40 cm, 25 cm, and 20 cm, which is consistent with the shape derived from track densities [7]. For ALHA78084, Keyes, and Knyahinya we adopt preatmospheric radii of 15 cm, 31 cm, and 45 cm, respectively. Exposure ages based on the production rates of ^{21}Ne and ^{38}Ar agree within 5% for each of the meteorites. Further, the model reproduces the shape of the measured depth profiles of ^{10}Be, ^{21}Ne, ^{22}Ne, ^{38}Ar, and ^{53}Mn within error limits, which of course are large compared to those of the ^{22}Ne/^{21}Ne ratios. Differences between ^{3}He ages and ^{21}Ne ages are up to 10%, and a comparison of measured and predicted ^{3}He/^{21}Ne ratios yields similar differences. This indicates a shortcoming of our model which predicts a size and shape independent linear correlation between the ratios ^{3}He/^{21}Ne and ^{22}Ne/^{21}Ne. In distinction, the correlation lines of all three test meteorites are considerably flatter than the one of Knyahinya.

Fig. 2 shows calculated production rates of ^{21}Ne versus ^{22}Ne/^{21}Ne ratios for spherical meteoroids of various radii. The ^{22}Ne/^{21}Ne ratio is widely used to calculate shielding corrected exposure ages. The dotted line in Fig. 2 shows the empirically determined shielding dependence of P(^{21}Ne) proposed by Nishiizumi et al. [8]. Because most meteorites have preatmospheric radii between 10 - 50 cm and the shielding depth of most samples exceed several centimeters, the relation between P(^{21}Ne) and ^{22}Ne/^{21}Ne ratios is an approximation that allows in some cases the determination of exposure ages with an uncertainty of 10-20%. However, Fig. 2 shows clearly, that the ^{22}Ne/^{21}Ne ratio does not uniquely quantify the shielding conditions of a sample. It is expected, that the shielding dependence of production rate ratios is in general smaller than that of production rates. For many years, ratios of stable and radioactive nuclides were used to determine exposure ages. Thereby the production rate ratio of the two nuclides has to be known. Our model predicts, that 3-isotope correlations which use the same reference are linear [9]. This might be an oversimplification, especially for the correlations of ^{3}He/^{21}Ne and P(^{26}Al)/P(^{21}Ne) ratios with

$^{22}Ne/^{21}Ne$ [3]. However, within error limits such a correlation exists for the $P(^{10}Be)/P(^{21}Ne)$ ratios of Knyahinya, St. Severin, and ALHA7808. It can be used to compute size and shielding corrected exposure ages in chondrites:

$$\frac{t}{1-\exp(-4.6\times10^{-7} \times t)} = \frac{P(^{10}Be)/P(^{21}Ne)\{1.11\} + (0.053 \pm 0.03)(^{22}Ne/^{21}Ne-1.11)}{(^{10}Be/^{21}Ne)\{m\}}$$

The production rate ratio $P(^{10}Be)/P(^{21}Ne)\{1.11\}$ is given in atoms/atom and for a $^{22}Ne/^{21}Ne$ ratio of 1.11. The index m denotes the measured values. Adopting an exposure age for Knyahinya of 40 Ma [2], we determine $P(^{10}Be)/P(^{21}Ne)\{1.11\} = 0.141 \pm 0.002$. Exposure ages of St. Severin and ALHA78084 derived by this method agree within 5% with those based on noble gas profiles. Note, that the slope of the correlation line may be 0 within 2σ error limits, indicating that the production of ^{10}Be by lower energy particles is about as important as for ^{21}Ne.

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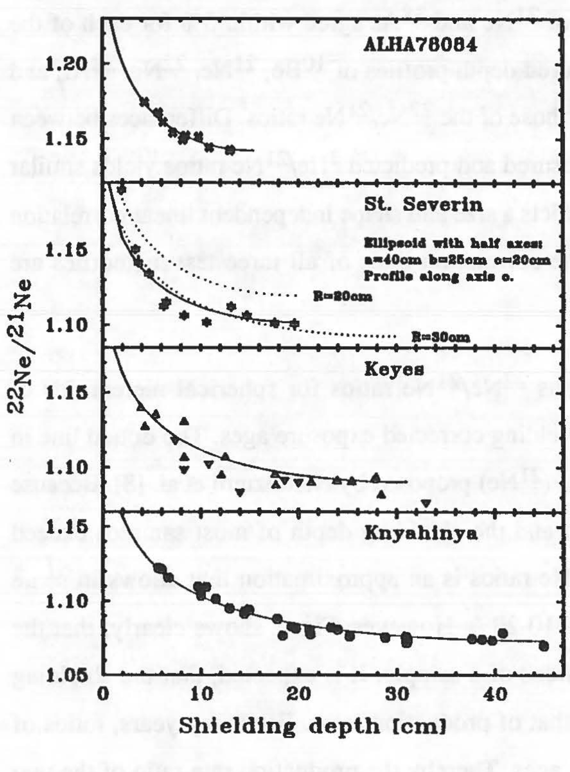

Fig. 1

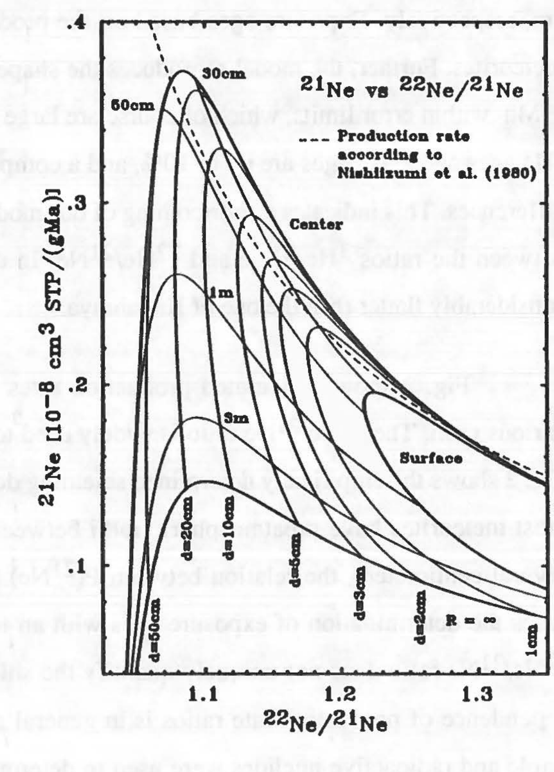

Fig. 2

COMPOSITION DEPENDENCE OF COSMOGENIC NUCLIDE PRODUCTION RATES;
G.F. Herzog, Dept. Chemistry, Rutgers Univ., New Brunswick, NJ 08904.

The rate P_i at which cosmic rays produce a cosmogenic nuclide *i* in a meteoroid or a planet depends in part on the composition of the irradiated body (Equation 1):

$$(1) \qquad P_i = \sum_j N_j \sum_k \int_0^{\infty} \sigma_{i,j,k}(E)\, \phi_k(E)\, dE$$

Here N_j represents the absolute elemental abundances, the index k runs over all types of nuclear-active particles (principally p, α, n), ϕ refers to the various particle fluxes and σ gives the cross sections for the formation of the nuclide as a function of the bombarding energy E. To the extent that ϕ_k is independent of composition and other factors, one can approximate P_i as a linear combination of terms, $P_i = \Sigma_j N_j P_{ij}$, where P_{ij} may be regarded as an elemental production rate. A set of numerical values for P_{ij} has practical utility: With such a set, one may normalize the concentrations of cosmogenic nuclides measured in bodies with different compositions to those expected in some compositional standard. Two related methods for estimating P_{ij} directly from measurements of cosmogenic nuclides were first applied to the cosmogenic noble gases.

Stauffer [1] analyzed the He, Ne and Ar contents of an assortment of meteorites with known and markedly different compositions. By using regression analysis, he obtained production coefficients for the ratios $^{21}Ne/^{3}He$ and $^{38}Ar/^{3}He$. With the assumption that P_3 is constant, the expressions he derived become estimates of the relative elemental production rates of ^{21}Ne and ^{38}Ar. Hintenberger et al. [2] modified the approach by analyzing minerals separated chemically from a single specimen of the L6 chondrite Holbrook. The restriction to one sample removes from the regression analysis noise due to shielding differences at the possible cost of some loss of generality. Bogard and Cressy [3] applied this method to minerals separated magnetically and by density from Bruderheim (L6) and reviewed earlier work for light noble gases. Table 1 presents a partial summary of results for GCR production of selected cosmogenic nuclides. To facilitate comparisons we have normalized production rates to those expected for the principal target element.

Model calculations and simulation experiments usually provide information about the composition dependence of production rates in tabular or graphical rather than equation form (e.g., [4,5]). Hohenberg et al. [6] and Regnier et al. [7] give elemental production rates for the cosmogenic noble gases in the moon. Table 1 includes an approximation of Reedy's calculations of P_{10} in St. Severin. It also includes some average values of P_{ij} for P_{21} and P_{26} from simulation experiments [8].

The assumption that $\phi_k(E)$ is independent of composition (and hence the inference $P_i=\Sigma_j P_{ij} N_j$) fails under certain conditions. **A)** If a nuclide is produced to a significant degree by thermal neutrons (e.g., ^{36}Cl [9], ^{80}Kr and ^{82}Kr [10], and ^{129}I [11]), then P_i will not equal $\Sigma_j N_j P_{ij}$ when the matrices to be compared contain different concentrations either of hydrogen (because H moderates the neutron spectrum effectively) or of elements with high cross sections for reactions with neutrons [12]. **B)** Begemann and Schultz [13] argue that the assumption of composition-independent $\phi_k(E)$ breaks down for the products of interactions at somewhat higher energies, e.g., ^{38}Ar from Ca. They suggest that the rate of secondary production should vary with the average atomic number of the matrix. **C)** The assumption of constant ϕ_k may fail for reasons not directly related to the composition of the body (temporal and spatial variation of the primary flux or the occasional influence of solar cosmic rays). In practice, these effects are treated separately and indeed, may be identified by the failure of the conventional composition- and shielding-dependent equations to reproduce measured values [14].

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Table 1. Relative production rates for selected isotopes.

Isotope	P_{ij}							Ref.
	O	Mg	Al	Si	S	Ca	Fe	
^{10}Be	1.0	0.94	≡1.1Mg	≡0.5Mg	≡0.5	≡0.3	≡0.16	15
	1.0	0.36		0.21			0.11	16
	1.0	0.32	0.28	0.17				8
	Mg	Al	Si	S	Ca	Fe	Ni	
^{21}Ne	1.0	≡1.35Si	0.15					1
	1.0		0.55	0.16		0.01		2
	1.0	≡1.35Si	0.19		≡~3Fe	0.006	≡Fe	17
	1.0		0.19	0.13	0.04	0.01	≡Fe	3
	1.0	0.36	≡0.19	≡0.13	≡0.04	≡0.01	≡Fe	18
	1.0	0.42	0.38					8
^{26}Al	≡0	1.0	0.65	0.08	≡0.0157	≡0.005		19
	0.02	1.0	0.22	0.12	≡0.02	≡0.002	≡Fe	20
	0.09	1.0	0.56	≡0.27	≡0.05	≡0.006		18
	0.65	1.0	0.24					21*
			K	Ca	Ti-Mn	Fe	Ni	
^{38}Ar				1.0		0.06		1
			7.0	1.0	0.22	0.056	≡Fe	3
				1.0		0.030		22
^{53}Mn						1.00	0.33	23

*for lunar sample with mass = 1 kg.

SATURATED ^{26}AL IN STONY METEORITES; J. E. Keith[1], H. R. Heydegger[2] and K. E. Kavana[2] 1. Johnson Space Center, Houston, TX. 2. Purdue University Calumet, Hammond, IN.

We have assembled from the literature a data base in which over 300 meteorites appear and which contains information on the bulk chemical analyses of these meteorites and their ^{26}Al content. Most numerical information in the data base is the average of several measurements.

We have regressed the ^{26}Al values on the chemical contents using the standard linear model with the pure constant set to zero. We have used an iterative algorithm which systematically eliminates under- and super-saturated ^{26}Al values, by forcing the residuals to be normally distributed. As a result, we obtain three sets of observations: 10 supersaturated, 128 saturated and 50 undersaturated, and an expression for the saturated ^{26}Al content as a function of the chemical composition. In the figure we compare the residuals predicted by our expression to those predicted by the expressions of other workers (1,2,3,4), class by meteorite class. The ideal result is zero, which is not forced, since in no case is the pure constant set to zero. As an examination of the figure will show, there is no bias in our prediction of saturated ^{26}Al content as a function of meteorite class, but there are biases in all previous predictive expressions.

We have explored the question of whether the regression coefficients will approach simple functions of the nuclear reaction cross sections, given increasing sample size. We show that this is not to be expected unless the mathematical model is correct, or the set of additional observations happens to be orthogonal to those comprising the assumed model. We demonstrate the consequences of attempting multiparameter regressions with nearly collinear data sets such as these without examining both the correlation structure of the X matrix and the residuals. We also examine the effects of increasing collinearity and decreasing sample size.

