THE ASTROPHYSICAL JOURNAL, 472:L119–L122, 1996 December 1
© 1996. The American Astronomical Society. All rights reserved. Printed in U.S.A.

ON THE PRODUCTION OF ^{26}Al IN THE EARLY SOLAR SYSTEM BY LOW-ENERGY OXYGEN COSMIC RAYS

NICHOLAS P. T. BATEMAN[1]
Wright Nuclear Structure Laboratory, Yale University, New Haven, CT 06520-8124; bateman@hermes.physics.yale.edu
PETER D. PARKER
Wright Nuclear Structure Laboratory, Yale University, New Haven, CT 06520-8124; peter@riviera.physics.yale.edu
AND
ARTHUR E. CHAMPAGNE
TUNL and University of North Carolina, Chapel Hill, NC 27599; aec@tunl.tunl.duke.edu
Received 1996 August 26; accepted 1996 September 17

ABSTRACT

Clayton & Jin have proposed that the high abundance of ^{26}Al found in meteorites was produced by cosmic rays in the early solar system through the ^{12}C(^{16}O, x)^{26}Al$_{gs}$ reaction. We have measured the yield of ^{26}Al in the ground state (i.e., ^{26}Al$_{gs}$) from this reaction and find that, if this mechanism produced the meteoritic ^{26}Al, a substantial fraction of the solar system oxygen must have entered the solar system as low-energy cosmic rays. This does not seem plausible. If the proto-Sun itself was the source of the oxygen cosmic rays, they must have carried off some 5% of the power of the protosolar wind for 1 Myr. This too seems unlikely. Although we do not address the role of other cosmic-ray species in the production of ^{26}Al, it appears that ^{26}Al was produced in a stellar environment, and not by cosmic rays.

Subject headings: cosmic rays — meteors, meteoroids — nuclear reactions, nucleosynthesis, abundances — solar system: formation

1. INTRODUCTION

Measurements of calcium-aluminum inclusions (CAIs) from a variety of carbonaceous chondrites suggest that in the early solar system a typical value of the ^{26}Al/^{27}Al ratio was 5×10^{-5} (Wasserburg 1985). The half-life of ^{26}Al$_{gs}$ is only 0.7 Myr (^{27}Al is stable), so it is hard to understand how its abundance could have been so high. This high abundance has generally been interpreted as evidence that the protosolar cloud was injected with freshly synthesized radioactive material (e.g., Cameron & Truran 1977). However, it is difficult for a single injection event to produce all of the activities that have been observed in meteorites.

The Compton Telescope (COMPTEL) on the *Compton Gamma Ray Observatory* has observed 4.4 and 6.1 MeV gamma rays from Orion (Bloemen et al. 1994). These are the characteristic de-excitation gamma rays of ^{12}C and ^{16}O. The cosmic rays that are producing these gamma rays must be strongly depleted in hydrogen and helium so that they do not deposit more energy into the Orion complex than is radiated in the infrared (Bloemen et al. 1994). Furthermore, because gamma rays from the de-excitation of nuclides like neon, magnesium, and iron are not observed, the cosmic rays must be strongly depleted in these elements too (Ramaty, Kozlovsky, & Lingenfelter 1995). So it appears that the Orion complex, which contains the nearest giant molecular clouds in which stars are forming, is being irradiated by cosmic rays that are highly enriched in carbon and oxygen. The existence of these cosmic rays in Orion led Clayton & Jin (1995a) to suggest that they may exist in all star-forming regions, and that the protosolar cloud may have been subject to irradiation by similar cosmic rays. If these cosmic rays could have produced the abundances of radioactive nuclides that are inferred from meteoritic measurements, it would be unnecessary to invoke an injection event to explain these abundances.

The abundance of ^{26}Al is critical to this scenario. It has the second shortest half-life of all of the radioisotopes that have been observed in meteorites, and has a very high initial abundance. Clayton & Jin (1995a) propose that the cosmic rays in Orion, and, therefore, the cosmic rays that irradiated the early solar system, are similar to the anomalous cosmic rays (ACRs) that are observed in the present-day solar system, which are strongly enriched in oxygen. Consequently, they propose that oxygen cosmic rays produced the meteoritic radionuclides, and believe that the ^{12}C(^{16}O, x)^{26}Al$_{gs}$ reaction might be responsible for the meteoritic ^{26}Al abundance.

