this reaction occur at lower mass values than those measured. This again can be attributed to an insufficient number of absorptions near the nuclear surface.

Indications from the model are that π^0's are produced about 1% of the time from π^--absorption events. There have been no experiments performed to detect this reaction to date.

The theoretical predictions of the charge-exchange cross section for 180-MeV π^+ on carbon and oxygen are in good agreement with experiment although there appear to be data for only two reactions.

The model fails to accurately predict the double-charge-exchange cross sections for relatively low-energy pions. These reaction cross sections are quite small, and hence the predictions are known to be inaccurate, but the model may also be beyond the limits of its validity at these energies.

There are measurements that indicate that there is a breakdown of charge symmetry for the double-charge-exchange reactions. These results are in disagreement with those from the model because the assumption of charge symmetry has been incorporated therein.

There are a great many interesting experiments that can be performed, to both verify some of the existing discrepancies and test the validity of the model in its ability to predict other quantities. To name a few, measurements of the energy spectra of the nucleons and pions following the inelastic interaction of pions with nuclei, their angular distribution, particle multiplicities, etc., would be very useful.

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Cross Sections of Li, Be, and B Emitted in 125-MeV p and 90-MeV α-Particle Interactions with C and N—Application to Nucleosynthesis

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The production cross sections for Li, Be, and B fragments emitted in medium-energy proton and α-particle reactions with the C, N, and O nuclei of a nuclear emulsion have been measured. The corresponding results for the p-induced and α-induced reactions have been compared. Since helium abundance in the universe is about 10%, these reactions must be taken into account when considering the nucleosynthesis of Li, Be, and B.

I. EXPERIMENTAL TECHNIQUE

TWO experiments were carried out, both involving Ilford K0-K5 emulsion stacks exposed to a flux of 10^5 particles/cm^2. For the proton beam, we used the Orsay synchrotron at an incident energy of 138.7 ± 0.3 MeV. α particles of 98.5 ± 2.5 MeV [1] came from the Karlsruhe synchrotron.

After chemical processing, the emulsions were scanned to find the interaction stars, and all useful geometric parameters were measured. These data were transmitted to an IBM 360-65 computer, where an appropriate program interpreted the track lengths in terms of the energy, and permitted us to look for possible reactions on carbon, nitrogen, and oxygen targets, taking into account energy and momentum conservation.[2]

II. EXPERIMENTAL RESULTS

A. Study of the Reactions with 125-MeV Incident Protons

Altogether, 256 interaction stars were measured. For some of them the number of acceptable solutions was too large, and the reactions could not be identified; those interactions generally had a great number of emitted prongs and corresponded to an oxygen target. For that reason, we could not obtain meaningful cross sections for reactions with oxygen.

Table I. Cross sections (in mb) and isotopic ratios of different elements emitted in p+C and p+N reactions at 126 MeV.

Fragments	p+C reactions	p+N reactions
^{6}He	<0.4	6.4 ± 3.7
^{6}Li	8.3 ± 2.1	12.7 ± 4.9
^{7}Li	6.5 ± 1.9	9.5 ± 4.2
^{7}Li/^{6}Li	0.78 ± 0.24	0.75 ± 0.40
^{7}Be	4.0 ± 1.4	1.6 ± 1.6
(^{7}Li+^{7}Be)/^{6}Li	1.26 ± 0.35	0.86 ± 0.44
(^{7}Li+^{7}Be)/(^{6}Li+^{6}He)	1.26 ± 0.35	0.58 ± 0.30
^{9}Be	2.5 ± 1.0	4.8 ± 2.8
^{10}Be	<0.4	1.6 ± 1.6

The different cross-section values and isotopic ratios for the emitted fragments are given in Table I. For the carbon target, we did not find any ^{6}He or ^{10}Be fragments. According to our statistics, the corresponding cross sections have an upper limit of 0.4 mb.

* ESRO fellow.
[1] C. Kern, University of Strasbourg Report D.E.A., 1967 (unpublished).
[2] C. Jacquot, thesis, University of Strasbourg, 1965 (unpublished).

