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CROSS SECTIONS FOR THE PRODUCTION OF Li and Be ISOTOPES IN CARBON TARGETS IRRADIATED BY 300 GeV PROTONS

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ABSTRACT

Cross sections for the production of Li and Be isotopes in carbon targets irradiated by 300 GeV protons have been measured by mass spectrometry. The results are compared with lower energy measurements and discussed in terms of the variation of the cosmic ray L/M ratio in this energy region.

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One of the most interesting discoveries in cosmic ray physics in recent years is the observation that the chemical composition changes as one goes to high (E > 10 GeV) energies (1). These changes can be classified into two categories. First, heavy primary nuclei (such as Fe) are increasing in abundance relative to lighter primaries (such as C, O). Secondly, nuclei which are formed by nuclear spallation of the primary species during their propagation in the interstellar medium, appear to be decreasing in abundance relative to their progenitor species. This latter observation has widely been interpreted as showing that the higher energy cosmic ray particles interact with a smaller amount of matter between their acceleration and their arrival in the solar system. Such a conclusion has very important consequences for cosmic ray propagation models. It is clear that in order to make a quantitative evaluation of this effect it is necessary to unfold any possible variations of the relevant nuclear cross sections at the energies involved. Unfortunately there are at the moment still very few cross section measurements reported at > 30 GeV, and none for reactions directly relevant to the cosmic ray problem.

In order to study this problem we have undertaken to measure the cross sections of Li and Be isotopes produced in a carbon target irradiated by 300 GeV protons*. These reactions have been chosen because Li, Be and B are the most outstanding group of secondary spallation products in cosmic rays, their abundance at the source generally believed to be negligible, with carbon and oxygen being their most important progenitors. In addition, the isotope ^{10}Be has a particular importance because its half-life ($1.5 \pm 0.3 \times 10^6 \gamma$ years, where γ = the Lorentz factor) makes it an excellent candidate as a probe of cosmic ray " age ". It is therefore important to know whether the relative abundance of ^{10}Be compared to ^{7}Be and ^{9}Be changes with energy.

In addition to their relevance to the cosmic ray propagation problem, the reactions studied here have an interest from the point of view of the nuclear physics involved. The presently available cross section measurements at 300 GeV have been carried out on medium (2, 3) or heavy (4) mass target nuclei. Such reactions are generally described as proceeding through a " two-step " process consisting of a fast " cascade ", followed by a slower " evaporation " step. For a target nuclei as light as carbon such a model is not expected to be applicable, since the small number of nucleons make the idea of statistical equilibrium of excitation energy rather unrealistic. Some attempt has been made to describe such reactions by a model in which the evaporation step is replaced by a " break-up " mechanism, in which the distribution of final products is controlled by the phase space available (5).

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* This being the equivalent reaction to a 300 GeV/nucleon ^{12}C interacting with an interstellar H atom.

It is therefore interesting to see whether reactions of this type have the same apparent energy independance above 30 GeV as suggested by the heavier target results (2-4).

The mass spectrometric techniques used in this work are similar to those described earlier for Li and Be production in carbon targets (6, 7). The targets consisted of eight layers of graphite (48 x 40 x 1 mm), wrapped in Al foil. Before irradiation the graphite was heated to $\sim$ 2500° C for 30 seconds under an argon atmosphere to ensure that the Li and Be content were less than 10^{-13} g/g. Irradiations were carried out parasitically in the neutrino beam line of the FNAL accelerator several inches in front of the main production target. Two irradiations were performed, lasting 45 and 60 days, and receiving total integrated fluxes of $\sim 3 \times 10^{17}$ and $\sim 1 \times 10^{18}$ protons respectively. The proton energy was always 300 GeV except for a period representing $\sim$ 5 % of the flux of the second irradiation, in which it was 400 GeV. On the basis of what follows, we do not believe this significantly effects our results.

Several weeks after irradiation the targets were returned to our laboratory for analysis. Using ^{7}Be activity it was determined that most (> 90 %) of the beam had been confined to a spot $\sim$ 1 mm^2 in area. This observation indicates that reactions induced by secondary particles are not significant. For each analysis, a small piece of carbon (containing $\sim 10^{-10}$ g of ^{7}Be) was selected from this active region of the target. After combustion and heating under vacuum to remove Li, the relative abundance of the isotopes ^{7}Be, ^{9}Be and ^{10}Be can be measured directly (6). By carrying out the combustion and analysis of the ^{7}Li/^{6}Li ratio in different layers of the target over

a period of many months, the ^{6}Li and ^{7}Li abundances can also be related to ^{7}Be (6, 7).

