PHYSICAL REVIEW C, VOLUME 60, 028801

Thick target yields of $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ from the $^{16}\mathrm{O}(^{16}\mathrm{O},x)^{26}\mathrm{Al}_{\mathrm{g.s.}}$ and $^{16}\mathrm{O}(^{14}\mathrm{N},x)^{26}\mathrm{Al}_{\mathrm{g.s.}}$ reactions

K. O. Yildiz,* N. P. T. Bateman,† Y. M. Butt,‡ A. A. Chen, K. B. Swartz, and P. D. Parker
Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520-8124

(Received 12 January 1999; published 13 July 1999)

Extending the earlier work of Bateman *et al.*, we have measured the energy-integrated yield of $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ from the $^{16}\mathrm{O}(^{16}\mathrm{O},x)^{26}\mathrm{Al}_{\mathrm{g.s.}}$ and $^{16}\mathrm{O}(^{14}\mathrm{N},x)^{26}\mathrm{Al}_{\mathrm{g.s.}}$ reactions. We find that although the yield from the $^{16}\mathrm{O}(^{16}\mathrm{O},x)^{26}\mathrm{Al}_{\mathrm{g.s.}}$ reaction is several times larger than from the $^{12}\mathrm{C}(^{16}\mathrm{O},x)^{26}\mathrm{Al}_{\mathrm{g.s.}}$ reaction, the abundance of fossil $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ observed in carbonaceous chondrite meteorites could be produced by oxygen-rich cosmic rays via the $^{16}\mathrm{O}(^{16}\mathrm{O},x)^{26}\mathrm{Al}_{\mathrm{g.s.}}$ reaction only under the improbable scenario that more than 40% of the solar system oxygen was injected into the protosolar nebula as cosmic rays. [S0556-2813(99)02908-8]

PACS number(s): 26.40.+r, 25.70.Gh, 96.10.+i, 98.80.Ft

Evidence (in the form of excess $^{26}\mathrm{Mg}$ in aluminum-rich minerals in carbonaceous chondrites [1]) has been found for the presence of $^{26}\mathrm{Al}$ in the protosolar nebula at levels which are about 10 times higher than its current abundance in the interstellar medium [2]. This motivated Clayton and Jin [3] to suggest that irradiation of the protosolar nebula by energetic, oxygen-rich cosmic rays might be responsible for the production of short-lived radioisotopes at the time of the formation of the solar system. In particular, they suggested that the $^{12}\mathrm{C}(^{16}\mathrm{O},x)^{26}\mathrm{Al}_{\mathrm{g.s.}}$ reaction might be responsible for the production of $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ in the early solar system. In order to test this proposal, Bateman *et al.* [4,5] measured the energy-integrated yield of that reaction and found that it was too low to explain the abundance of $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ observed in carbonaceous chondrites. Since $^{14}\mathrm{N}$ and $^{16}\mathrm{O}$ are the other two most abundant isotopes in the protosolar nebula capable of producing $^{26}\mathrm{Al}$, we have extended Bateman's work by measuring the energy-integrated yield for the $^{16}\mathrm{O}(^{16}\mathrm{O},x)^{26}\mathrm{Al}_{\mathrm{g.s.}}$ and $^{16}\mathrm{O}(^{14}\mathrm{N},x)^{26}\mathrm{Al}_{\mathrm{g.s.}}$ reactions.

A comparison of previous measurements of the $^{16}\mathrm{O}(^{16}\mathrm{O},x)^{26}\mathrm{Al}$ reaction and a comparison of CASCADE [6] model calculations (using the code's default parameters together with various published level-density parameters) are displayed in Fig. 1; they both show a factor of 2 or more uncertainty in the size of this cross section at the energies of interest, from 60 to 160 MeV. The $^{16}\mathrm{O}(^{14}\mathrm{N},x)^{26}\mathrm{Al}$ cross sections are even less well determined. Some of the uncertainty in the previously measured cross sections arises from the difficulties in separating $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ and $^{26}\mathrm{Al}^{m}$ yields in those reaction studies. The results of the CASCADE model calculations include the *total* yield of $^{26}\mathrm{Al}$($^{26}\mathrm{Al}_{\mathrm{g.s.}}$ and $^{26}\mathrm{Al}^{m}$). However, because the $^{26}\mathrm{Al}$ isomer ($E_x = 228$ keV; $J^{\pi} = 0^{+}$; $t_{1/2} = 6.3$ sec) does not decay to $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ but instead β decays directly to $^{26}\mathrm{Mg}_{\mathrm{g.s.}}$, the isomeric $^{26}\mathrm{Al}$ could not have contributed to the abundance of $^{26}\mathrm{Al}$ in the early solar system. We have utilized the activation method developed by Bateman *et al.* [5], to separate out the $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ yield by measuring the $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ decay off line via the 1809-keV γ-ray line associated with 99.7% of the $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ decays. This method is doubly insensitive to any $^{26}\mathrm{Al}$ produced in its 6.3-sec isomer which decays directly to $^{26}\mathrm{Mg}_{\mathrm{g.s.}}$ (without emitting the 1809-keV γ ray which we measured), long before our off-line counting began.