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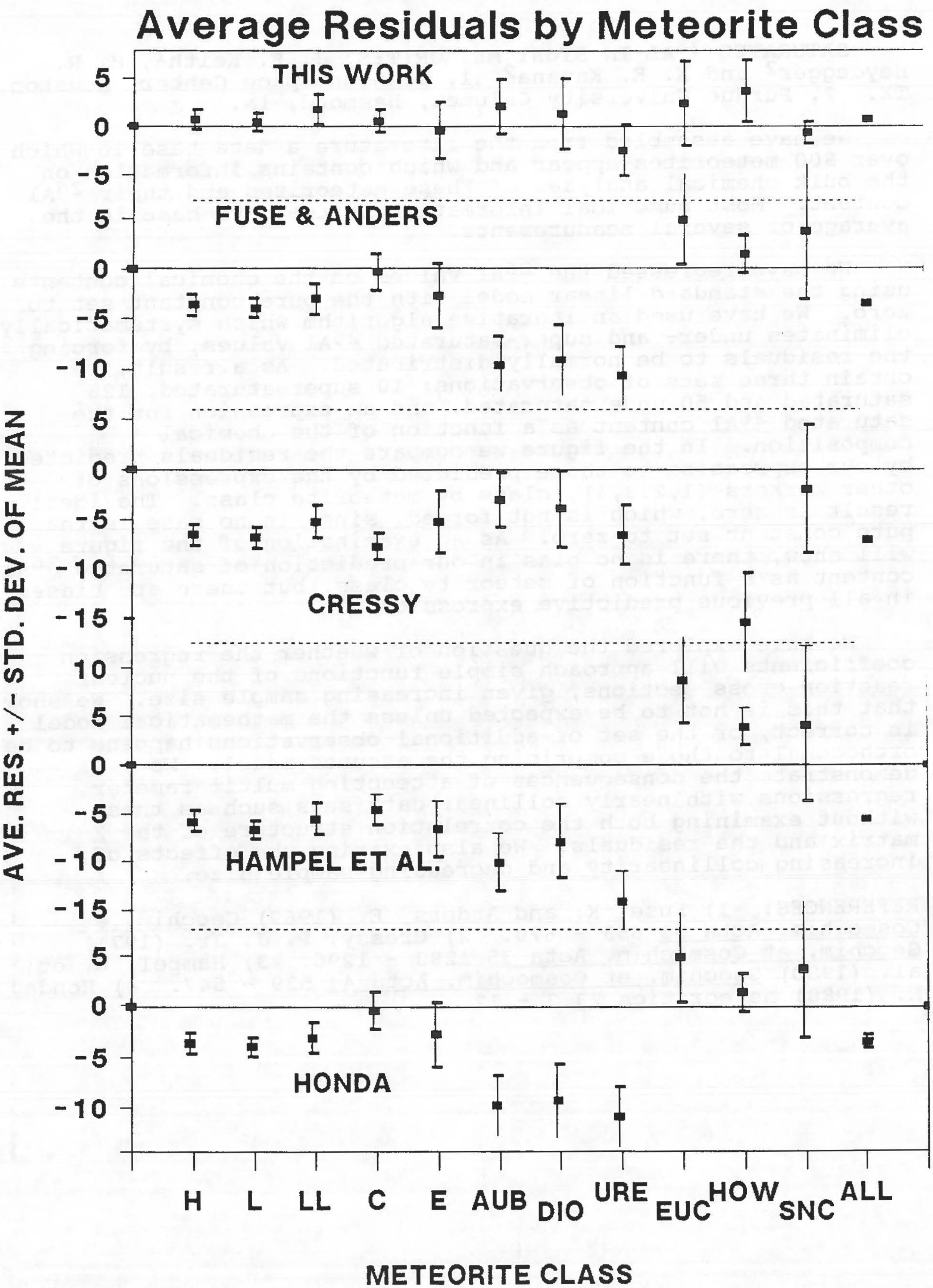
Average Residuals by Meteorite Class
THIS WORK
FUSE & ANDERS
CRESSY
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COSMOGENIC NUCLIDE PRODUCTION IN EXTRATERRESTRIAL OBJECTS; D. Lal,
Scripps Institution of Oceanography, GRD, A-020, La Jolla, CA 92093

Within a decade of discovery of cosmogenic ^{3}He in iron meteorites, a large number of cosmogenic nuclides were found in meteorites; their studies were then recognized as potential for delineating the complex evolutionary history of meteorites as well as the history of corpuscular radiation in space (1,2). Meteorites also contain an explicit decodable record of solid state damage produced by solar wind and multiply charged cosmic ray nuclei (3). By mid-1965, a voluminous study of cosmogenic effects had been carried out in chondrites and in iron meteorites. These studies constituted direct and the only means of studies of (i) exposure ages of meteorites, (ii) temporal variations in the flux of galactic cosmic radiation (called GCR) during during the history of the solar system, and (iii) the characteristics of low energy charged particles (mostly protons) accelerated by the Sun (this radiation is called SCR, the solar cosmic radiation), during the recent and early history of the solar system. The field received a major impetus in 1969-1970 with the start of availability of unique extraterrestrial samples, namely the lunar samples and antarctic meteorites. Lunar samples constituted the first documented extraterrestrial objects; they provided a rich record of low energy corpuscular irradiation at different epochs. This considerably widened the scope of cosmogenic nuclides in meteorites and extraterrestrial materials in general (3,4,5).

The cosmogenic isotope field received another major push with the development of the accelerator mass spectrometry (AMS) in 1977 (6), whereby it became possible to study several long-lived radionuclides, e.g. ^{129}I (half-life, 1.6×10^7 yrs), ^{10}Be (half-life, 1.6×10^6 yrs), ^{26}Al (half-life, 7.1×10^5 yrs) and ^{36}Cl (half-life, 3×10^5 yrs) at concentration levels of $\sim 10^6$ atoms in a sample. This, besides proving economical on the sample size needed for an analysis, led to a rapid increase in the measurements of concentrations of AMS detectable nuclides in extraterrestrial samples.

The field of cosmogenic nuclides in extraterrestrial samples is continually expanding its frontiers because of the continued availability of a larger number of extraterrestrial samples, and the achieved higher sensitivity of measurements. Our ability to interpret the cosmogenic data has also undergone a substantial improvement. Thus, in the final analysis, the cosmogenic field is alive and doing well. I will attempt to review the present and past efforts made in the field to understand the evolutionary history of extraterrestrial objects, and the history of energetic cosmic ray particles in the (1-3) A.U. space based on these studies. Special emphasis will be put on shortcomings in our present work, and on potential studies which should be made in the near future. The discussions will include:

(1) Cosmogenic nuclide production rates due to GCR and SCR particles in meteorites and the moon,

(2) Cosmogenic nuclide production in the Martian atmosphere, and in the surface rocks of Mars, and

(3) Cosmogenic nuclide production on the earth at atmospheric pressures 200 gm $\cdot$ cm^{-2} to 500 kg $\cdot$ cm^{-2}.

To date, the "standard model" used for cosmogenic production in extraterrestrial samples has been that proposed by Reedy and Arnold (7). The production of nuclides by SCR is straight forward (3,7,8) provided the nuclide excitation functions are known. The GCR model however needs considerable modifications to match the diversity of the size of the objects irradiated, and the nature of the problem studied. In particular, in small size objects (radius < 5 cms), the production becomes very sensitive to the shape of the GCR spectrum. The problem has been addressed by Reedy (9,10). In larger meteorites, (of radii 20-45 cms), the recently measured depth profiles of several cosmogenic nuclides in several meteorites have warranted (10,11,12,13) revision of theoretical production rates (6,11,12). The work of Michel, Englert and their collaborators on simulated artificial irradiation of objects of radii 10-25 cm has produced an invaluable data set for improving on our production rate modeling capabilities (14,15,16). At present, the largest uncertainties in the prediction of production rates must be ascribed to uncertainties in galactic cosmic ray fluxes and nuclide excitation functions for neutrons of energy 0.01-1.0 GeV.

The recent improvements in cosmogenic nuclide production rates have already made a significant impact on our understanding of meteoritic processes, e.g. the exposure ages of H-chondrites and parent body structure (17). In the course of time it is hoped that our interpretations of several of the observed cosmogenic effects would improve, as production estimates are improved. A confidence in our capability to predict production rates of course increases our capability of interpreting the cosmogenic data. The earlier interpretations, e.g. the near constancy of cosmic ray flux within a factor of two (1), reflected on our predictive capabilities then. With improvements (10,12), we can hopefully see appreciable variations in cosmic ray fluxes in the past, if they occurred.

An interesting example is that of the time integrated average SCR fluxes. The implications of the meteoritic data have recently been discussed (18). The review will also consider the newly emerging areas of cosmogenic effects in ancient regoliths (19,20) and recent irradiations in shielded materials on the earth (21).

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STATUS OF CHARGED PARTICLES AND NEUTRONS INDUCED NUCLEAR REACTIONS LEADING TO STABLE AND RADIOACTIVE ISOTOPES ; B. Lavielle , Centre d'Etudes Nucléaires de Bordeaux-Gradignan , Le Haut Vigneau 33170 GRADIGNAN, FRANCE

Cosmogenic nuclides are produced in meteorites and lunar samples by nuclear reactions induced by solar or galactic cosmic-ray irradiation. They are formed either by the primary cosmic-ray particles or by induced cascade of secondary particles including protons and neutrons and covering the whole energy range.

The table 1 lists cosmogenic nuclides which are frequently measured in this type of study.

Table 1: Nuclides	Half life(years)	Targets
$^{124,126,128-132,134,136}Xe$	S	Te,Ba,La,Ce,I
^{129}I	1.6 10^7	Te,Ba,La,Ce
$^{78,80,82,83,84,86}Kr$	S	Zr,Y,Sr,Br
^{81}Kr	2.1 10^5	Zr,Y,Sr,Br
^{60}Co	5.27	Co,Ni
^{54}Mn	312 days	Fe,Ni
^{53}Mn	3.7 10^6	Fe,Ni
^{41}Ca	1.0 10^5	Ca,Fe,Ni
$^{39,41}K$	S	Fe,Ni
^{40}K	1.3 10^9	Fe,Ni
^{39}Ar	269	Fe,Ni,Ca,K
^{37}Ar	35 days	Fe,Ni,Ca,K
$^{36,38}Ar$	S	Fe,Ni,Ca,K
^{36}Cl	3 10^5	Fe,Ni,Ca,K
^{26}Al	7.1 10^5	Si,Al,Fe
^{22}Na	2.6	Mg,Al,Si,Fe
$^{20,21,22}Ne$	S	Mg,Al,Si,Fe
^{14}C	5730	O,Mg,Si,Fe
^{10}Be	1.6 10^6	O,Mg,Si,Fe
^{3}He,^{4}He	S	O,Mg,Si,Fe
^{3}H	12.3	O,Mg,Si,Fe

The main target elements from which most production of the considered isotopes occurs are also reported . Many cosmogenic nuclides such as neon isotopes or ^{26}Al can simultaneously be produced by distinct mechanisms such as spallation nuclear reactions induced by high and medium energy protons (e.g. $Fe(p,X)^{21}Ne$) or interaction with low energy neutrons (e.g. $^{27}Al(n,2n)^{26}Al$). Although these different processes are generally understood, data interpretation could certainly be improved. In many cases, a lack of experimental data such as production cross sections still represents a limitation of the production rates calculations which are essential to the determination of the irradiation age and of the shielding depth and size dependence of the investigated samples.

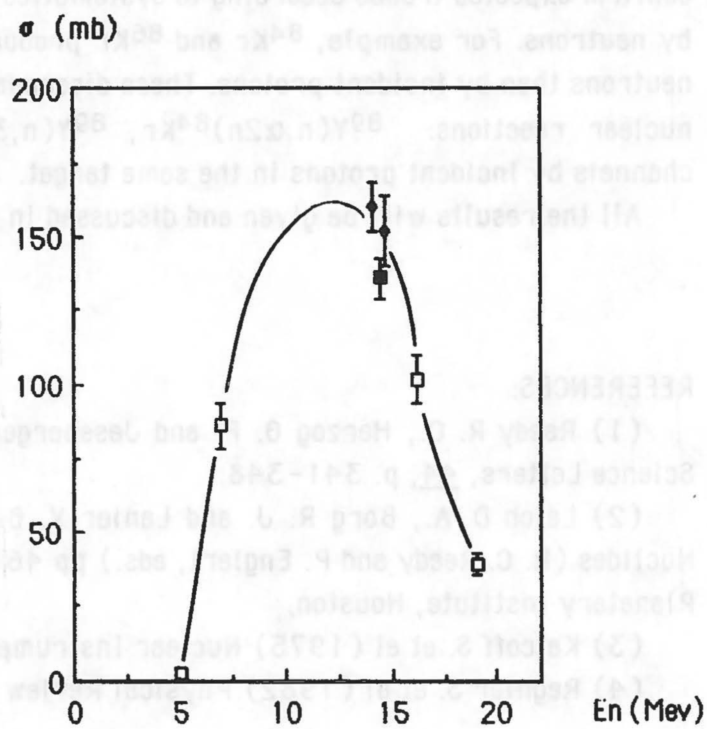
So, the purpose of this talk is to show which excitation functions of production are satisfactory documented and which ones still require additional measurements. Protons induced nuclear reactions will be discussed as well as neutron induced nuclear reactions.