Previous measurements of the ^{12}C(^{16}O, x)^{26}Al reaction rate showed an inconsistency of about a factor of 5 in normalization. Furthermore, the interpretation of these experiments is complicated by the existence of an isomeric state of ^{26}Al at 228 keV in excitation. This state decays directly to the ground state of ^{26}Mg with a half-life of 6.3 s, so it cannot be responsible for the meteorite observations. However, in experiments where the recoiling nucleus was measured, it was not possible to distinguish between the ground and isomeric states. The other experimental technique that had been used to measure the ^{12}C(^{16}O, x)^{26}Al cross section, detection of de-excitation gamma rays, requires detailed knowledge of the gamma-ray cascade in ^{26}Al. Thus, both methods suffer from considerable systematic uncertainties. Clearly, another measurement of this reaction rate was needed.

2. EXPERIMENT

Under the proposal of Clayton & Jin (1995a), the cosmic rays that made the protosolar ^{26}Al were similar to the present-day ACRs. Oxygen ions of these energies will stop in 10 mg cm^{-2} of material of solar composition, which means that if the

---

[1] Present address, TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, Canada V6T 2A3.

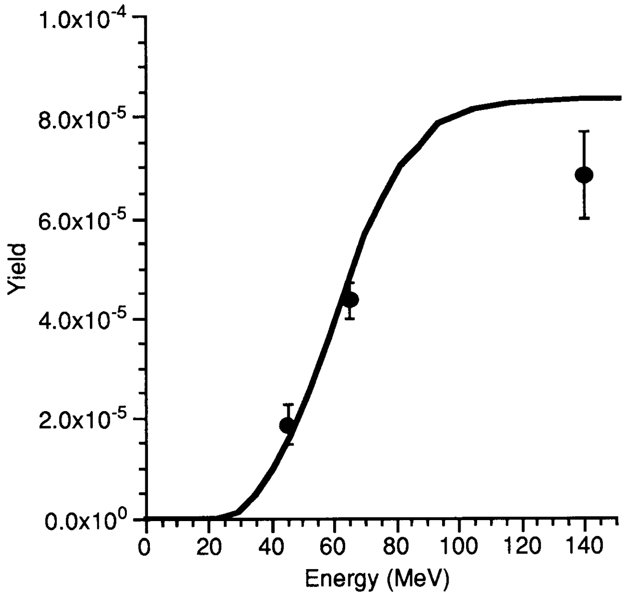

FIG. 1.—Experimental data, and the calculated yield for oxygen ions stopping in graphite, are shown. The yield (*abscissa*) is defined as the number of $^{26}\mathrm{Al}_{\mathrm{gs}}$ nuclei produced divided by the number of ^{16}O ions stopped (see eq. [1]). The calculated curve is consistent with the data, so the calculated cross section was used to represent the excitation function of the $^{12}\mathrm{C}(^{16}\mathrm{O}, x)^{26}\mathrm{Al}_{\mathrm{gs}}$ reaction.

density of the protosolar cloud is greater than about 10^4 cm^{-3}, they will all be stopped in the cloud. So the quantity of interest is the total yield, defined as the number of $^{26}\mathrm{Al}_{\mathrm{gs}}$ nuclei produced for each oxygen atom that stops. This thick-target yield is given by

$$Y(E_i) = \frac{N_{\mathrm{A}}}{A} n_t \int_O^{E_i} \frac{\sigma}{dE/dx} dE , \qquad (1)$$

where E_i is the initial energy of the oxygen ion (in MeV), dE/dx is the energy-dependent stopping power of material in the protosolar cloud [in MeV (g cm^{-2})$^{-1}$], σ is the energy-dependent total cross section (in cm^2), N_{A} is Avogadro's number, A is the molecular mass of the target, and n_t is the average number of target atoms (i.e., carbon atoms) per target molecule. In this Letter, whenever we use the word *yield*, the definition of equation (1) is implied. To perform the integral in equation (1), we need to know the excitation function, $\sigma(E)$, for this reaction. By stopping the beam in the target, we were able to measure the integrated yield, so we did not need to measure the detailed excitation function.