In our measurements, the $^{26}\mathrm{Al}$ was produced via the bombardment of thick oxygen targets by accelerator beams of $^{14}\mathrm{N}$ or $^{16}\mathrm{O}$ at energies up to 150 MeV. The targets were prepared (CBL Ceramics, Ltd.) in the form of 99.9% pure beryllium oxide (BeO), hot pressed into cylinders, 7 mm in diameter and 10 mm long. BeO was used as the target material because of the low Z of Be, because $^{9}\mathrm{Be}+^{16}\mathrm{O}$ cannot produce $^{26}\mathrm{Al}$, and because of its high melting point (2530 °C) and high thermal conductivity. These thermal properties allowed these samples to be bombarded at power levels of up to 20 W, reaching temperatures of 1500 to 1800 °C without melting or fracturing. During the irradia-

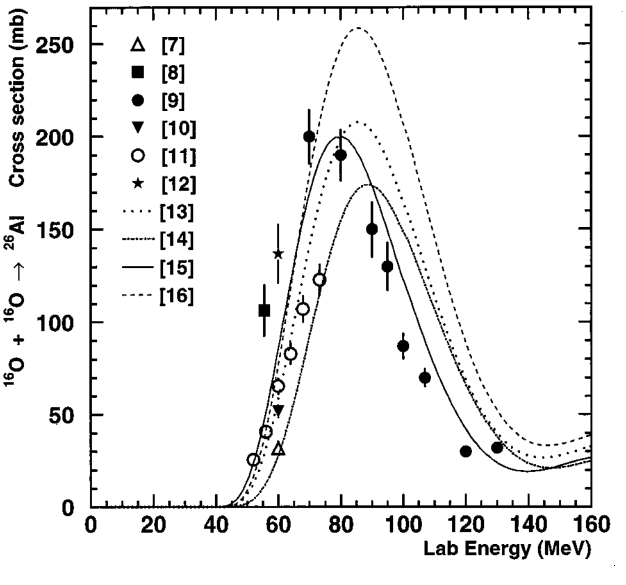

FIG. 1. Intercomparison of previous experimental measurements of the $^{16}\mathrm{O}+^{16}\mathrm{O} \rightarrow ^{26}\mathrm{Al}+x$ cross section (Refs. [7–12]) together with a variety of CASCADE [6] calculations (Refs. [13–16].

---

*Present address: Custom One Design Inc., 10 Corey St., Melrose, MA 02176.

†Present address: TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3.

‡Present address: C.F.A., 60 Garden St., Cambridge, MA 02138.