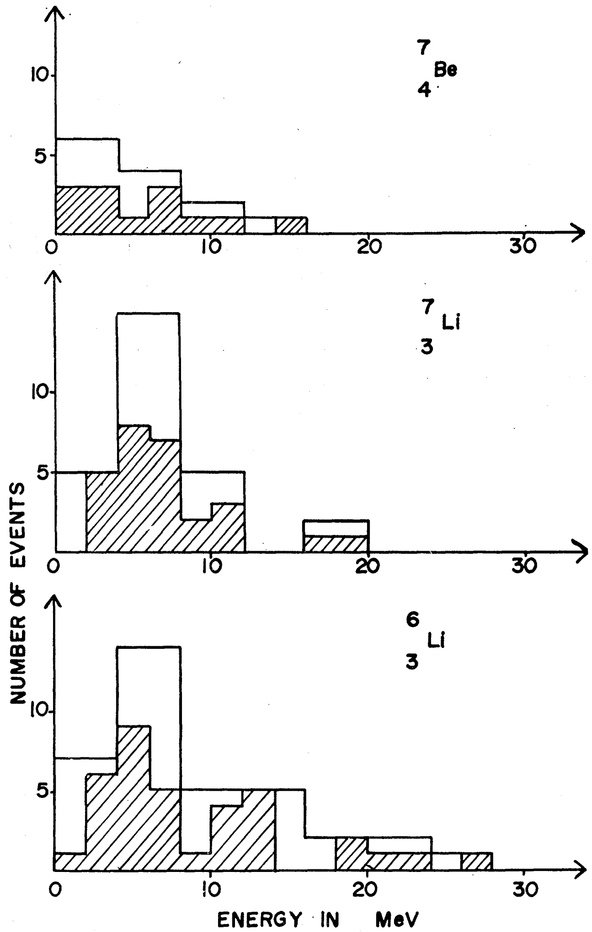

FIG. 1. Energy spectra of fragments emitted in proton interactions.

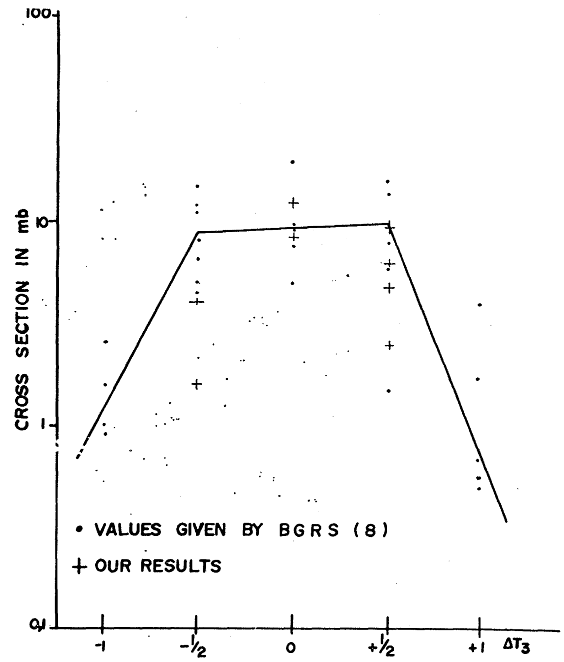

FIG. 2. Cross sections of the fragments emitted in proton-induced reactions plotted according to ΔT_3.

In Table II,[3–9] a comparison is made between our values and those given by other authors. The agreement is satisfactory for the experimental and theoretical production cross sections for ^{6}Li, ^{7}Li, and ^{10}Be. On the other hand, our values for ^{7}Be are smaller than those measured by Cumming,[5] George,[8] and Valentin.[9] In the following, we shall try to study the reasons for this difference.

The first possibility for a loss of ^{7}Be in our statistics might be the detection threshold of the emulsion. For the kind of fragments which are interesting here, the detection threshold goes down to 0.5 MeV. Figure 1

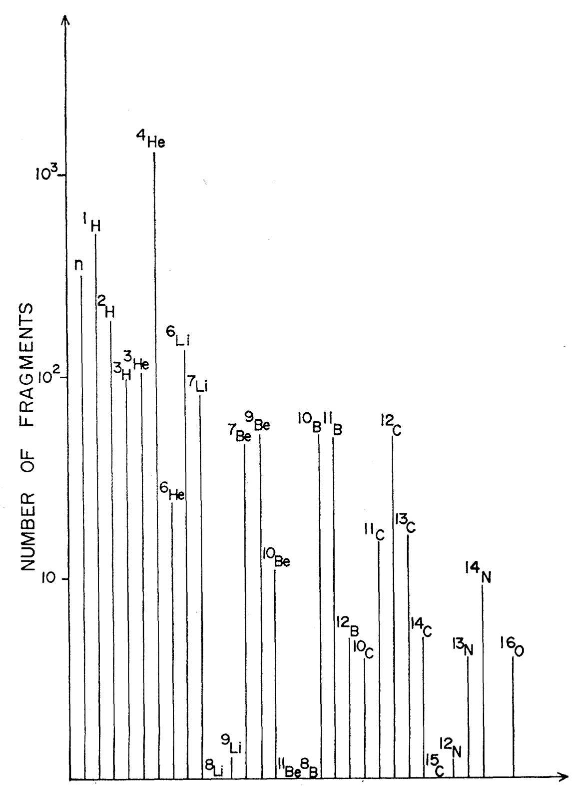

FIG. 3. Summary of the fragments emitted in α+C, N, or O reactions at 90 MeV.

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[3] M. Honda and D. Lal, Nucl. Phys. 51, 363 (1964).

[4] E. Gradsztajn, thesis, University of Paris, Orsay, 1965 (unpublished).

[5] J. B. Cumming, Ann. Rev. Nucl. Sci. 13, 261 (1963).

[6] R. Klapisch and R. Bernas, Laboratory Joliot-Curie, Report No. E 65-01 (unpublished).

[7] R. Bernas, E. Gradsztajn, and H. Reeves, and E. Schatzman, Ann. Phys. (Paris) 44, 426 (1967).

[8] R. George, thesis, University of Paris, Orsay, 1962 (unpublished).