CROSS SECTIONS OF NEON AND KRYPTON ISOTOPES PRODUCED BY NEUTRONS; B. Lavielle , H. Sauvageon and P. Bertin , Centre d'Etudes Nucléaires de Bordeaux-Gradignan , Le Haut Vigneau 33170 GRADIGNAN, FRANCE

The interaction of cosmic rays with meteoroids in space produces numerous species of stable and radioactive isotopes. The concentration of the cosmogenic production of rare gas may allow the determination of the exposure age. But, a good knowledge of the excitation functions of the implied nuclear reactions is required in order to take into account parameters like the cosmic-ray flux, the shielding depth of the sample, the size and shape of the meteoroid, and its chemical composition.

The evaluation of the production of nuclides induced by the energetic secondary neutrons suffers from a notable lack of experimental cross sections. So, two different types of irradiation by neutrons were performed in order to improve this situation.

<u>Irradiation of natural Mg target by neutrons of 5,7,16 and 19 Mev</u>



<u>figure 1</u> : excitation function of ^{21}Ne in Mg

Cross sections of neon isotopes were measured in Mg target irradiated by neutrons fluences of 5.0-8.5 10^{12} neutrons.cm^{-2} at Bruyères Le Châtel ,(France) in collaboration with G. Haouat.

As shown in figure 1 for ^{21}Ne , new measured cross sections agree very well with previous data [1],[2]. A similar agreement has also been obtained for ^{20}Ne and ^{22}Ne.

These results complete the excitation functions of neon isotopes produced by neutrons below 20 Mev in Mg, specially concerning the shape of the peak.

Irradiation by neutrons in the energy range 25-180 Mev

Targets of Al,Mg, Rb_2SO_4, SrF_2 and Y were irradiated with a medium energy intense neutron facility at the Brookhaven 200 Mev LINAC in collaboration with S. Katcoff and Y. Y. Chu. Characteristics of the neutron flux and procedure for calibration of absolute cross section determination were previously described by collaborators [3]. The neutron energy flux appears to be almost flat between 25 Mev and 180 Mev. The measured effective cross sections approximately correspond to averaged cross sections on the considered energy range. So, $^{20,21,22}Ne$ in Al, Mg and $^{78,80-86}Kr$ in Rb, Sr and Y effective cross sections were measured leading to a better determination of the excitation functions in an energy range where no experimental data are available.

Compared to Kr cross sections produced by protons in Y [4], the new data seem to confirm expected trends according to systematics of nuclear reaction channels induced by neutrons. For example, ^{84}Kr and ^{86}Kr production appear to be higher by incident neutrons than by incident protons. These discrepancies can mainly be attributed to the nuclear reactions: $^{89}Y(n,\alpha 2n)^{84}Kr$, $^{89}Y(n,3pn)^{86}Kr$.which have no equivalent channels by incident protons in the same target.

All the results will be given and discussed in detail in the talk.

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EXPOSURE AGES AND LONG-TERM VARIATIONS OF THE COSMIC RAY FLUX; K. Marti, Chem. Dept., B-017, Univ. of Calif., San Diego, La Jolla, Calif., 92093-0317

The flux of cosmic rays in the inner solar system changes with time. At least some of these variations are known to be due to solar modulation. While the recent cosmic ray flux has been studied by satellites and terrestrial radionuclide production rates (e.g. atmospheric ^{14}C), cosmic-ray-produced stable and radioactive nuclides in meteorites are widely used to study past variations of the cosmic ray flux. Galactic cosmic rays (GCR) dominate the average intensity of energetic particles above about 200 MeV. Therefore, long term variations, as observed in meteoritic ^{38}Ar versus ^{40}K-^{41}K production rates, may also reflect changes in the interstellar medium. It is expected that solar modulation would mainly affect low energy particles and change the energy spectrum of GCR, while changes in the interstellar medium may affect the flux at all energies. The depth dependence of the production rates in meteorites is, at the present time, not sufficiently well known to decide between these possibilities.

Iron Meteorites: The radionuclide ^{40}K (1.3×10^9a) relative to stable ^{41}K measured in iron meteorites indicates that the intensity of the cosmic ray flux on a 1Ga time scale was smaller than the present one (1). It was suggested that this increase may have taken place less than 200 Ma ago (2). The long half-life of ^{40}K renders the ^{40}K-^{41}K method inappropriate for tests of flux changes on this time scale. A new method involving ^{129}I (1.6×10^7a) and stable ^{129}Xe in troilite inclusions of iron meteorites was proposed (3) and is now being developed to constrain the time of change. This method is self-correcting for the shielding dependence of the production rates. The assumptions in the evaluations of ^{38}Ar production rates based on the ^{40}K-^{41}K systematics (2) will be discussed, and the evidence for complex exposure histories presented.

Lunar Rocks and Craters: A determination of the exposure age of a lunar rock requires, in general, a knowledge of the target element abundances, in addition to the relevant noble gas data. Furthermore, the shielding depth during the exposure must be known, and no major shielding changes by erosion or turnover must have taken place. Circularities in the evaluations can largely be avoided by the ^{81}Kr-^{83}Kr method, which determines an age from the ratio of (radioactive) cosmogenic ^{81}Kr to (stable) cosmogenic ^{83}Kr, and does not depend on target element concentration, absolute production rates, or depth (or other geometrical effects) of shielding, as long as these parameters remain constant. The method requires a knowledge of the relative production rates of ^{81}Kr and ^{83}Kr. Statistically significant numbers of rocks from the ejecta of Cone Crater and North and South Ray Craters yield ages of 25, 50 and 2.0 Ma, respectively. The evidence for other clusters will be reviewed. The agreement of calculated and observed production rates and ratios is quite reasonable. For example, very good agreement is observed for the $^{78}Kr/^{83}Kr$ ratios in samples with different shielding depths and varying chemical compositions (4).

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SIMULATION OF COSMOGENIC NUCLIDE PRODUCTION; J.Masarik and P.Povinec

A method for calculation of absolute production rates of cosmogenic nuclides based on the Monte Carlo simulation of hadron cascade processes in matter is presented. The calculations start with inelastic collision of primary cosmic particle with energy in the range from one to tens of GeV, with target nuclei. The number of inelastic collisions of k-type particle from the ith-energy region in the space volume V_{ij} is given by the quantity

$$\psi_{ijk}(E) = \int_{\Gamma_{ij}} d^3\vec{r}\, dE\, \psi_k(\vec{r}, E', E)$$

where $\psi_k(\vec{r}, E', E)$ is the inelastic collision density for the k-type particle with the energy E, the position $\vec{r}$ and $\Gamma_{ij} = (E_i, E_{i+1}) \times V_j$. At these energies new hadrons with energies sufficient for production of next generation of secondary particles are produced. High energy collisions in which secondary particles are produced and also collisions at lover energies transform the target nuclei mainly through spallation and evaporation processes to radioactive or stable nuclei. The depth dependence and the energy dependence of the production rates of cosmogenic nuclides with consideration of contribution from the evaporation processes are calculated as

$$P_j(E) = \sum_{k,i} \psi_{ijk}\, \sigma_k^{x}(E_i) / \sigma_k^{inel}(E_i)$$

Among strongly interacting particles it is sufficient to take into account only protons, neutrons and pions and to calculate the production probabilities of cosmogenic nuclides as a function of the type and the energy of cascade particles and the energy of the incoming particles. We assume an isotropic flux of CR protons, spectrum used in calculations was taken from (1) The form of the spectrum takes into account the influence of solar activity on the galactic CR intensity through the modulation parameter. The calculations have been carried out for

SIMULATION OF KGN PRODUCTION:, J.Masarik and P.Povinec

targets having the form of an infinite layer of material for lunar samples and an sphere for meteorite samples. The effective chemical composition was taken to be in agreement with that of real samples. From the comparison of calculated and measured (2,3) depth dependences of the production rate of ^{22}Na, ^{26}Al and ^{53}Mn follows that for ^{22}Na the best agreement between the theoretical and experimental data was found for the average galactic cosmic ray flux a few years before the sample collection, for the ^{26}Al for very soft modulation and for ^{53}Mn for unmodulated galactic cosmic ray flux.

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Prediction of Thin-Target Cross Sections of Neutron-Induced Reactions up to 200 MeV; R. Michel and H. Lange, Zentraleinrichtung für Strahlenschutz, Universität Hannover, F.R.G.

Nuclear reactions induced by secondary neutrons are the most important production modes of cosmogenic nuclides by galactic cosmic ray (GCR) particles in extraterrestrial matter. Only in cosmic dust and in very small meteoroids (R < 10 cm) the contributions of charged primary and secondary GCR particles exceed that of secondary neutrons. There are two important differences between neutrons and charged particle fields in meteoroids and planetary surfaces, e.g. [1]. First, the differential spectra are completely different, those of secondary neutrons decreasing monotonically with increasing energy, while those of charged particle show maxima around 100 MeV/A due to the action of electronic stopping at lower energies. This difference causes neutrons with energies below 100 MeV to outrange the protons by far. The second difference is with respect to depth and size dependences of particle fluxes. Secondary protons show a transition maximum around meteoroid radii of 30 cm, while secondary neutrons have not yet reached the maximum at a radius of 65 cm. Also the absolute fluxes of secondary neutrons are significantely higher (up to a factor of 3 in H-chondrites) than those of protons.

Consequently, neutron-induced reactions dominate the production of cosmogenic nuclides in normal-sized meteoroids and in planetary surfaces. Cross sections for n-induced reactions are most important for an accurate modelling of the production of cosmogenic nuclides in extraterrestrial matter. However, the available data base shows up with strongly differing quality depending on the neutron energy. At energies below 1 MeV, where besides some exceptional (n,p)- and ($n,^4He$)-reactions only neutron capture is of importance, there exists a comprehensive and accurate data base, e.g. [2], intended to satisfy the needs of nuclear technology. For the target nuclides of interest for meteoritics as well as for lunar and planetary science, such as ^{14}N, ^{35}Cl, ^{59}Co, $^{79,81}Br$, ^{128}Te, ^{131}Ba, ^{149}Sm, ^{152}Eu, ^{157}Gd, and ^{186}W, the required nuclear and cross section data exist and isotopic anomalies can be satisfactorily interpreted in the framework of existing models [3,4]. With these reactions we will not deal here further.

For neutron energies above 1 MeV the knowledge about production cross sections is completely insufficient. The existing data are nearly exclusively restricted to energies below 30 MeV using the $T(d,n)^4He$ or $^7Li(p,n)^7Be$ reactions as neutron sources. Moreover, most measurements are closely clustered around E_n = 14.7 MeV and only a few excitation functions have been measured over a larger energy range. A survey on compilations and evaluations of the existing data may be found elsewhere [5]. At higher energies either deuteron break-up, (p,n)- or spallation reactions are used as neutron sources. For all these fast neutron irradiation facilities experimental problems arise from the fact that the neutron beams are either not monoenergetic or have too low intensities. Details on the related experi mental techniques may be found elsewhere [6]. Though the number of fast neutron inrradiation facilities is increasing it will take several years until the necessary experimental data will be available.

In order to overcome this problem we started a programme to predict thin-target excitation functions for neutron-induced reactions for neutron energies up to 200 MeV on the basis of the hybrid model of preequilibrium reactions [7]. The capability of this model to predict unknown excitation functions and to perform a priori calculations of nuclear reactions cross sections for a wide variety of reactions types is an outstanding feature of this theory. However, there are distinct differences in the quality of such calculations depending on the type of bombarding particle and on the excitation energies of the reacting systems. For p-induced reactions up to 200 MeV this model finally proved to be well capable to predict cross sections for the production of radionuclides from a wide range of target elements [8,9, and references therein].

A first set of excitation functions [10,11] was calculated using the hybrid model in the form of the code ALICE LIVERMORE 82 [12]. The calculated excitation functions were used successfully to interprete the experimental production rates measured in the course of the experiment CERN SC-96 [13,14]. Here, we report on a new data base, the excitation functions of which were calculated by the code ALICE LIVERMORE 87 [15], which is an extended version of the former one. This recent version of the hybrid model [15] of preequilibrium (PE) reactions has several advantages compared to the earlier versions. It contains some improvements which are essential for such calculations. First it allows to use experimental nuclide masses as far as available. Secondly, it allows for the choice of broken exciton numbers, thus taking into account the statistical distribution of different possible initial exciton configurations. A detailed discussion of this feature was given by Blann and Vonach [16]. Thirdly, it takes into account multiple PE decay, allowing for both the emission of more than one nucleon from a single exciton configuration and for the PE emission of several nucleons in sequential exciton configurations.

The new data base "ZFS-NSIG-89" up to now contains thin-target excitation functions for the target elements Na, Mg, Al, Si, K, Ca, Ti, V, Mn, Fe, Co, Ni, Cu, Rb, Sr, Y, Zr, Ba, and La for neutron energies between 1 and 200 MeV. With regard to the product nuclides it covers all relevant cosmogenic radionuclides as well as stable rare gas isotopes with the exceptions stated below. For the long-lived and stable products the data are cummulative, i.e. they contain the contributions of shortlived progenitors. There are no cross sections for the production of H- and He-isotopes and there still are some important target elements as e.g. O and C for which we do not have calculations. For the latter target elements the capabilities of the hybrid model are currently being tested for p-induced reactions.