A beam of monoenergetic ^{16}O ions was stopped in a sample of graphite, and the gamma rays from the beta decay of $^{26}\mathrm{Al}_{\mathrm{gs}}$ were observed off-line. Full details of the experiment will be given elsewhere (Bateman 1996; Bateman et al. 1996). The $^{26}\mathrm{Al}_{\mathrm{gs}}$ yield was measured at three energies, and the results are shown in Figure 1. The statistical model code CASCADE (Pülhofer 1977) was used to calculate the excitation function for the $^{12}\mathrm{C}(^{16}\mathrm{O}, x)^{26}\mathrm{Al}_{\mathrm{gs}}$ reaction using the level densities of Chan et al. (1978), the code TRIM91 (similar to that described in Ziegler, Biersack, & Littmard 1985) was used to calculate stopping powers in carbon, and the calculated yield curve is also shown in Figure 1.

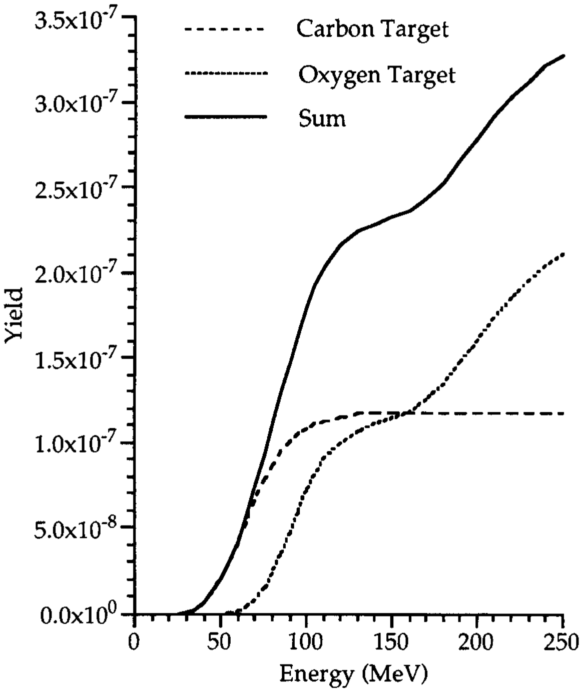

FIG. 2.—Calculated yield of ^{26}Al for ^{16}O ions stopping in material of solar composition. The most important target species are ^{12}C and ^{16}O. The total yield is found by summing the contributions of both species. Note that cosmic-ray energies are constrained to be less than about 160 MeV by the light-element abundances. The true yield from the oxygen atoms in the ambient medium may be smaller than shown here; if a significant portion of the solar system oxygen entered the solar system as such cosmic rays, the oxygen abundance before these cosmic rays stopped in the solar system was smaller than it is now.

3. PRODUCTION OF A UNIFORM ^{26}Al ABUNDANCE THROUGHOUT THE PROTOSOLAR CLOUD

Equation (1) can be used to determine the yield of $^{26}\mathrm{Al}_{\mathrm{gs}}$ for cosmic rays in the protosolar cloud, if the excitation function and stopping power in the protosolar cloud are known. Because the curve in Figure 1 is consistent with the measured yields in graphite, the excitation function from CASCADE that was used to derive it was used to represent the excitation function of the $^{12}\mathrm{C}(^{16}\mathrm{O}, x)^{26}\mathrm{Al}_{\mathrm{gs}}$ reaction. Stopping powers for material of solar composition were calculated with TRIM. TRIM can calculate stopping powers for a mixture of as many as four elements, so the solar abundances of hydrogen, helium, and oxygen were used (from Anders & Grevesse 1989), and the average of all the other elements was used as the fourth element. The stopping is dominated by hydrogen and helium, so this is a reasonable approximation.

Stopping powers are sensitive to the physical conditions in the target; for instance, if the target is a plasma, the stopping powers could be 3 times higher (Ramaty et al. 1996). Such uncertainties dominate the uncertainty in our calculated yields. The calculated yield of $^{26}\mathrm{Al}_{\mathrm{gs}}$ from the $^{12}\mathrm{C}(^{16}\mathrm{O}, x)^{26}\mathrm{Al}_{\mathrm{gs}}$ reaction (i.e., from reactions on the carbon in the protosolar cloud) is given by the dashed curve in Figure 2.