0556-2813/99/60(2)/028801(4)/$15.00

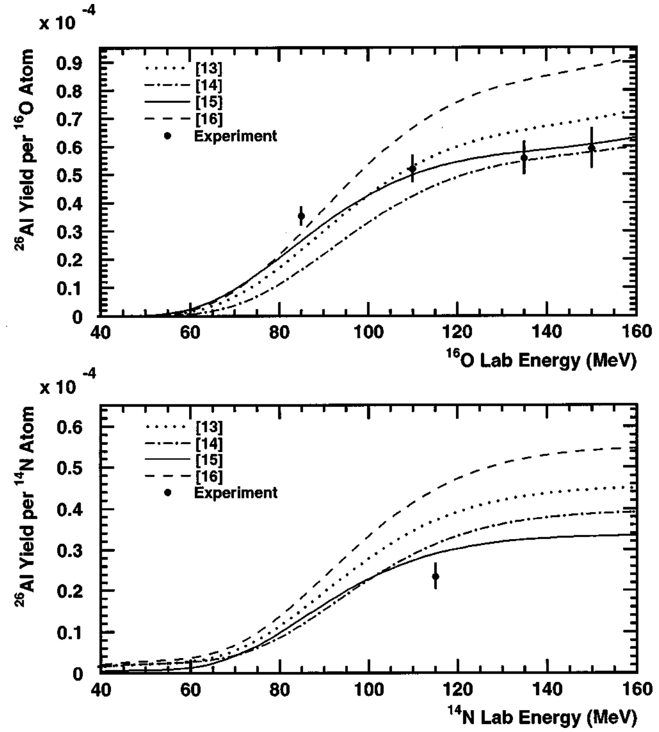

FIG. 2. The calculated yields for the $^{16}O(^{16}O,x)^{26}Al_{g.s.}$ and $^{16}O(^{14}N,x)^{26}Al_{g.s.}$ reactions integrated via Eq. (2) and compared with our mreasured thick-target experimental yields. The curves represent CASCADE calculations utilizing a variety of level density parameters. 1-σ uncertainties (including both statistical and systematic uncertainties) are plotted for the experimental points.

tion, the BeO sample was placed at the end of a 15-cm long, 2-cm diameter copper tube in order to ensure accurate charge integration; the tube was lined with copper foil to collect any activity which might boil off or be sputtered off the surface of the sample.

The only difference between our current γ-ray counting measurements and those of Ref. [5], was the acquisition of a calibrated ($\pm 2.5\%$) ^{26}Al source for use as part of the efficiency measurements for the Ge detector. This source allowed us to make an efficiency calibration measurement *at* the gamma-ray energy of interest, *directly* including *all* the corrections for self-vetoing caused by interactions of the 511-keV β^+ annihilation photons with the detector's BGO shield which was used as a cosmic ray shield, as well as an anti-Compton shield. (This source eliminated any uncertainties introduced by interpolations between a variety of radioactive sources with other γ-ray energies. Calibrations based on the ^{26}Al source were checked against our earlier measurements and agreed within $\pm 1.2\%$.)

For each run, off-line γ-ray spectra were measured for the BeO target, the target holder, and the copper foil liner. Each of these spectra was analyzed to extract the number of counts (N) corresponding to the 1809-keV transition by fitting that peak with its location and width fixed on the basis of the measured peak from the calibrated ^{26}Al source. The number of $^{26}Al_{g.s.}$ in each piece was then determined as

$$n_i = N_i (0.997 \eta_i \lambda t_i)^{-1}, \tag{1}$$

where 0.997 is the branching ratio for $^{26}Al_{g.s.}$ decays through this transition, η_i is the measured efficiency (including self-vetoing), λ is the decay rate of $^{26}Al_{g.s}$, and t_i is the total counting time for the piece. The total number of $^{26}Al_{g.s}$ produced in the run is then just Σn_i, and the energy-integrated thick-target yield per incident beam particle is just this summation divided by the total number of incident beam particles.

It should be emphasized that these experiments were designed to measure the energy-integrated yield which is directly related to the astrophysical yield in the Clayton-Jin hypothesis. The measured thick-target yields are plotted in Fig. 2, in comparison with integrated yields $Y(E)$ based on the energy dependent cross sections from calculations using the Hauser-Feshbach code CASCADE [6] for the four different level density parametrizations shown in Fig. 1:

$$Y(E) = \int_o^E \frac{\sigma(e)}{\varepsilon_{\text{eff}}(e)} de, \tag{2}$$

where $\varepsilon_{\text{eff}}(e)$ is the effective stopping power per oxygen target atom in eV/(atoms/cm^2) [17]. From this plot it appears that of the four parametrizations, Dilg *et al.* [15] provides the best description of our data. The Dilg parametrization also provides a consistent description of both the energy dependence and magnitude of the previous cross section data (plotted in Fig. 1). Therefore, with the caveat that this calculation includes the $^{26}Al^m$ yield as well as the $^{26}Al_{g.s.}$ yield, we have made a strictly empirical decision to use the Dilg *et al.* cross sections as a convenient energy dependence for integrating and discussing the production of $^{26}Al_{g.s}$ in the protosolar nebula.