The comparison of the calculated cross sections with experimental data in the low energy (E_n < 30 MeV) region shows the same good quality of the calculations as was earlier observed for proton-induced reactions for various target elements [9]. A comparison of excitation functions for the same target element/product combinations demonstrates that there can be strong differences between the cross sections of neutron- and proton-induced reactions and that the often made assumption of neutron cross sections being equal to those of proton-induced reactions is not justified.

The calculated neutron cross sections have been successful used to calculate the depth and size dependent production rates measured in a number of 600 MeV simulation experiments [13,14] as well as for dosimetry purposes in radiation damage experiments in spallation neutron sources [17]. It has, however, to be stated that these neutron cross section just are first aid to satisfy our cross section needs for neutron-induced reactions. Measured data will easily replace them as soon they are available.

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Thin-Target Cross Sections for the Production of Cosmogenic Nuclides by Charged-Particle-Induced Reactions; R. Michel, R. Bodemann, M. Lüpke, Zentraleinrichtung für Strahlenschutz, Universität Hannover, F.R.G.; U. Herpers, B. Dittrich, Abteilung Nuklearchemie, Universität zu Köln, F.R.G.

Thin-target cross sections for charged-particle-induced reactions provide the basis for a quantitative description of the production of cosmogenic nuclides by solar cosmic ray (SCR) particles. Combining reliable excitation functions of the underlying nuclear reactions with depth-dependent SCR particle spectra resulting from simple stopping calculations, SCR effects can be accurately described. Also any modelling of the interactions of galactic cosmic rays (GCR) with terrestrial and extraterrestrial matter depends on accurate reaction data, though the occurences of GCR interactions with matter are much more complex and in spite of the fact that charged particles in most cases only contribute to a minor degree to the GCR production of cosmogenic nuclides.

Solar and galactic cosmic ray particles consist of about 90 % protons and 10 % alpha-particles, both particle types having roughly the same spectra as function of energy per nucleon. Thus, protons are the most important ones. But for an accurate modelling the complete knowledge of the cross sections of both proton- and alpha-induced reactions is necessary. A survey on the cosmogenic nuclides of interest and the target elements to be considered is given in table 1 without claiming completeness for this compilation.

Unfortunately, up to now the cross section data base is neither complete nor accurate. For many cosmogenic nuclides of interest no data exist at all. Moreover, many of the experimental data reported in the past suffer from severe lack of accuracy, so that often there are uncertainties of up to an order of magnitude when looking for non-evaluated experimental data. Such uncertainties do neither allow for tests of nuclear reaction models nor are they tolerable for the various applications of high-energy integral cross sections, in particular for an accurate modelling of cosmic ray interactions with matter.

Therefore a research program was initiated to measure the required excitation functions and to establish a consistent set of cross sections for the p- and alpha-induced production of cosmogenic nuclides from most relevant target elements. Irradiations and measurements are done in collaboration of groups from Ahmedabad, Cologne, Hannover, Jülich, Philadelphia, Studsvik, Zürich, and Uppsala. Thin-target cross sections for the production of stable and radioactive nuclides by proton-induced reactions on O, Mg, Al, Si, Ca, Ti, V, Mn, Fe, Co, Ni, Cu, Zr, Rh, Ba, and Au are measured up to 2600 MeV using accelerators at GWI/Uppsala ($E_p < 200$ MeV), CERN/Geneve ($E_p = 600$ MeV), LANL/Los Alamos ($E_p = 800$ MeV), and Saclay ($E_p = 1200$ and 2600 MeV). For alpha-induced reactions former measurements [1] are extended with respect to target element and product nuclide cover

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Table 1: Survey on target elements to be considered for the production of cosmogenic nuclides by charged-particle-induced reactions. All cross sections must be cummulative with regard to shortlived progenitors. This table neglects nuclides as ^{46}Sc, ^{48}V, ^{51}Cr, ^{54}Mn, ^{56}Co, ^{57}Co, ^{58}Co, which can be importance in freshly fallen meteorites. * of interest for alpha-induced reactions only.

PRODUCTS	$T_{1/2}$	TARGET ELEMENTS								
^{22}Na	2.6 a	Na	Mg	Al	Si	S	Ca	Fe	Ni	
^{60}Co	5.26 a	Ni								
^{3}H	12.3 a	C	O	Mg	Al	Si	S	Ca	Fe	Ni
^{44}Ti	47.3 a	Ca	Ti	Fe	Ni					
^{14}C	5.73 ka	O	Mg	Al	Si	S	Ca	Fe	Ni	
^{59}Ni	75. ka	Fe*	Ni							
^{36}Cl	300. ka	K	Ca	Fe	Ni					
^{26}Al	716. ka	Na*	Mg	Al	Si	S	Ca	Ti	Fe	Ni
^{41}Ca	103. ka	K	Ca	Ti	Fe	Ni				
^{81}Kr	210. ka	Sr	Y	Zr						
^{10}Be	1.6 Ma	C	O	Mg	Al	Si	S	Ca	Fe	Ni
^{53}Mn	3.7 Ma	Mn	Fe	Ni						
^{129}I	15.7 Ma	Ba	La	REE						
^{40}K	1.28 Ga	K	Ca	Ti	Fe	Ni				
He	stable	C	O	Mg	Al	Si	S	Ca	Fe	Ni
Ne	stable	Na	Mg	Al	Si	S	Ca	Fe	Ni	
Ar	stable	S*	Cl	K	Ca	Ti	Fe	Ni		
Kr	stable	Br	Rb	Sr	Y	Zr				
Xe	stable	Ba	La	REE						

age in order to establish production cross sections for stable and longlived cosmogenic nuclides by irradiations at PSI/Würenlingen and at KFA/Jülich.

The stacked-foil technique is used to investigate proton- and alpha-energies up to 200 MeV. Above 200 MeV single energy points are investigated in order to minimize interferences from secondary particles. Gamma- and X-spectrometry as well as conventional and accelerator mass spectrometry are used to measure the residual nuclides, in particular all relevant cosmogenic nuclides. Up to now, final results were obtained for short- and medium-lived nuclides. The measurements for longlived nuclides as well as the data evaluation still are going on. Also the mass spectrometric measurements are not yet finished. First data for a p-energy of 600 MeV were already pub lished [2,3]. The new data represent a consistent data set of thin-target cross sections of more than 300 individual spallation reactions. Together with the cross sections for proton energies up to 200 MeV measured earlier by our group [4,5], and references therein, they give the complete excitation functions from the thresholds up to 2600 MeV.

Though not all experimental cross sections are available right now, it is possible to perform a critical review of earlier experimental data and to to do some comparison of the new data with the results of model calculations. The existing data already now allow for a discussion of the quality of parametric models [6,7], which are often used for the calculation of spallation cross sections. However, a comparison of the new experimental data with those calculated by Rudstam's CDMDG formula [6] and by the formula proposed by Silberberg and Tsao [7] using the code SPALL by Routti and Sandberg [8] in the energy range from 600 to 2600 MeV showed partially discrepancies. Though considerable improvements have been achieved in the more recent formula [7], in particular with respect to the production of light fragments, for many nuclides theory and experiment deviate by more than a factor of two. It has to be emphasized that the calculational accuracy obtained so far is not sufficient for model calculations of cosmogenic nuclides.

Further, the question of theoretical predictions of thin-target cross sections on the basis of theories of nuclear reaction theories is adressed. For this purpose hybrid model calculations using the code ALICE LIVERMORE 87 [9] for p-energies up to 200 MeV were performed, which demonstrated the same excellent quality of a priori calculations as observed before [5]. For higher energies Monte Carlo calculations of the intranuclear cascade were performed using the high energy transport code HETC/KFA-2 within the newly developed HERMES code system [10]. Absolute production cross sections were obtained by evaluating the history of residual nuclei. First results on the target element Fe look very promising [2]. Presently, these calculations are extended to other target elements in order to obtain a systematic survey on the quality of such calculations and on the possibility to reliably predict unknown excitation functions.

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Monte Carlo Modelling of the Production of Cosmogenic Nuclides in Extraterrestrial Matter by Galactic Cosmic Ray Particles; R. Michel, Zentraleinrichtung fuer Strahlenschutz, Universitaet Hannover, Hannover, F.R.G., P. Dragovitsch, G. Dagge, P. Cloth, D. Filges, Institut fuer Kernphysik, KFA Juelich, Juelich, F.R.G.

Monte Carlo (MC) techniques provide a tool to describe quantitatively the complex occurences of high energy hadronic interactions with matter on the basis of current nuclear physics models and have been successfully applied in various fields of basic and applied sciences. In particular, MC calculations with the HERMES code system [1] have been extremely successful in describing the production of residual nuclides in a number of 600 MeV thick-target irradiation experiments performed in order to simulate the production of cosmogenic nuclides in meteoroids [2,3]. Based on the experience from this validation a new model for the production of cosmogenic nuclides in extraterrestrial matter by galactic cosmic ray particles was proposed [4].

In this model the size- and depth-dependent production rates of cosmogenic nuclides are calculated for meteoroids as well as for planetary surfaces by combining the depth- and size-dependent spectra of primary and secondary particles resulting from MC calculations with composition-weighted thin-target production cross sections of the contributing nuclear reactions. The advantage of this method is that it strictly distinguishes beteeen two completey different physical quantities, namely the spectra of the primary and secondary GCR particles in the respective material on the one hand and the cross sections of the underlying nuclear reactions on the other. This allows to derive from one set of MC calculations the depth- and size-dependent production rates of all cosmogenic nuclides wanted. Moreover, the calculations can easily be extendend to a new nuclides if the respective cross sections are at hand. Presently, the cross sections for p-induced reactions are based on an evaluated set of experimental data and on our own recent data [2,3,5]. Those for n-induced reactions are calculated ones using the code ALICE LIVERMORE 87 [6]. Still existing gaps in the experimental cross sections were closed in the same way.

MC calculations using the HERMES system were performed for GCR protons irradiating stony meteoroids, some selected irons and the lunar surface. The spectra of primary protons, secondary protons and secondary neutrons as function of size of and depth inside an extraterrestrial body were derived for energies between 1 MeV and 10 GeV in case of protons, while the neutrons were followed from 10 GeV to thermal energies. However, for a complete description of GCR interactions galactic He-nuclei must be taken into account, because their contribution makes up 30 % of the total GCR interactions with respect to both the number of nucleons as well as to the energy input. In our present calculations He-nuclei are only taken into account by assuming them to break up immediately in the first collision and further to act in the same way as primary GCR protons. The exact calculations for GCR He-nuclei will be performed in due course.

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As primary GCR proton spectrum an average of the observed spectra during times of a quiet sun (1965, M = 450 MV) and an active sun (1969, M = 900 MV) was taken for the calculations. M is the force field parameter as used in the parameterization of the GCR spectra by Castagnoli and Lal [7]. The influence of solar modulation onto primary and secondary GCR particle spectra and consequently onto production rates in meteoroids was investigated performing independent MC calculations for the 1965 and 1969 primary spectra. The results describe the sensitivity of the production rates of different cosmogenic nuclides to changes in the GCR spectrum and allow for a discussion of the constancy of GCR fluxes in the past.

The particle spectra in meteoroids as well as the depth and size dependences of integral particle fluxes are strongly different for protons and neutrons, the latter being the dominant species. The highest n-fluxes were found for meteoroid radii of 65 cm, while the p-fluxes show a maximum at radii around 30 cm. While the results for meteoroids are in contrast to earlier calculations, the data obtained for the lunar surface agree well with those reported earlier by Armstrong and Alsmiller [8]. A detailed survey on the particle spectra and fluxes is given and the influences of the chemical composition of the irradiated body on primary and secondary particle fields are quantitatively described.

Up to now, depth profiles for the production of ^{26}Al, ^{53}Mn and ^{20,21,22}Ne have been calculated for stony meteoroids with radii up to 65 cm, for the lunar surface and for an iron meteorite with 40 cm radius. The results are compared with experimental depth profiles and discussed with respect to the depth and size dependences of elementary production rates, production rate ratios and average production rates of different meteoroid classes.

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COSMOGENIC BE-10 AND AL-26 IN METAL AND STONE PHASES OF METEORITES.

H. NAGAI, M. HONDA, NIHON UNIV.,TOKYO
M. IMAMURA, INST.NUCLEAR STUDY, UNIV.TOKYO
K. KOBAYASHI,RES.CENT.,NUCLEAR SCI.TECHN.UNIV.TOKYO
H. OHASHI,INST.COSM.RAY RES.UNIV.TOKYO

Cosmogenic ^{10}Be and ^{26}Al were determined in metal and stone fractions of meteorites by the AMS, accelerator mass-spectrometry. The tandem van de Graaf accelerator at the Univ. of Tokyo was employed for these measurements by applying the internal beam monitor method. Enriched ^{17}O was added to the sample of ^{10}Be and enriched ^{10}B to ^{26}Al respectively. The monitoring beam of $^{9}Be^{17}O^-$ is injected in the accelerating tube along with the main beam of $^{10}Be^{16}O^-$. The monitor beam of $^{10}B^{16}O^-$ is introduced along with the $^{26}Al^-$ beam(1).