Obviously, the protosolar cloud contained elements other than carbon, and such elements could have contributed to the yield of $^{26}\mathrm{Al}_{\mathrm{gs}}$. In particular, the solar abundance of oxygen is about twice that of carbon, and oxygen can readily produce $^{26}\mathrm{Al}_{\mathrm{gs}}$ through the $^{16}\mathrm{O}(^{16}\mathrm{O}, \alpha pn)^{26}\mathrm{Al}_{\mathrm{gs}}$ reaction. We have performed CASCADE calculations to find the excitation function for this reaction, using the same parameters that were used to find the $^{12}\mathrm{C}(^{16}\mathrm{O}, x)^{26}\mathrm{Al}_{\mathrm{gs}}$ excitation function. We have converted the results of this calculation into the total yield for oxygen ions stopping in solar material, and the results are shown in Figure 2. Nitrogen is probably the only other element that might have contributed to the production of ^{26}Al by oxygen cosmic rays, and its abundance is 8 times smaller than that of carbon (Anders & Grevesse 1989), so we have neglected it.

Because the cosmic rays under consideration stop in the protosolar cloud, and thus remain in the solar system, the total fluence of such cosmic rays is limited by the total amount of oxygen in the solar system, which is given by the abundance ratio of $^{26}\mathrm{Al}/^{16}\mathrm{O}$. If the meteoritic abundance of ^{26}Al is characteristic of the protosolar cloud, the cloud had a $^{26}\mathrm{Al}/^{27}\mathrm{Al}$ ratio of 5×10^{-5}. Then, from the oxygen and aluminum abundances of Anders & Grevesse (1989), $^{26}\mathrm{Al}/^{16}\mathrm{O}$ was 1.9×10^{-7} in the early solar system. From Figure 2, this number is within a factor of 2 of the total yield of ^{26}Al from 10 MeV nucleon^{-1} oxygen ions. In other words, if the ^{26}Al was produced by oxygen cosmic rays, about half of the solar system oxygen must have entered the solar system as such cosmic rays. The constraint is really even stronger than this simple calculation would suggest, because this scenario requires that a large proportion of the solar system oxygen entered the protosolar cloud as cosmic rays. Therefore, the abundance of oxygen must have been significantly smaller than its ultimate abundance before the cosmic-ray irradiation. Thus, during the initial stages of the irradiation the abundance of the oxygen target nuclei must have been less than solar, and therefore the yield per incident ion must have been lower. Furthermore, the above discussion does not allow for any $^{26}\mathrm{Al}_{\mathrm{gs}}$ decay, so the time between the cosmic-ray irradiation and the formation of the CAIs is (implicitly) assumed to be much less than 1 Myr. This is probably not a realistic assumption. As an extreme case we can neglect these problems and allow a very generous factor of 10 uncertainty for our yield calculation. Under these assumptions, the scenario of Clayton & Jin (1995a), in which ^{26}Al is produced throughout the protosolar cloud by oxygen cosmic rays, still requires that more than 5% of the solar oxygen have once been at roughly 15 MeV nucleon^{-1}. Such a picture is implausible at best.

In addition, Ramaty et al. (1996) have pointed out that the production of light elements can also constrain the flux of low-energy cosmic rays in the early solar system, and while they consider various abundance distributions in cosmic rays, a stronger constraint can be obtained by considering a flux of pure oxygen ions. We have repeated the light-element calculation of Clayton & Jin (1995a), using our more realistic yields for the $^{12}\mathrm{C}(^{16}\mathrm{O}, x)^{26}\mathrm{Al}_{\mathrm{gs}}$ and $^{16}\mathrm{O}(^{16}\mathrm{O}, x)^{26}\mathrm{Al}_{\mathrm{gs}}$ reactions. We find that for oxygen energies greater than 9 MeV nucleon^{-1} the ratio of the yield of ^{26}Al to that of ^{6}Li (which provides a stronger constraint than ^{9}Be) exceeds the abundance ratio in the early solar system.