Because the irradiation times were comparable to the ^{7}Be half-life (53.2 days), it is necessary to have some method of correcting for the decay of this isotope during the bombardment. We have done this in two ways. First, we have used a log of the daily integrated intensities in our beam line, as recorded by the FNAL staff. Secondly, using a Ge(Li) diode, we have analyzed an Al foil included in our target package for ^{7}Be and ^{22}Na (half-life = 2.6 years) activities. Knowing the production ratio for these two isotopes in Al (8), we can calculate the " effective " decay time for ^{7}Be. The " effective midtime " determined by these two methods agreed to within 8 and 2 days for the two irradiations. By taking the average of the two methods in each case, we thus introduce an uncertainty of $\pm$ 5 % and $\pm$ 1 % in the ^{7}Be decay for the two irradiations.

In Table I we give the results of our measured ratios, compared to similar measurements at 25 GeV (9). We see that, within the experimental uncertainties, the results are identical. The energy independence of such ratios above 30 GeV is consistant with similar data for heavier targets (2-4).

Since our mass spectrometric technique measures only isotopic ratios, we must rely on the radioactive nuclide ^{7}Be in order to deduce absolute cross sections. Unfortunately there is at present no experimental value for this cross section at 300 GeV. In fact, we wish here to stress a point which we feel has not been sufficiently emphasized in previous discussions in this

area, and that is that there exist, at present, no absolute nuclear cross section measurements at > 30 GeV. While both theoretical ideas, and results at lower energies suggest that no energy dependence is expected at these energies, an experimental confirmation of this is obviously very important. We have thus been forced to adopt the same assumption made by all other workers in this field, namely that a " reference " cross section (in our case ^{7}Be in carbon) is the same at 300 GeV as at 30 GeV (10). Using this assumption we can calculate cross sections for the other isotopes, and these are given in Table I along with their estimated uncertainties

In summary, it appears that the mechanism for the production of Li and Be isotopes from carbon at 300 GeV is very similar to that at 30 GeV. Thus, subject to the uncertainty mentioned above regarding lack of an absolute cross section monitor, it seems unlikely that variations in nuclear production cross sections can explain the observed variation in the cosmic ray Li Be B/CNO ratio at energies of > 10 GeV. We emphasize that this conclusion cannot necessarily be generalized to lower energies (for ex. 1-10 GeV) and heavier targets (Fe region) where such cross section variations do exist, and must be taken into account in analyzing the propagation process.

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10 - Other workers have generally employed as a reference the reaction $^{27}Al\ (p,x)^{24}Na$. In our case this was not practical because of the length of the irradiation. In addition, this reaction is very susceptible to secondary neutrons, which were expected to be numerous at the location of our target.

TABLE I

Cross sections for production of Li and Be isotopes in a carbon target bombarded by 25 and 300 GeV protons

Proton Energy (GeV)	$\frac{\sigma\ ^{10}Be}{\sigma\ ^{7}Be}$	$\frac{\sigma\ ^{10}Be}{\sigma\ ^{9}Be}$	$\frac{\sigma\ ^{7}Be}{\sigma\ ^{6}Li}$	$\frac{\sigma\ ^{7}Li}{\sigma\ ^{6}Li}$	^{7}Be (mb)	^{9}Be (mb)	^{10}Be (mb)	^{6}Li (mb)	^{7}Li (mb)
300	0.41 ±.07	0.61 ±.05	0.65 ± .10	0.90 ±.08	9.1 (b)	6.1 ±0.9	3.7 ± 0.6	14.1 ± 1.8	12.7 ± 2.0
25 (a)	0.40 ±.07	0.59 ±.04	0.60 ±.10	0.94 ±.06	9.1±0.4	6.1 ±0.9	3.6 ± 0.6	15.5 ± 3	14.5 ± 3

(a) From Refs. (9)

(b) Adopted reference cross section