Chondrites, including fragments of the Jilin chondrite, and stony irons were processed to separate their metal and stone phases. Because of higher ^{26}Al contents in their stone phases, extensive purifications for the metals had to be made. The contamination levels are to be less than 1% stone, and the corrections were made. The sample sizes were 50-400 mg of metals and ca.100 mg of stones. The metal size was limited mainly due to a shortage of available samples. Atomic ratios of $^{10}Be/Be$ and $^{26}Al/Al$ were adjusted to the order of 10^{-11} by addtions of smaller amounts of carriers for metal samples, down to 200 and 500 micro g.Be and Al respectively.

Some examples of determinations are shown in Table 1. The fragments of the Jilin are characterized by the ^{21}Ne contents, which essentially reflect the depth profile of the 1st stage irradiation. The contributions from the 2nd stage can be estimated for long-lived activities.

In general, the following equation, or the equivalent, can be used for the estimations of various production rates ,P, in iron and stone meteorites (2).

$$P(A,Z) = f(A,Z)*k_1'(\Delta A + a)^{-k_2'},$$

where a=4 can be inserted as an empirical term. The two sets of linear relations are obtained by plotting log($^{10}Be/^{53}Mn$) vs. shielding index, k_2', for stones and metals. Similar relations were observed for ^{26}Al. An effective ΔA for ^{10}Be in metal is estimated at 18, in a wide range of k_2'= 1.8 and higher than 3, the same as those of ^{38}Ar and ^{3}He; and P(^{10}Be) is nearly constant among chondrite; for ^{10}Be in stones, ΔA=8 can be assigned(3). In achondritic targets the same can be said as shown in mesosiderites. This relation is extended to the Jilin and to the lunar samples; the net ^{53}Mn and ^{10}Be in the 1st stage of the Jilin can be refered to the galactic productions near the lunar surface. Under the 2 pi irradiation, the k_2's increase linearly with depths where the productions decrease exponentially.

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TABLE 1 BE-10 AND AL-26 FOUND IN METAL AND STONE FRACTIONS

SAMPLE	CLASS	ID	----METAL FRACTION---- dpm/kg BE-10	AL-26	stone %	---STONES----- dpm/kg BE-10	AL-26
A77299	H3		4.58±.25	3.41±.26	.13	17.7±1.1	43±2
Y7301	H5		3.93±.22		.04		
Y74117	L6		4.64±.19			16.4±.9	
Y74455	L6		5.94±.27	3.4 ±.2	.15	18.3±1.1	49±2
Y74663	L6		5.55±.27	3.0 ±.2	.03	18.1±1.1	39±1
ETTER	L6	H47,260	2.36±.13		.46	19.2±.7	
LA CRIOLLA	L6	1985	3.63±.18		.01	20.0±.7	63±2
NEW CONCORD	L6	1860	3.95±.15		.12	14.6±.6	69±3
NUEVO MERC.	H5	1978	4.39±.13		.20	22.4±1.4	
TSAREV	L5		1.41±.11		.12	5.21±.46	
JILIN	H5	1976					
fragm.		$^{21}Ne*10^{-8}$ cc/g					
TOKYO A,No.1		1.64	1.93±.09		.34	11.4±.3	39±1
K2,Carneg.Inst		(1.4)	1.76±.11	1.47±.13	.34	12.0±.6	24±3
MAINZ B,No.1		0.99	1.23±.05				
TOKYO B,No.1		0.82	0.86±.06		.24	10.6±.4	
TOKYO E,No.1		0.62	0.93±.06	0.69±.04	.27	10.3±.4	31±1
TOKYO 4AB,No.4		0.51	0.78±.09	0.82±.06	.26	6.3±.2	26±3
NAINZ A,No.4		0.43	0.91±.04				
HEIDELB.I,No.1		0.42	0.87±.07		.48		26±1
HEIDELB.II,No.4		0.38	0.87±.11	0.80±.17	.36	6.5±.5	25±1
STONY IRONS							
BENCUBBIN	MES	#1	5.04±.24		.50	26±1	80±2
BUDULAN	MES	#1	3.28±.18	2.55±.28	.40	20±.6	119±6
CRAB ORCH	MES	#1	4.21±.16	2.99±.18	.04	24±.8	82±3
EMERY	MES	#1	5.9 ±.1	3.89±.18	.52	22±.9	92±3
UDEI STATION	IA	#1	3.8 ±.3	4.0±.4	.32	22±.8	
TAWALLAH V.	IVB		5.26±.20	3.85±.19			
TOCOPILLA	IIA		2.28±.17	1.17±.09			
TRENTON	IIIA	AII-22+2	3.35±.11	2.54±.12			

#1: Begemann et al(1976)

DEPTH PROFILES OF RADIONUCLIDE PRODUCTION IN SOLIDS WITH 2Π GEOMETRY

K. Nishiizumi, R. C. Reedy*, and J. R. Arnold
Department of Chemistry, B-017, University of California, San Diego, La Jolla, CA92093
*Earth and Space Science Division, MS-D438, Los Alamos National Lab, Los Alamos, NM87545

The lunar surface presents, in many ways, an ideal case for cosmogenic nuclide study. The surface of the moon has been bombarded by both SCR (solar cosmic rays) and GCR (galactic cosmic rays) for a few million to a few hundred million years at the same geometry and the same location in the solar system (1 A.U.). The cosmic ray bombardment geometry for lunar samples can be determined on a mm scale, a precision which can't be obtained with meteorites. Complications are caused by surface gardening and by erosion by micrometeorite impact, which change the static production profile. However, the knowledge of these effects, which can be gained from lunar studies, can be applied to model asteroid regolith and cometary surfaces. The moon is a limiting case for cosmogenic nuclide production since its radius is effectively infinity and the samples therefore experience a 2π geometry to cosmic ray bombardment. However, as we obtain a more precise understanding of the 2π bombardment case, we also learn more about bombardment in meteorites since the lunar model calculations can be extended to them fairly easily. The 2π lunar case can also apply to model development for bombardment at the surface of the earth, except for the importance of muon reactions in the earth's atmosphere in contrast to the importance of pion reactions for a solid body.

SCR: Production by solar particles (SCR) is confined to bodies without a significant atmosphere or magnetic field, and to a thin surface layer (<few g/cm^2). It is visible in all lunar surface material because of the absence of ablation. Other than in lunar material, SCR produced nuclides have been observed only in some cosmic spherules and in a very few meteorites. The Reedy-Arnold production model [1] fits the experimental data very well in those cases where all proton cross section data are available. Presently there is a lack of low energy (below 100 MeV) proton cross section data for production of ^{10}Be, ^{14}C, and ^{36}Cl. The knowledge of these low energy proton excitation functions is needed to pin down the SCR history during the last few million years. Figure 1 shows ^{53}Mn and ^{10}Be profiles in rock 68815 [2,3]. The depths of the samples measured in this study are the most carefully determined to date. The SCR production in lunar soil has not been emphasized in past discussions except for studies of gardening [4], but its integral value is useful for SCR studies of production in rocks and meteorites since the erosion problem is eliminated (but replaced by the gardening problem).

GCR: Production by galactic cosmic rays (GCR) extends to a depth of meters in solid matter. The most extensive studies to determine GCR production profiles were those of the Apollo 15 long core (up to 400 g/cm^2). Figure 2 shows ^{10}Be, ^{26}Al, ^{36}Cl, and ^{53}Mn depth profiles measured for this core [5,6]. These data represent the test for all production models, as well as the constant-flux model that underlies them. The Reedy-Arnold model fits the measured profiles very well except that a normalization is required to adjust the absolute activity levels due (we believe) to the lack of neutron cross sections. There is also a small discrepancy for the ^{36}Cl profile due to the exclusion of the ^{35}Cl(n,γ) reaction in the Reedy-Arnold model. For a nuclide produced only by neutron capture (such as ^{60}Co), the depth profile would look very different, with little production near the surface [7]. Mixing in the lunar regolith is not rapid enough to affect the profile of these radionuclides except close to the surface (~10 g/cm^2). The exposure time of lunar soil is also long enough to saturate all cosmogenic radionuclides (with the hypothetical exception of ^{40}K in metal or anorthite).

Each lunar core has a different chemical composition. The production rates from different target elements can be obtained by comparing several core samples with different chemical compositions if the samples come from the same shielding depth, because the exposure geometry has been precisely measured for these lunar samples.

Only lunar samples preserve a record of the details of the SCR history and provide accurate determination of 2π GCR production profiles from 0 to 400 g/cm^2. Measurements of ^{14}C, ^{41}Ca, and ^{129}I in long lunar cores are in progress. We need low energy proton and neutron cross section data to improve the model. Profile measurements on a longer core (6-8m) would extend the data into a region not yet investigated and provide a check on the model calculations. Obtaining such a sample should be one goal of a future mission.

One limitation of all studies on *in situ* bombardment effects in extraterrestrial matter is that the measurements are "integral", that is, that they reflect the entire history of the bombardment for each sample under study. Given the slow evolution of lunar (or meteoritic) surfaces, effects are averaged over long periods, in contrast for example to ^{14}C studies of tree rings on earth. There is at least one possible way to approach a differential record more closely. This is to collect a core at the bottom of a narrow rille or cleft into which material is steadily being transported by gardening, but which is more or less shielded from further bombardment and material loss by impact. A returned core from such a "sediment" would be a fascinating object of study.

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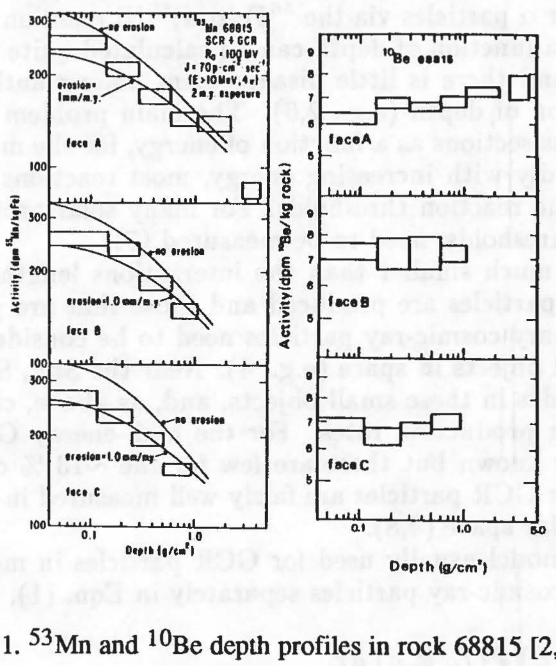

Fig. 1. ^{53}Mn and ^{10}Be depth profiles in rock 68815 [2,3].

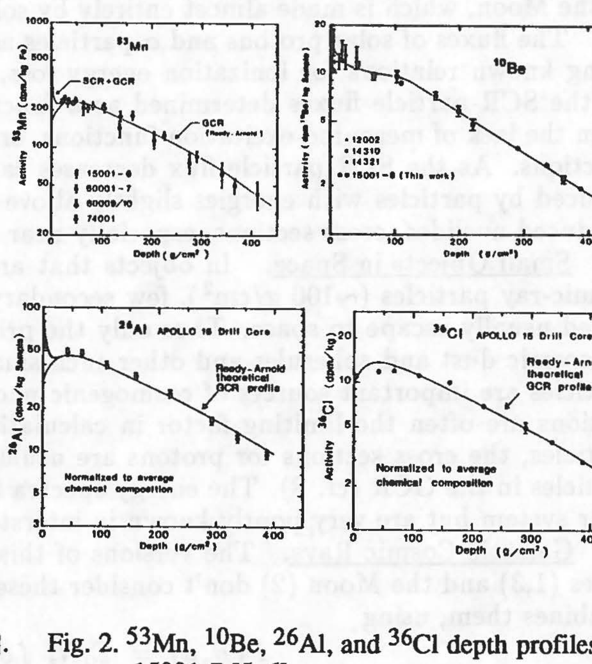

Fig. 2. ^{53}Mn, ^{10}Be, ^{26}Al, and ^{36}Cl depth profiles in 15001-7 [5, 6]

COSMOGENIC-NUCLIDE PRODUCTION RATES CALCULATED USING PARTICLE FLUXES AND CROSS SECTIONS*; **Robert C. Reedy**, Earth and Space Sciences Division, Mail Stop D438, Los Alamos National Laboratory, Los Alamos, NM 87545.

There have been several approaches used to predict the production rates of cosmic-ray-produced nuclides in extraterrestrial matter. The method reviewed here uses fluxes of cosmic-ray particles and cross sections for nuclear reactions. It is used both for particles in or made by the galactic cosmic rays (GCR) as well as for solar-cosmic-ray (SCR) particles. The use of derived energy spectra for the cosmic rays coupled with cross sections was first well developed by Arnold, Honda, and Lal (1) in 1961 for iron meteorites. The model was extended to the Moon in 1972 by Reedy and Arnold (2) and later to stony meteorites (e.g., 3). It is also the basic approach used to predict cosmogenic nuclide production rates in small particles in space (e.g., 4) and for production by the protons and alpha particles in the solar cosmic rays (e.g., 2).