Therefore, as noted by Clayton & Jin (1995a), the light-ion abundances restrict the possible energies of oxygen cosmic rays in the early solar system to less than 10 MeV nucleon^{-1}, but the abundance ratio of $^{26}\mathrm{Al}/^{16}\mathrm{O}$ in the early solar system is so high that, no matter what energies oxygen cosmic rays may have, they cannot produce the meteoritic ^{26}Al abundance throughout the solar system.

4. ALTERNATIVE COSMIC-RAY SCENARIOS

Another way in which ^{26}Al may have been produced in the early solar system is through the action of carbon-rich cosmic rays. As noted above, the COMPTEL observations are consistent with an irradiation of oxygen- and carbon-rich cosmic rays. We have repeated the calculations described above to determine the yield of $^{26}\mathrm{Al}_{\mathrm{gs}}$ from the $^{16}\mathrm{O}(^{12}\mathrm{C}, x)^{26}\mathrm{Al}_{\mathrm{gs}}$ reaction. For carbon ions with more than 8 MeV nucleon^{-1} the total yield per incident ion is 3.7×10^{-7}, which is smaller than the solar $^{26}\mathrm{Al}/^{12}\mathrm{C}$ abundance ratio of 4.2×10^{-7}. Although the uncertainties associated with this calculation are the same as those in the calculation for oxygen cosmic rays, it is clear that irradiation of the early solar system with carbon cosmic rays (or, indeed, with any combination of oxygen and carbon cosmic rays) cannot produce the ^{26}Al meteoritic abundance.

Another possibility is that ^{26}Al was inhomogeneous in the early solar system. In this case, the diverse measured abundances of ^{26}Al from different inclusions would reflect this inhomogeneity. Because the composition of the bulk material of the carbonaceous chondrites is characteristic of the composition of the solar system, the meteorites themselves must have formed from material that was reasonably well homogenized. Thus, this scenario requires that the site of condensation of the CAIs (which contain the ^{26}Al and so must have formed from material that was not well homogenized) be distinct from the site of condensation of the meteorites themselves. Liffman (1992) has pointed out that the mixing time for cloud cores, which are much larger than 1 $M_{\odot}$, is less than 0.2 Myr, so that, unless the CAIs were formed in this timescale, any ^{26}Al inhomogeneities would be washed out by mixing. From our discussion of the relative abundance of ^{26}Al and oxygen (or carbon), those parts of the early solar system that were enriched in ^{26}Al must have stopped large quantities of oxygen (or carbon) ions. Therefore, in this scenario the material from which the CAIs condensed must have been enriched in oxygen (or carbon). Unfortunately, the CAIs are very refractory, so it is difficult to test this proposition.

Another scenario has been suggested by Clayton & Jin (1995b). They propose that energetic particles from the proto-Sun irradiated the surface layers of the accretion disk, producing ^{26}Al in this part of the disk as they stopped. The CAIs were formed in this ^{26}Al-rich medium and then sank to that part of the disk where the bulk meteorites were formed. Essentially, this is a variant of the "inhomogeneous" scenario discussed above; therefore, if oxygen cosmic rays are responsible for the production of ^{26}Al, our results require that the CAIs formed from oxygen-rich material. Clayton & Jin (1995b) calculate the energetics for helium-rich cosmic rays. We have used our results to repeat this calculation for oxygen cosmic rays.

The spectrum of the present-day ACR oxygen is consistent with the form

$$\frac{\partial N}{\partial E} = \left(\frac{E}{E_0}\right)^{-1.5} \exp\left(-\frac{E}{E_0}\right), \qquad (2)$$