Measurements of excess ^{26}Mg (fossil ^{26}Al) in aluminum-rich inclusions in carbonaceous chondrites [1] indicate a $^{26}Al/^{27}Al$ ratio of 5×10^{-5}, which corresponds to a $^{26}Al/^{16}O$ ratio of 1.8×10^{-7} in the solar system at the time of the formation of these meteorites. Bateman *et al.* [5] determined that even if *all* of the ^{16}O in the solar system entered the protosolar nebula as energetic (9 MeV/nucleon) cosmic rays, it could produce a $^{26}Al/^{16}O$ ratio of only 1.2×10^{-7} via the $^{12}C(^{16}O,x)^{26}Al_{g.s.}$ reaction. Our measured $^{16}O(^{14}N,x)^{26}Al_{g.s}$ integrated yield per ^{14}N atom is approximately a factor of 3 less than the integrated yield per ^{12}C atom from the $^{12}C(^{16}O,x)^{26}Al_{g.s.}$ reaction [5] and approximately a factor of 2 less than our measured integrated yield per ^{16}O atom from the $^{16}O(^{16}O,x)^{26}Al_{g.s.}$ reaction. Coupled with the factor of 5 to 8 times smaller abundance of ^{14}N relative to ^{12}C and ^{16}O, respectively, in the protosolar nebula [18], this means that the $^{16}O(^{14}N,x)^{26}Al_{g.s}$ reaction will be the least important (by a factor of ≈ 15) of these three reactions for possibly producing $^{26}Al_{g.s}$ in the early solar system. Figure 3 displays the $^{26}Al_{g.s}$ yield from each of these three reactions resulting from the irradiation of the protosolar nebula by oxygen rich cosmic rays with energies of up to 9 MeV/nucleon calculated using Eq. (2), with the effective stopping power for ^{16}O in the protosolar nebula determined on the basis of the *current* mixture of elements given by the standard solar system abun-

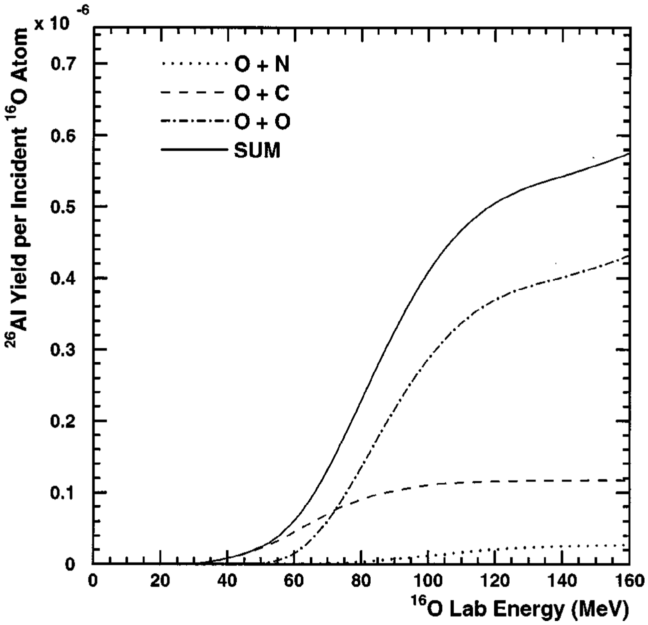

FIG. 3. $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ yield per incident $^{16}\mathrm{O}$ atom for the case in which the $^{16}\mathrm{O}$ atoms are stopping in material with the current solar system composition. The integrated yield curves for the $^{16}\mathrm{O}$ and $^{14}\mathrm{N}$ targets were determined using the cross sections calculated for the $^{16}\mathrm{O}(^{16}\mathrm{O},x)^{26}\mathrm{Al}_{\mathrm{g.s.}}$ and $^{16}\mathrm{O}(^{14}\mathrm{N},x)^{26}\mathrm{Al}_{\mathrm{g.s.}}$ reactions via the code CASCADE [6], incorporating the level density parameters of Dilg *et al.* [15]. The yield curve for the $^{12}\mathrm{C}(^{16}\mathrm{O},x)^{26}\mathrm{Al}_{\mathrm{g.s.}}$ reaction is taken from the measurements of Bateman *et al.* [4,5].