The basic model. The production rate for a cosmogenic nuclide at depth d in an object of radius R, $P(R,d)$, can be calculated as the sums over target elements, i, and cosmic-ray particles, j, and the integral over energy, E, of

$$P(R,d) = \Sigma_i N_i \, \Sigma_j \int \sigma_{ij}(E)\, F_j(E,R,d)\, dE \qquad (1)$$

where N_i is the abundance of the ith element, $\sigma_{ij}(E)$ is the cross section as a function of energy for making the nuclide from element i with particle j, and $F_j(E,R,d)$ is the flux of particle j with energy E at depth d in an object of radius R. Both the GCR and SCR consist mainly of protons, some α particles and ~1 % of heavier nuclei. For SCR particles, which mainly have energies of ~10–100 MeV, only the primary particles are considered (2). For the high-energy (~ 1–10 GeV) GCR particles, many secondary particles can be made, such as neutrons and pions, and all of these primary and secondary particles should be considered in Eqn. (1). Uses of this type of model will be briefly reviewed in order of both greater particle energy and increasing target size. The main concerns in this model are getting the two key terms in Eqn. (1), the particle fluxes, $F_j(E,R,d)$, and the cross sections, $\sigma_{ij}(E)$, for all important energies.

Solar Cosmic Rays. Most of the relatively-low energy SCR particles are stopped in matter by ionization energy losses (2). The few SCR particles that react tend to produce few secondary particles; most SCR calculations ignore these secondaries. As α particles constitute only ~2 % of the SCR, they usually are ignored and only the protons are considered. The main exception is ^{59}Ni in the Moon, which is made almost entirely by solar α particles via the ^{56}Fe(α,n)^{59}Ni reaction (5).

The fluxes of solar protons and α particles as a function of depth can be calculated quite well using known relations for ionization energy loss, and there is little disagreement among authors on the SCR-particle fluxes determined as a function of depth (e.g., 2,6). The main problem has been the lack of measured excitation functions, cross sections as a function of energy, for the major reactions. As the SCR-particle flux decreases rapidly with increasing energy, most reactions are induced by particles with energies slightly above the reaction thresholds. For many solar-proton-produced nuclides, cross sections, especially near thresholds, need to be measured (7).

Small Objects in Space. In objects that are much smaller than the interactions lengths of cosmic-ray particles (~100 g/cm^2), few secondary particles are produced and those that are produced usually escape to space. Thus only the primary cosmic-ray particles need to be considered for cosmic dust and spherules and other such small objects in space (e.g., 4). Near the Sun, SCR particles are important sources of cosmogenic nuclides in these small objects, and, as above, cross sections are often the limiting factor in calculating production rates. For the high-energy GCR particles, the cross sections for protons are usually known but there are few for the ~13 % of α particles in the GCR (cf. 8). The energy spectra for GCR particles are fairly well measured in the solar system but are very poorly known in interstellar space (4,8).

Galactic Cosmic Rays. The versions of this model usually used for GCR particles in meteorites (1,3) and the Moon (2) don't consider these cosmic-ray particles separately in Eqn. (1), but combines them, using

$$P(R,d) = \Sigma_i N_i \int \sigma_i(E)\, F(E,R,d)\, dE \qquad (2)$$

where the flux term $F(E,R,d)$ now includes all types of particles. The justification for this inclusion of all primary and secondary particles into one term is that primary and secondary particles at higher energies ($\gtrsim$100 MeV) tend to have similar cross sections while most particles with E $\lesssim$100 MeV are neutrons (1,2). For the high energies, cross sections for proton-induced reactions are usually used and assumed to apply to other energetic species (e.g., primary α particles and secondary neutrons and pions) with the same energies. The scarcity of high-energy cross sections for these other particles has been a major factor in adopting this assumption. Thus, in a sense, the use of Eqn. (2) is somewhat like using Eqn. (1) with only two types of particles: lower-energy neutrons and higher-energy strongly-interacting particles. Because of the great complexity in the cascade of particles produced by high-energy cosmic rays in large objects, such as the large variety of secondary particles and the huge range of energies, assumptions like those above have been a feature of almost all models for predicting rates of GCR-produced nuclides.

Getting both the flux and cross-section terms in Eqn. (2) have been difficult. For the fluxes of GCR particles in iron meteorites, Arnold *et al.* (1) mainly used measurements of GCR particles in the Earth's atmosphere and only considered three fluxes that varied in shape above 100 MeV. In extending this model to the Moon, Reedy and Arnold (2) made the flux term a continuous function of depth and had the flux shapes both below and above 100 MeV vary as a function of a "shielding" parameter. When the Reedy-Arnold model was shown to work reasonably well for the Moon, it was modified for stony meteorites by getting flux models that fit cosmogenic nuclide data for several meteorites, such as St. Severin (9). This model was later generalized to spherical meteoroids of any radius (3), although the flux models and calculated production rates have often been poor, especially for fairly small (R $\lesssim$ 20 g/cm^2) and large (R $\gtrsim$ 150 g/cm^2) objects.

There also is often a lack of cross sections to use in GCR calculations, usually for neutron-induced reactions. This lack is especially true for the higher neutron energies, as very few neutron cross sections have been measured above 20 MeV. Often measured cross sections for proton-induced reactions are assumed for neutrons. There is good evidence that this assumption of equality for proton-induced and neutron-induced reactions is not valid for many target/product pairs. In some cases, the reactions for the two types of incident particles are known to be different, such as ^{24}Mg(n,α)^{21}Ne versus ^{24}Mg(p,n3p)^{21}Ne (9).

Discussion. One virtue of this flux/cross-section approach to calculating cosmogenic-nuclide production rates is its flexibility. If one wants to calculate rates for a new nuclide, one only needs excitation functions for making that product and can use the established particle fluxes. It also can be used for simulation experiments if particle fluxes in the irradiated object are measured or calculated (e.g., 10). For SCR particles and/or small objects, it is the main approach for calculating production rates. It has worked very well for the top $\sim$ 300 g/cm^2 of the Moon, although absolute rates calculated with the model and the presently adopted excitation functions often need to be normalized by factors of as much as $\sim$40 %.

The model's limitations are the need for both good fluxes and excitation functions. The fluxes for interstellar GCR particles are very poorly known (4,8). The flux models for meteorites are poor, especially for small and large objects, and only have been developed for spherical meteoroids (3). Applications to SCR-produced nuclides has been limited by the lack of good excitation functions (Re+89). For GCR calculations, a serious problem is the lack of cross sections for neutron-induced reactions.

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PRODUCTION RATES OF COSMOGENIC PLANETARY GAMMA RAYS.*

R. C. Reedy[1] and **P. A. J. Englert**.[2] (1) Earth and Space Sciences Division, Mail Stop D438, Los Alamos National Laboratory, Los Alamos, NM 87545; (2) Department of Chemistry, San Jose State University, San Jose, CA 95192-0101.

Planetary gamma rays are energetic ($E \sim 0.2$–10 MeV) photons that can be used to determine the elemental composition of a planet's surface (1,2). The γ rays are made during the de-excitation of atomic nuclei, and their energies usually indicate uniquely which nucleus and excited level produced them. Such γ rays were used to determine the abundances of several elements in the Moon by gamma-ray spectrometers on Apollos 15 and 16 (e.g., 3,4). There are four main sources of the γ rays used to determine the elemental compositions of planets: (1) natural decay of ^{40}K, thorium, uranium, and their daughters; (2) capture of thermal neutrons, such as ^{56}Fe(n,γ); (3) nonelastic scatter of low-energy ($E \sim 0.4$–15 MeV) neutrons, e.g., ^{56}Fe(n,nγ)^{56}Fe; and (4) reactions by higher-energy ($E \gtrsim 15$ MeV) particles, such as ^{28}Si(p,p$\alpha\gamma$)^{24}Mg. The latter three sources use particles in or made by the galactic cosmic rays. Gamma-ray spectroscopy can be used for planets with no (e.g., Moon) or very thin (e.g., Mars) atmospheres and also for smaller objects like asteroids and comets. Planetary gamma-ray spectroscopy can be used to determine a wide range of elements, ranging from most major elements, some important minor elements (such as the radioactive ones like uranium), and certain volatile elements, such as hydrogen (5) and carbon (6). A gamma-ray spectrometer is scheduled to be part of the Mars Observer mission (7).

In many ways, the determination of production rates of the planetary γ rays made by cosmic rays is similar to determining production rates of cosmogenic nuclides by galactic-cosmic-ray (GCR) particles. Sometimes, the same reaction can make both γ rays and a cosmogenic nuclide, such as the ^{56}Fe(n,2nγ)^{55}Fe or ^{35}Cl(n,γ)^{36}Cl reactions. However, there are some differences, such as most γ rays tending to be made by much lower-energy ($E \lesssim 15$ MeV) reactions than those making most cosmogenic nuclides. Two main approaches have been used in helping to determine production rates of cosmogenic γ rays: simulation experiments and calculations using particle fluxes and cross sections.

<u>Fluxes and Cross Sections</u>. If the flux of cosmic-ray particles in a planet's surface is known as a function of depth and particle energy, then the rate that a γ ray is produced can be calculated by integrating over energy the product of flux times cross section (1,2). The distributions of cosmic-ray particles from thermal to GeV energies are well known in the Moon, but not for other planets. On Mars, the presence of a thin atmosphere and possibly high concentrations of volatiles containing hydrogen and carbon cause the cosmic-ray-particle flux to deviate significantly from a lunar-like one (e.g., 6–8). An additional complication for large planets is that thermal neutrons are gravitationally bound and thus thermal neutrons that escape can return to the surface (9). Measurements of the neutrons that escape from a planet will help in mapping various elements such as hydrogen and carbon (8,9) and will provide information on particle fluxes and nuclear interactions occurring in the planet's surface. When samples are returned from Mars or a comet, a knowledge of these cosmic-ray-particle fluxes will be needed to help in the interpretation of the cosmogenic nuclides observed in these samples.

Many γ-ray-producing cross sections have been measured, especially inelastic-scattering reactions induced by neutrons having energies below ~ 15 MeV, but many cross sections for reactions of interest to planetary gamma-ray spectroscopy have not been measured (e.g., 2,7). Reactors are used in measuring yields for the production of capture γ rays. Some (n,xγ) and (p,xγ) cross sections as a function of energy are being measured. These irradiations often can be done at the same accelerators as used to determine cross sections for the production of cosmogenic nuclides. One advantage of measuring prompt γ rays instead of activation products is that time-of-flight techniques can be used to identify the energy of the neutron inducing the reaction or to reduce backgrounds in the γ-ray detector.

<u>Simulation Irradiations</u>. Cosmogenic nuclides have often been measured in thick targets irradiated by energetic particles. This approach simulates the bombardment of the Moon or meteorites by the GCR, and some of our earlier understanding of the distribution of cosmogenic nuclides came from such irradiations. Similarly, γ rays can also be measured from targets irradiated by energetic

particles. This is also a good simulation of what happens when a gamma-ray spectrometer is operated near a planet. The incident projectiles used in such γ-ray simulations have ranged from 6-GeV protons (10) to neutrons with energies of as much as 78 MeV (11) down to 0–14 MeV (12). These simulations have helped to confirm theoretically calculated γ-ray fluxes, such as those from iron by nonelastic (10) and thermal (12) reactions. More simulation irradiations are planned. Cosmogenic nuclides measured in samples from inside these targets would help to confirm how well natural conditions have been simulated (e.g., 13).

Simulation experiments have been good help in planning for planetary gamma-ray spectrometer missions. The γ-ray spectra from thick-target irradiations should be similar to those observed from a planet. Many features in these spectra, such as γ-ray line widths or backgrounds, can be identified and studied. Most γ rays are emitted with energy spreads that are narrower than the few keV widths seen in pulse height spectra from high-resolution germanium detectors. Among the γ rays that have a broad spread of energies as emitted from planets are those from inelastic-scattering reactions with carbon (e.g., 12). Simulations showed that energetic neutrons escaping from the target produce relative broad background peaks as a result of inelastic-scattering reactions with nuclei in the germanium detector (10,12). However, on the whole, simulation experiments have confirmed that planetary gamma-ray spectroscopy should work well in determining the abundances of many elements in the top few tens of centimeters of a planet's surface.

<u>Discussion</u>. Planetary gamma rays are often made by reactions very similar to those that make cosmogenic nuclides. Results from the study of cosmogenic nuclides have helped in predicting γ-ray fluxes, as was the case for the Moon. Work on understanding and measuring γ rays from Mars and comets will help us to predict the production rates of cosmogenic nuclides in samples from these different and often volatile-rich objects. Similar models are used to calculate rates for making γ rays and cosmogenic nuclides, and similar irradiations are done to measure their production cross sections. Simulations experiments, like those that were valuable in predicting rates and profiles for cosmogenic nuclides, are now being used in planning for planetary gamma-ray spectroscopy missions. The overlap of the planetary-gamma-ray and the cosmogenic-nuclide communities has been, and will continue to be, beneficial to both.