where E_0 is 50 MeV nucleon^{-1} (Mewaldt, Spalding, & Stone 1984), and we have assumed a low-energy cutoff of 1 MeV nucleon^{-1}. This spectral shape is expected theoretically for shock acceleration with maximum compression. Cosmic rays with this spectrum will produce an average of 9.5×10^{-8} ^{26}Al atoms per oxygen ion as they stop in material of solar composition. Their mean energy is 120 MeV, so 2000 ergs are deposited in the ambient material for every ^{26}Al nucleus produced. The mean range of the ^{16}O ions in material of solar composition is about 10 mg cm^{-2}; following Clayton & Jin (1995b), we assume a disk thickness of 300 g cm^{-2}, so that 7×10^{-5} of the disk mass is irradiated by these ions. The minimal solar disk has a mass of 0.02 $M_{\odot}$, so 1.7×10^{41} ^{26}Al atoms must be produced in the surface of the disk. This requires that 3.4×10^{44} ergs be deposited in the surface of the disk. The dissipation timescale of the solar accretion disk (Cameron 1988) and the half-life of ^{26}Al are both about 1 Myr, and if the energy is deposited on this timescale, the power in the cosmic rays corresponds to 0.003 $L_{\odot}$. Although this is an order of magnitude more favorable than the case of helium cosmic rays considered by Clayton & Jin (1995b), it still corresponds to about 5% of the power in the strongest stellar winds of T Tauri stars (Bertout 1989), and it is not clear how so much of the power of the protosolar wind could end up in particles with energies greater than 1 MeV nucleon^{-1}. Furthermore, it is not clear that such strong winds can persist for 1 Myr. It is possible that the disk was depleted in hydrogen and helium because of dust enhancements; this would lower the power requirements in this scenario. However, in the above discussion we have only considered cosmic rays composed of pure oxygen; the ACRs are about 10% oxygen by mass (Cummings & Stone 1996), and the presence of hydrogen and helium in the cosmic rays will increase the power requirements. On balance, this scenario seems implausible, but we cannot exclude it.

5. CONCLUSION

Our measurement of the yield of ^{26}Al$_{gs}$ from the ^{12}C(^{16}O, x)^{26}Al$_{gs}$ reaction shows that oxygen cosmic rays can only produce the meteoritic ^{26}Al abundance throughout the protosolar cloud if a significant fraction (probably more than 10%) of the solar oxygen entered the solar system as low-energy cosmic rays in the million years before the formation of the carbonaceous chondrite meteorites. This does not seem plausible. The energetics of an alternative picture of ^{26}Al production, proposed by Clayton & Jin (1995b), also present serious problems. We have only addressed the role of oxygen cosmic rays in the production of ^{26}Al, but Clayton & Jin (1995a) believe that these are the best candidates. These shortcomings in the cosmic-ray production scenario of the meteoritic ^{26}Al suggest that the solution to the problem of the production of the extinct nuclides lies in a picture like that of Cameron et al. (1995), wherein radioactive products of stellar evolution are accelerated to high energies and stopped in the protosolar cloud.

This work was supported by the US Department of Energy under grants DE-FG02-91ER-40609 and DE-FG05-88ER-40442.

REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Bateman, N. P. T. 1996, Ph.D. thesis, Yale Univ.
Bateman, N. P. T., et al. 1996, in preparation
Bertout, C. 1989, ARA&A, 27, 351
Bloemen, H., et al. 1994, A&A, 281, L5
Cameron, A. G. W. 1988, ARA&A, 26, 441
Cameron, A. G. W., Höflich, P., Myers, P. C., & Clayton, D. D. 1995, ApJ, 447, L53
Cameron, A. G. W., & Truran, J. W. 1977, Icarus, 30, 447
Chan, Y. D., Bohn, H., Vandenbosch, R., Bernhardt, K. G., Cramer, J. G., Sielemann, R., & Green, L. 1978, Nucl. Phys. A, 303, 500
Clayton, D. D., & Jin, L. 1995a, ApJ, 451, 681
———. 1995b, ApJ, 451, L87
Cummings, A. C., & Stone, E. C. 1996, in The Heliosphere in the Local Interstellar Medium, ed. R. von Steiger, R. Lallemont, & M. A. Lee (Dordrecht: Kluwer)
Liffman, K. 1992, ApJ, 398, L111
Mewaldt, R. A., Spalding, J. D., & Stone, E. C. 1984, ApJ, 283, 450
Pülhofer, F. 1977, Nucl. Phys., A280, 267
Ramaty, R., Kozlovsky, B., & Lingenfelter, R. E. 1995, ApJ, 438, L21
———. 1996, ApJ, 456, 525
Wasserburg, G. J. 1985, in Protostars and Planets II, ed. D. C. Black & M. S. Matthews (Tucson: Univ. Arizona Press), 703
Ziegler, J. F., Biersack, J., & Littmard, U. 1985, Code TRIM85, The Transport of Ions in Solids (New York: Pergamon)