dances [18]. As has been pointed out earlier [4,19], for oxygen energies greater than 9 MeV/nucleon the ratio of the yields of $^{26}\mathrm{Al}$ and $^{6}\mathrm{Li}$ would exceed the abundance ratio in the early solar system. From this graph, it is seen that the primary contribution to the production of $^{26}\mathrm{Al}_{\mathrm{g.s}}$ via bombardment of the protosolar nebula by energetic oxygen-rich cosmic rays would have come from the $^{16}\mathrm{O}(^{16}\mathrm{O},x)^{26}\mathrm{Al}_{\mathrm{g.s.}}$ reaction.

If these oxygen cosmic rays stop in the protosolar cloud, then an upper limit on the total fluence of oxygen cosmic rays in the protosolar cloud is given by the total amont of oxygen in the solar system. However, if the total fluence of oxygen-rich cosmic rays in the Clayton-Jin proposal were sufficiently large to be comparable to the solar system oxygen abundance, then a correction would need to be made to Fig. 3 to take into account the increasing oxygen abundance, as the cosmic rays stop in the cloud during the bombardment. In this case, the ratio of the $^{26}\mathrm{Al}$ abundance at the time of chondrite formation to the current abundance of $^{16}\mathrm{O}$ in the solar system can be expressed as [20]:

$$\frac{N(^{26}\mathrm{Al})}{N_f(^{16}\mathrm{O})}=\left\{y_{26}(\mathrm{C})+y_{26}(\mathrm{N})+\frac{y_{26}(\mathrm{O})}{2}\left(1+\frac{N_i(^{16}\mathrm{O})}{N_f(^{16}\mathrm{O})}\right)\right\}\times\left(1-\frac{N_i(^{16}\mathrm{O})}{N_f(^{16}\mathrm{O})}\right), \tag{3}$$

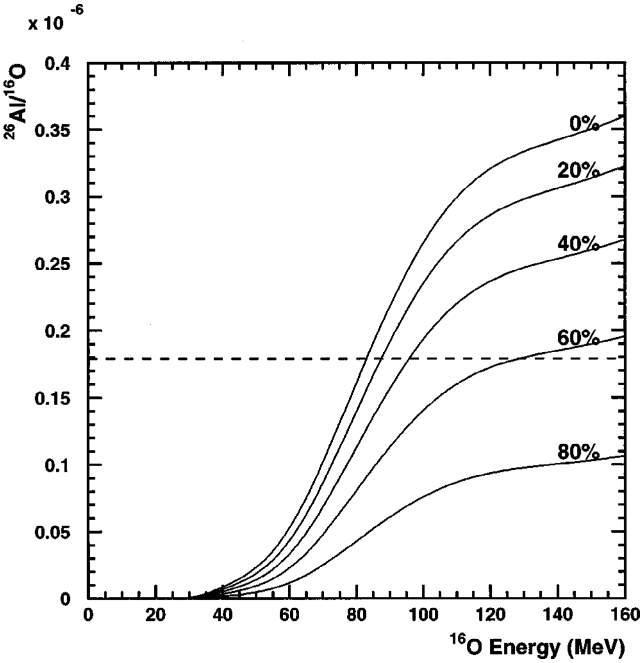

FIG. 4. Dependence of the yield of $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ produced in the protosolar nebula on the *initial* abundance of $^{16}\mathrm{O}$ (as a percentage of its present abundance). The horizontal, dashed line indicates the meteoritic ratio of $^{26}\mathrm{Al}_{\mathrm{g.s.}}/^{16}\mathrm{O}$.

where $y_{26}(X)$ is the yield calculated and plotted in Fig. 3 for element X for the current solar system abundance of X, and where $N_i(^{16}\mathrm{O})$ and $N_f(^{16}\mathrm{O})$ are the abundances of $^{16}\mathrm{O}$ in the protosolar nebula before and after the proposed $^{16}\mathrm{O}$ cosmic ray bombardment. These calculations were made assuming an external source of monoenergetic $^{16}\mathrm{O}$ cosmic rays with energy $E(^{16}\mathrm{O})$ which stop in the protosolar cloud. Figure 4 displays the result of a series of calculations in which the initial oxygen abundance (as a percentage of the current abundance) is varied in 20% steps. This plot shows that in order to account for the $^{26}\mathrm{Al}$ present in the protosolar nebula ($^{26}\mathrm{Al}/^{16}\mathrm{O}\approx 1.8\times 10^{-7}$) within the Clayton-Jin proposal, approximately 40% of the solar system oxygen would have to have been injected into that nebula in the form of energetic cosmic rays. The required percentage would be even larger if the energy spectrum of these cosmic rays were included (not all the incident oxygen cosmic rays will have an energy of 9 MeV/nucleon) and if the decay half-life of $^{26}\mathrm{Al}_{\mathrm{g.s}}$ were included.