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CROSS SECTIONS FOR GALACTIC-COSMIC-RAY-PRODUCED NUCLIDES.*

R. C. Reedy,[1] K. Nishiizumi,[2] and J. R. Arnold.[2] (1) Earth and Space Sciences Division, Mail Stop D438, Los Alamos National Laboratory, Los Alamos, NM 87545; (2) Department of Chemistry, B-017, University of California, San Diego, La Jolla, CA 92093-0317.

One of the most commonly used approaches for predicting the production rates of nuclides made by galactic-cosmic-ray (GCR) particles in extraterrestrial matter (1) is one that uses fluxes of cosmic-ray particles and cross sections for nuclear reactions. This use of GCR-particle fluxes coupled with cross sections was first developed by Arnold, Honda, and Lal (2) in 1961 for iron meteorites, then was extended to the Moon in 1972 by Reedy and Arnold (3) and later to stony meteorites (e.g., 4). This family of models has worked well, but one of their limitations is the lack of good measured cross sections for the production of many nuclides. This lack of cross sections for GCR-induced reactions is also a problem for the approach of using theoretically calculated particle fluxes in studies of artificially or naturally irradiated targets (e.g., 5). Needed cross sections for solar-proton calculations were presented in (6).

In this approach (2,3), the production rate for GCR particles making a cosmogenic nuclide at depth d in an object of radius R, $P(R,d)$, is calculated as the sum over target elements, i, and the integral over energy, E, of

$$P(R,d) = \Sigma_i N_i \int \sigma_i(E) F(E,R,d) dE \qquad (1)$$

where N_i is the abundance of the ith element, $\sigma_i(E)$ is the cross section as a function of energy for making the nuclide from element i, and $F(E,R,d)$ is the flux of GCR particles with energy E at depth d in an object of radius R. The primary particles in the GCR consist mainly of protons, ~13 % α particles, and ~1 % of heavier nuclei (7). From the high-energy (~ 1–10 GeV) GCR particles, many secondary particles can be made, such as neutrons and pions. All of these primary and secondary particles should be considered in the flux and cross-section terms of Eqn. (1). The main concerns in applying this model have been getting the two key terms in Eqn. (1), the GCR particle fluxes, $F(E,R,d)$, and the cross sections, $\sigma_i(E)$, for all important energies. This type of model and some weaknesses in the flux models are reviewed in another paper presented at this Workshop (8). Below is discussed the need for cross sections for use in calculating rates for the GCR production of cosmogenic nuclides.

At high energies (E $\gtrsim$ 100 MeV), cross sections for proton-induced reactions are usually used and assumed to apply to other energetic species (e.g., primary α particles and secondary neutrons and pions) with the same energies, mainly because of the scarcity of high-energy cross sections for these other particles. At energies below a few hundred MeV, cross sections for neutron-induced reactions are used in Eqn. (1), as neutrons are the dominant particle at such energies because lower-energy charged particles are fairly rapidly stopped by ionization energy losses (3). The energy above which neutrons cease being over ≈50 % of all particles depends on the depth and the target's size but is ~200–400 MeV (2,9) for deep in large objects.

In the discussions below, it is usually assumed that existing measurements are correct or that the measurement uncertainties are not too large. However, a few old measurements may be incorrect, for example the beam flux was poorly monitored. In some cases, the product of interest might not have been quantitatively separated from the target, as was possibly the case for the $^{16}O(p,3p)^{14}C$ cross sections of (10). Sometimes two measurements of a cross section differ by an amount much greater than the quoted errors, for example for ^{26}Al from silicon (cf., 1) or ^{10}Be from oxygen at 135 MeV (cf., 11). Thus it is good to have independent measurements of important cross sections, or additional ones if there are disagreements among existing results.

<u>High-Energy Cross sections</u>. At energies above a few hundred MeV, there usually are adequate cross sections for most cosmogenic nuclides. Except for a few proton energies (e.g., ~200–600 MeV or $\gtrsim$3 GeV), there are usually several accelerators available for such cross-section measurements. Cross sections for proton-induced reactions usually are used at such energies, and there are few indications that adopting such proton cross sections is a poor assumption, especially at energies $\gtrsim$1 GeV. One case where proton-induced cross sections are very poor for energies above 100 MeV is for ^{10}Be from oxygen, for which neutron-induced cross sections appear to be much higher than

proton-induced ones up to energies of $\sim$ 1 GeV (11). Another case might be ^{14}C from oxygen, another example of a very neutron-rich product.

Usually cross sections at high energies are missing for cosmogenic nuclides that are rarely studied. Often this is a case for nuclides for which new measurement techniques have been fairly recently developed. Recently, the use of accelerator mass spectrometry (AMS) to measure long-lived radionuclides has often created the need for cross section measurements. This need is especially true for radionuclides that recently or are just "coming on line" for routine AMS measurements, such as ^{36}Cl, ^{41}Ca and ^{129}I. Often there are few cross sections for minor target elements, such as nickel for calculations involving nuclides made in iron meteorites or metallic phases of chondrites. Sometimes there is a large gap between energies for measured high energy cross sections. While cross sections at high ($\gtrsim$100 MeV) energies almost always behave smoothly with energy, interpolations across large energy gaps can yield relatively poor cross sections, especially if the cross section was still increasing at the lower energy.

Low-Energy (Neutron) Cross sections. There is usually a lack of cross sections for neutron-induced reactions. This lack is especially true for the higher neutron energies, as very few neutron cross sections have been measured above 20 MeV. Often measured cross sections for proton-induced reactions are assumed for neutrons. There is good evidence that this assumption of equality for proton-induced and neutron-induced reactions is not valid for many target/product pairs. In some cases, the reactions for the two types of incident particles are known to be different, such as $^{24}Mg(n,\alpha)^{21}Ne$ versus $^{24}Mg(p,n3p)^{21}Ne$ (12), or are strongly believed to be different, such as for ^{14}C (3) or ^{10}Be (11) from oxygen.

There are only a very few cases where there are adequate cross sections for neutron-induced reactions. These are usually where production occurs at low energies ($E_n \lesssim 20$ MeV) and for cosmogenic nuclides with relative short half-lives. Cases where there are a number of neutron cross sections include $^{40}Ca(n,\alpha)^{37}Ar$, $^{39}K(n,p)^{39}Ar$, and $^{23}Na(n,2n)^{22}Na$. Usually such neutron cross sections can be found in data compilations like (13), but not always, such as the Mg(n,α)Ne measurements of (12). Even in these cases it would be good to have some additional cross sections for neutron energies $\gtrsim$15–20 MeV. The list of needed cross sections for neutron production of cosmogenic nuclides would be long. The best approach here would be to first concentrate on the commonly studied product nuclides, such as ^{26}Al and ^{21}Ne.

The major problem in getting such neutron-induced cross sections is locating good sources of energetic neutrons. Two approaches, using mono-energetic neutrons or sources with a continuum of neutron energies, should be used. Below $\approx$20 MeV, monoenergetic neutrons often are made by reactions involving deuterons and tritons, but when neutrons with E $\gtrsim$ 20 MeV are made by such reactions there are also lower-energy neutrons made by break-up reactions. Other reactions, such as $^{7}Li(p,n)^{7}Be$, can be used to produce neutrons that are quasi-monoenergetic in that most neutrons occur at the highest neutron energy. Above 20 MeV, it is usually hard to get intense mono-energetic neutron sources. Thus spallation or other reactions are used to get "white" neutrons with a broad continuum of energies. Such spallation sources usually produce high intensities of neutrons. However, some mono-energetic cross-section measurements are needed to get cross sections for monitor reactions or a few known cross sections for the cosmogenic nuclides of interest prior to unfolding the measurements made using "white" sources.

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A NEW SEMI-EMPIRICAL FORMULA FOR SPALLATION AND FRAGMENTATION REACTIONS INDUCED BY HIGH ENERGY PROTONS. H. Sauvageon, CENBG, UA 451, 33170 Gradignan, France

Spallation and fragmentation by high energy protons are very important processes occuring in the production of cosmogenic nuclides. Since about fifteen years a large amount of new experimental results have been obtained concerning these two mechanisms. So it is now possible to built a new semi-empirical formula based on some clear and simple experimental features.

This calculation gives cross sections of spallation and fragmentation products with $9 \leqslant Z \leqslant 68$ formed in targets going from Aluminium to Uranium bombarded by protons of $E_p \geqslant 300$ MeV.

The general principle of this calculation has already been presented at the 51th meeting of the Meteoretical Society in Fayetteville (1). It consists to fit the evolution of experimental isotopic distributions of independently formed spallation and fragmentation nuclides by a gaussian curve of which the expression is :

$$\sigma = (\sigma_{max})_{Ep} \quad \exp\left[-(A-A_M)^2 \;/2\, S^2\right]$$

where σ is the cross section of the nuclide of mass A obtained in the interaction and index M refers to the maximum of the distribution. S is related to the FWHM (Full-Width at Half-Maximum), ΔA, of the gaussian $S=\Delta A/2.35$; $(\sigma_M)_{Ep}$ is the cross section of the maximum of the isotopic distribution for a given incident energy.

This calculation consequently requires the knowledge of four types of data :

- The position of the maximum of isotopic distributions in the N-Z plane ;
- The evolution of the widths of the distributions ;
- The evolution of the values of maxima cross sections ;
- The shapes of excitation functions.

All these parameters have been obtained from experimental results with a good precision and their variations give a coherent description of the main characteristics of the cross sections for spallation and fragmentation nuclides.

This formula is simple and very easy to program on a small computer.

In the whole considered mass range the results are in good agreement ($0.7 \leqslant \sigma_{calc}/\sigma_{mes} \leqslant 1.5$) with experimental values as well for independently as for cumulatively produced nuclides.

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PRODUCTION RATES OF NOBLE GASES IN METEORITES - A REVIEW;

Ludolf Schultz, Max-Planck-Institut für Chemie, D-6500 Mainz

Introduction

Meteoroids as meter-sized bodies interact with cosmic radiation during their flight in space. As a result cosmogenic stable and radioactive nuclides are produced within the meteoroid by the primary radiation and also by secondary particles of lower energy. The production rates of cosmogenic isotopes depend mainly on (1) the chemical composition of the irradiated material, (2) the size of the meteoroid and (3) the location of the analyzed sample within the meteoroid. The two last parameters are difficult to determine in meteoritic samples because during atmospheric transit a considerable part of the meteoroids mass is lost.

Stable cosmogenic noble gas isotopes in extraterrestrial materials are cumulated over the time of irradiation and can be used to study the history of these objects. For this purpose production rates must be obtained either via measured cosmogenic radionuclides or basic calculations. The production rate of cosmogenic radionuclides is equal to their saturation activity. Those of stable nuclides cannot be measured directly but must be calculated from their concentration and the exposure age of the meteorite. In this paper our present knowledge of cosmogenic noble gas production rates is reviewed.

Absolute ^{21}Ne production rates

Noble gases in meteorites are a mixture of different components: Radiogenic, trapped and cosmogenic gases as well as possible atmospheric contaminations. Besides ^{3}He (which could be affected by diffusive loss) and ^{38}Ar (where large trapped concentrations mask the cosmogenic component), cosmogenic ^{21}Ne can be obtained best. Therefore, this isotope is widely used for the calculation of exposure ages.

The production rate of ^{21}Ne in meteoritic samples is calculated using exposure ages which have been determined via activities of radionuclides. This is possible for meteorites with low exposure ages where the radionuclide is not yet in saturation; however, in this case the saturation activity is needed and must be taken from other meteorites. Furthermore, an exposure age can be calculated if a radioactive and a stable cosmogenic nuclide are measured and the production rate ratio of these two nuclides is known from other sources. This method yields good results for isotope pairs like ^{40}K-^{41}K or ^{81}Kr-^{82}Kr.

A summary of ^{21}Ne production rates has been given recently by Eugster [1]. Absolute values for production rates in stone meteorites of L-group chemistry can be divided into two groups: While ^{26}Al-derived rates group around 0.47×10^{-8} ccSTP/gMa those calculated from other radionuclides are found between 0.30 to 0.33×10^{-8}ccSTP/gMa. The reason for this discrepancy is not known.

Shielding corrections

Due to the size and depth effect ("shielding"), the ^{21}Ne production rates can vary by more than a factor of two within a single meteorite. For stony meteorites with considerable Mg contents the cosmogenic $^{22}Ne/^{21}Ne$ ratio has been applied as a shielding parameter, which, however, cannot account for both factors, size and depth. It should be kept in mind that the use of this ratio as shielding correction still gives production rates with uncertainties of $\pm$ 20%, which, for extreme shielding ($1.07 < {}^{22}Ne/^{21}Ne > 1.20$), might be even higher.

Commonly used is the shielding correction formula of the production rate of ^{21}Ne P(21) given by Nishiizumi et al. [2]:

$$P(21) = P(21)_{1.11}F[21.77(^{22}Ne/^{21}Ne) - 19.32]^{-1}$$

with $P(21)_{1.11}$ as the ^{21}Ne production rate under the shielding condition given by $^{22}Ne/^{21}Ne = 1.11$ and F a correction factor for different chemical compositions.