These measurements support our earlier conclusions [4,5] that the $^{26}\mathrm{Al}_{\mathrm{g.s}}$ activity present in the solar system at the time of its formation must have come from some sort of external explosive event [21] rather than from bombardment of the nebula by energetic, oxygen-rich cosmic rays.

We would like to thank the staff at CBL Ceramics, Ltd., for their assistance in providing the BeO targets. This work was supported under U.S. Department of Energy Grant No. DE-FG02-91ER-40609.

[1] G. J. Wasserburg, in *Protostars and Planets II*, edited by D. C. Black and M. S. Matthews (University of Arizona Press, Tucson, 1985), p. 703.
[2] R. Diehl *et al.*, Astron. Astrophys. **298**, 445 (1995).
[3] D. D. Clayton and L. Jin, Astrophys. J. **451**, 681 (1995).
[4] N. P. T. Bateman, P. D. Parker, and A. E. Champagne, Astrophys. J. Lett. **472**, L119 (1996).
[5] N. P. T. Bateman, D. W. Bardayan, Y. M. Butt, A. A. Chen, K. O. Yildiz, B. M. Young, and P. D. Parker, Phys. Rev. C **57**, 2022 (1998).
[6] F. Pülhofer, Nucl. Phys. **A280**, 267 (1977).
[7] V. K. C. Cheng, A. Little, H. C. Yuen, S. M. Lazarus, and S. S. Hanna, Nucl. Phys. **A322**, 168 (1979).
[8] A. J. Cole, N. Longequeue, J. Menet, J. J. Lucas, R. Ost, and J. B. Viano, Nucl. Phys. **A341**, 284 (1980).
[9] H. Ikezoe, N. Shikazono, Y. Tomika, K. Ideno, Y. Sugiyama, E. Takekoshi, T. Tachikawa, and T. Nomura, Nucl. Phys. **A456**, 298 (1986).
[10] J. J. Kolata, R. C. Fuller, R. M. Freeman, F. Haas, B. Heusch, and A. Gallmann, Phys. Rev. C **16**, 891 (1977).
[11] J. J. Kolata, R. M. Freeman, F. Haas, B. Heusch, and A. Gallmann, Phys. Rev. C **19**, 2237 (1979).
[12] A. Weidinger, F. Busch, G. Gauli, W. Trautmann, and W. Zipper, Nucl. Phys. **A263**, 511 (1976).
[13] N. Carlin Filho, M. M. Coimbra, J. C. Acquadro, R. Liguori Neto, E. M. Szanto, E. Farrelly-Pessoa, and A. Szanto de Toledo, Phys. Rev. C **31**, 152 (1985).
[14] Y. D. Chan, H. Bohn, R. Vandenbosch, K. G. Bernhardt, J. G. Cramer, R. Sielemann, and L. Green, Nucl. Phys. **A303**, 500 (1978).
[15] W. Dilg, W. Schantl, H. Vonach, and M. Uhl, Nucl. Phys. **A217**, 269 (1973).
[16] A. Gilbert and A. G. Cameron, Can. J. Phys. **43**, 1446 (1965).
[17] J. F. Ziegler and J. Biersack, Computer code SRIM97, 1997.
[18] E. Anders and N. Grevesse, Geochim. Cosmochim. Acta **53**, 197 (1989).
[19] R. Ramaty, B. Kozlovsky, and R. E. Lingenfelter, Astrophys. J. **456**, 525 (1995).
[20] K. O. Yildiz, Ph.D. Thesis, Yale University, 1998.
[21] See, e.g., A. G. W. Cameron, P. Höflich, P. C. Myers, and D. D. Clayton, Astrophys. J. Lett. **447**, L53 (1995).