Chemical composition

Elemental production rates are needed to account for the different chemical composition of meteorite groups. In meteorites such production rates are obtained by analyzing mineral separates with different chemical composition from one meteorite. The dependence of the average production rate of ^{21}Ne, P(21), as function of the concentration of the for Ne-production important elements is (e.g. [3]):

$$P(21) = 1.63[Mg] + 0.6[Al] + 0.32[Si] + 0.22[S] + 0.33[Fe+Ni]$$

([X] - weight fraction of element X).

This production rate, however, depends also on the bulk composition of the meteorite because a meteorite with high concentrations of FeNi has higher production rates for isotopes which are mainly produced by low-energy secondary particles [4]. The higher multiplicity for the production of secondary neutrons from elements like Fe as compared to O or Si is the reason and limits the value of a production rate formula as given above.

In summary: The calculation of precise cosmic ray exposure ages from stable cosmogenic nuclides is limited. This is due to differences of absolute production rates calculated from different radionuclides. Furthermore, equations used for shielding corrections and adjustments to different chemical compositions are approximations only.

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EVOLUTION OF METEORITIC BODIES IN SPACE; G.K.Ustinova, V.A.Alexeev, and A.K.Lavrukhina; Vernadsky Institute of Geochemistry and Analytical Chemistry, USSR Academy of Sciences, Moscow, 117975 USSR

Determination of the pre-atmospheric sizes of meteorites by using the depth profiles of cosmogenic radionuclides allows to evaluate the average sizes of the meteorites for different time periods before their fall to the earth according to the half-lives of these radionuclides (1).Namely, short-lived radionuclides give us information about the sizes of meteorites just before their entering to the earth atmosphere, while stable cosmogenic isotopes as well as tracks characterize the average sizes of meteorites for all cosmic age. Such approach allows to investigate the evolution of the meteorites in space and their complex radiation history

The pre-atmospheric sizes of some stony meteorites have been investigated. The average sizes of the chondrites Bruderheim, Innisfree, Malakal, Peace River and St. Severin turned out constant over at least ~6 million years. On the contrary, the average sizes of the chondrites Harleton and Gorlovka for the last ~400 years and those of the Ehole chondrite for the last ~8 years were less of their average sizes for the last ~6 million years. In the case of the other chondrites under consideration the results are uncertain due to the large range of the errors, and higher precision of the measurements of radioactivity of the radionuclides is required to elucidate the evolution of these chondrites.

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COSMOGENIC RADIONUCLIDE PRODUCTION RATES IN METEORITES

S.Vogt, Rutgers University, Dept. Chemistry, New Brunswick, NJ 08903.

The production rate of cosmogenic nuclides depends significantly on a) the absolute abundance of target elements contributing to the production of the isotope, b) the size and shape of meteoroids which control the attenuation of the incident primary particles and the degree of build-up of the secondary particle cascade, and c) the energy spectrum and the flux intensity of the primary cosmic ray particles. In contrast to stable cosmogenic nuclides, radioisotopes reach secular equilibrium, if the half live of a particular radionuclide is short relative to the time interval of exposure to cosmic rays. If the average cosmic ray flux was constant over the mean life of the radioactive nuclide, the concentration defines the production rate.

Since 1958, when long-lived radionuclides in meteorites were first reported by Ehmann and Kohman [1], extensive studies have contributed to a rapid growth of radionuclide data. Valuable information about the recent history of meteorites such as exposure ages and terrestrial ages can be inferred. The combinination of radionuclide data with the results of noble gas and track studies permits a still more detailed interpretation of each meteorite. To assure the validity of the interpretation, absolute production rates of radionuclides under various conditions are required. Several methods are applied for evaluating the production rates of cosmogenic radionuclides in meteorites.

Average production rates can be derived from meteorites with exposure ages long enough to ensure secular equilibrium. In such cases, the evaluation of the composition dependence of production rates requires separate statistical approaches for each meteorite class. Heimann et al. [2] analyzed 18 chondrites and reported a ^{53}Mn production rate of 520 dpm/kg$_{Fe}$ consistent with results in iron meteorites. Englert's [3] extensive studies on the ^{53}Mn production rate from the analyses of 71 chondrites is about twenty percent lower. He considered only measured activites between 350 dpm/kg$_{Fe}$ and 550 dpm/kg$_{Fe}$; with this restriction he excluded meteorites subject to extreme size and shielding effects. Hampel et al. [4] compiled ^{26}Al production rates of almost 200 chondrites and provided average production rates of 56.1 dpm/kg for H-chondrites and 60.2 dpm/kg for L-chondrites. Moniot et al. [5] and Sarafin [6] report mean production rates of the radionuclide ^{10}Be of 18.9 dpm/kg and 19.4 dpm/kg$_L$, respectively.

To facilitate comparison of production rates in meteorites of distinctive chemical composition, attempts were made to infer mean elemental production rates. Approaches were made for the nuclides ^{10}Be and ^{26}Al. The elemental production rates were obtained by regression analyses (e.g. [4,5,7]) of data obtained for meteorites with known elemental abundances and for minerals in them.

Semi-quantitative information about shielding conditions can be derived from the ^{22}Ne/^{21}Ne ratio in chondrites [8]. Herzog and Cressy [9] reported a strong correlation between the ^{26}Al production rate and the ^{22}Ne/^{21}Ne ratio in chondrites. This observation was confirmed by Cressy [10], studying the correlation of the ^{26}Al production rate with ^{22}Ne/^{21}Ne ratio in six samples of varying depth of the Keyes chondrite. Similar correlations were found for the radionuclides ^{10}Be (e.g.[11]) and ^{53}Mn (e.g.[3]). Englert and Herr [12] report a linear correlation of the ^{53}Mn production rate with the ^{22}Ne/^{21}Ne ratio in the St. Severin chondrite and suggest the possibility of reducing uncertainties in the determination of ^{53}Mn exposure ages, arising from depth effects, by using shielding-corrected production rates. Nishiizumi et al. [13] compiled data for ^{53}Mn and ^{26}Al and the ^{22}Ne/^{21}Ne ratio and obtained equations for shielding corrections of the radionuclide production rates by linear regression analyses. The general agreement of this statistical approach with the depth profiles of the Keyes and St.Severin meteorites is excellent. However, both depth profiles exhibit a much steeper slope in their correlation. The authors concluded that larger meteorites in general appear to have larger variations in their production rates than smaller objects, which can cause larger uncertainties for shielding corrected production rates, especially of higher shielded samples.

PRODUCTION RATES IN METEORITES; Vogt, S.

Absolute depth profiles of as many cosmogenic nuclides as possible are desirable in order to optimize the interpretation of the history of single meteorites. Moreover, they facilitate a direct comparison and evaluation of results obtained by model calculations and simulation experiments (e.g. [14,15]). Tuniz et al. [16] determined the depth dependence of the ^{10}Be activities in the St.Severin chondrite and observed production rates exceeding the averaged production rate by about 30%. Sarafin [6] obtained comparable production rates for ^{10}Be in the L-chondrite Knyahinya. Bhattacharya et al. [17] report ^{53}Mn depth profiles and Sarafin et al. [18] ^{53}Mn, as well as one ^{26}Al, depth profiles of four small sized meteorites. No variations of the production rates could be detected, within analytical uncertainties, for either of these meteorites. The constancy is attributed to an incomplete build-up of the secondary particle cascade inside of small meteorites. The same observation was made on sample aliquots for the production rates of ^{10}Be and ^{26}Al by Vogt [19]. Vogt attributed the steady increase of averaged production rates with increasing meteorite size to the increasing influence of secondary particles of lower energies. By contrast, the ^{26}Al and ^{53}Mn, as well as extended studies of the ^{10}Be production rates in the Knyahinya chondrite, a large sized meteorite, revealed strong effects of depth on the production rates of all radionuclides [19]. Vogt [19] gives a compilation of all currently available depth profiles of radionuclides in chondrites, discusses correlations of the average production rates in these meteorites with their size, and compares the absolute depth profiles with model calculations.

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STUDY OF HIGH ENERGY PARTICLE PROPAGATION INSIDE SOLID MATTER AND DERIVATION OF COSMOGENIC NUCLIDE PRODUCTION RATES IN IRON METEORITES

B. Zanda
Muséum National d'Histoire Naturelle – 61, rue Buffon – 75005 Paris. FRANCE
Institut d'Astrophysique de Paris – 98,bis Bd Arago – 75014 Paris. FRANCE

Different approaches may be used in order to derive cosmogenic nuclide production rates as a function of depth inside irradiated bodies of various sizes. One main approach is a comparison with simulation experiments through the irradiation of thick targets. In these experiments, the transposition of the available beam geometry to the isotropic irradiation conditions in space has been obtained in different ways from mathematical corrections to rotating spherical targets in the beam [1]. A second type of approach consists in evaluating particle fluxes as a function of depth in the irradiated bodies. These fluxes are used together with nuclear reactions cross sections data to derive production rates. In this approach, fluxes have traditionally been derived in a semiempirical way through the study of meteoritical and thick target data or of stars induced in nuclear emulsions [2–4]. Monte Carlo modelling constitutes a third approach, based on the physical consideration of the processes involved and the following of intranuclear and internuclear cascades [5–7]. In the model we present here, the fluxes are determined in a physical way through a study of particle propagation inside solid matter. Different types of particles can be taken into account (we have so far considered protons and neutrons) by the simultaneous solving of the linked transport equations with an iterative method. Particle losses in nuclear interactions and slowing down of charged particles are studied together with secondary particle production. Secondary particle production is a fundamental process and its evaluation constitute a stumbling block to any physical model studying high energy particle propagation inside solid matter. Due to the lack of data in this field, this evaluation has been performed through the use of results from intranuclear cascades calculations.

Nuclear data used as input

(a) Secondary particle production: Monte Carlo intranuclear cascades calculations allow to estimate the total number of protons and neutrons produced per reaction (ν) as a function of the type of incident particle and of its energy (E'). They also allow to derive the energetic and angular spectrum of the emitted particles. Results from the HETC code have been shown to stand satisfactorily comparison with experimental data [8]. The estimation of the energy spectrum of the emitted particles is of great incidence over the derived fluxes as it is clearly very different to distribute the incident particle energy over a bunch of secondaries or to have a few fast ones taking most of it. This spectrum can be described as a function $KE^{-\beta(E')}$ where E is the energy of the emitted particles. The value of K is obtained from the normalization: $\int_{E_0}^{E'} KE^{-\beta(E')}dE = 1$, where E_0 is the lower energy cutoff used for the computation. An estimation of $\beta(E')$ can been obtained from the total energy taken out by the different types of emitted particles which is a side result of the Monte Carlo code: $\int_{E_0}^{E'} \nu(E')KE^{-\beta(E')}EdE = q(E')$ where $q(E')$ is the total amount of energy taken away by the secondary particles. From $\nu(E')$ and $q(E')$ for emitted neutrons and protons both from proton and neutron induced reactions, we have derived $\beta(E')$ for the same four cases.

(b) Reaction cross sections: The semiempirical formulae of Silberberg and Tsao (see

[9] and references therein) yield up to now the only possible way to estimate simultaneously and over a large energy range all the cross sections for proton induced spallation reactions. Their authors claim a standard deviation of $\approx 30\%$. The accuracy is usually better in the regions where sufficient data were available to ajust the formulae. On the contrary, the deviation is probably much more important in regions where no data are available. Depending on the product nucleus considered, there can consequently be no rule: data are to be used when available, they also can be fitted with the formulae or with functions derived from these formulae. We have done this for ^{10}Be, ^{21}Ne and ^{26}Al production from Fe. For ^{10}Be, the excitation function has been ajusted to fit the existing data at 600 MeV and 21 GeV. The "low energy" adjustment becomes of importance when production rates are computed in heavily shielded regions of irradiated objects where low energy secondary particles become dominant. For ^{26}Al the available data are in good agreement with the formulae, and for ^{21}Ne the formulae have equally been used as there are very few data. We also have used the same cross sections for neutron induced reactions because of the present lack of data. This approximation may become crude when lower energy reaction are considered. The whole situation of available cross sections is currently changing as new set of data become available [10,11].

Application to meteoritical data

Production rates have been computed for various depths in a set of spheres having the chemical composition of the iron meteorite Grant and with radii ranging from 30 to 60 cm. These results are compared to data from Graf et al [12]. Computed production rates range from 1 to 4.6 dpm/kg for ^{10}Be (P_{10}) and from 1 to 3 dpm/kg for ^{26}Al (P_{26}). Data range from 2.5 to 4.8 for ^{10}Be and from 2.0 to 2.8 for ^{26}Al, indicating that 30 cm may be close to the preatmospheric radius of the meteorite or that the deeper shielded points have not been measured. A linear correlation is moreover found between these production rates: $P_{10} = (2.1 \pm 0.4)P_{26}$, where the error bars are derived from a 10% admitted uncertainty on the cross sections. This correlation falls in the limit of the error bars of the one that can be deduced by eliminating $^4He/^{21}Ne$ between equations (1) and (2) of [12]. A linear correlation has also been found between the ^{21}Ne and ^{10}Be production rates: $P_{21} = (1.6 \pm 0.3)P_{10}$ (in at/g/s). This correlation allows to deduce from that observed in [12] a 570±60 Ma ^{21}Ne exposure age (with present cosmic ray flux) for Grant that can be compared with the 590±50 Ma estimate of the same age from [13].

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