[9] L. Valentin, G. Albouy, J. P. Cohen, and M. Gusakow, Phys. Letters 7, 163 (1963).

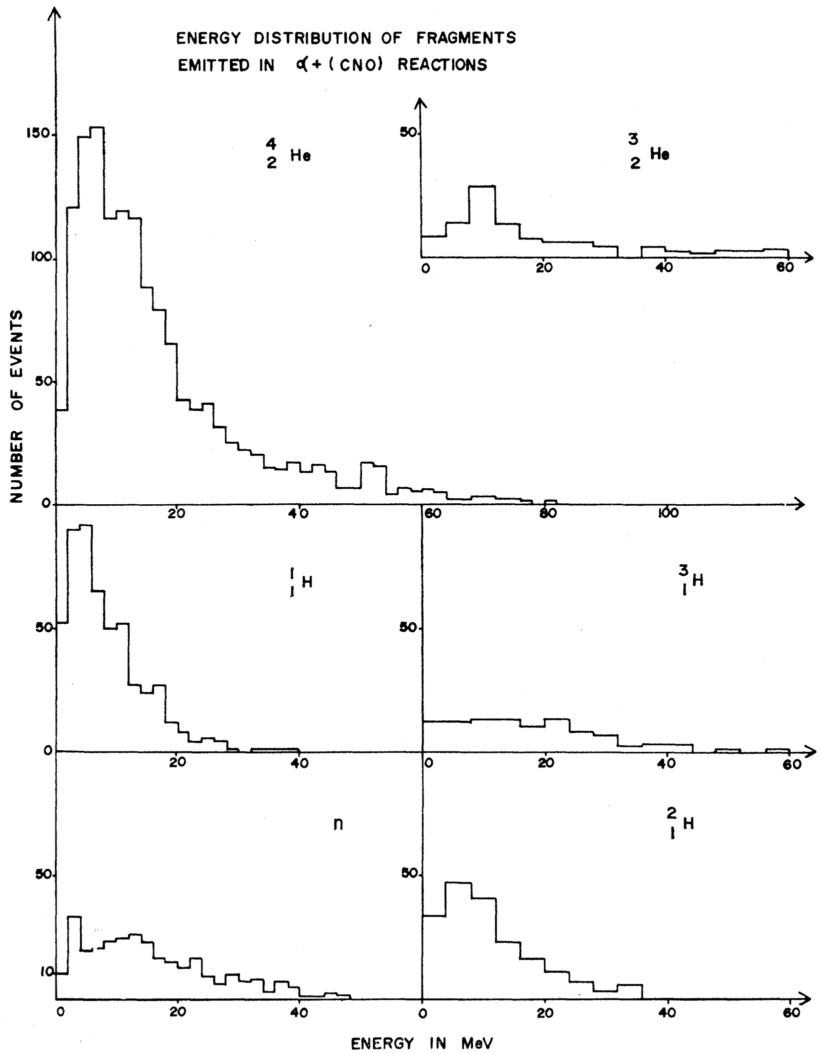

FIG. 4. Energy spectra of the fragments emitted in α+C, N, or O reactions.

shows an increase in the energy spectrum of ^{7}Be towards the lower energies, while for ^{6}Li and ^{7}Li fragments it appears to have a maximum between 4 and 8 MeV. This increase is not always sufficient to explain the observed cross-section differences.

Let us now discuss a second possibility for missing events. The neutrons are not detected by the emulsion, and with the help of kinematic calculations we can identify only the reactions with one emitted neutron. According to Gradsztajn's[4] calculations, the contribution of events with several emitted neutrons is not more than 20%, but it is also possible that this contribution is more important than supposed. Bernas *et al.*[7] have established the following relation between the third component of the isotopic spin of the residual nucleus and its production cross section:

$$\Delta T_3 = T_3(\text{target}) - T_3(\text{fragment}) = \tfrac{1}{2}(N-Z) \quad \text{if} \quad T_3(\text{target}) = 0.$$

For $\Delta T_3 = 0$ and $\Delta T_3 = \pm\frac{1}{2}$, the cross-section values are about 10 mb; they decrease to 1 mb for $\Delta T_3 = \pm 1$ and to 0.1 mb for $\Delta T_3 = \pm\frac{3}{2}$.

In Fig. 2, we have compared the cross-section values quoted by Bernas *et al.*, with our results. We notice that our values are within the limits given by other workers for $\Delta T_3 = 0$ and $\Delta T_3 = +\frac{1}{2}$, whereas most of them lie outside for $\Delta T_3 = -\frac{1}{2}$. In fact, fragments with $\Delta T_3 = \frac{1}{2}$ are lacking one neutron, and for that reason could be supposed to be produced in reactions emitting more neutrons than reactions giving fragments richer in neutrons, such as ^{7}Li. Since our method does not identify reactions with several neutrons, we necessarily find a lack of events in our statistics.

In conclusion, we think that if we have found lower production cross sections in the case of ^{7}Be than the radiochemists have, the difference may be due to reactions in which several neutrons are emitted. In that case, the proportion of such reactions might be bigger than theoretically predicted by Gradsztajn.[4]

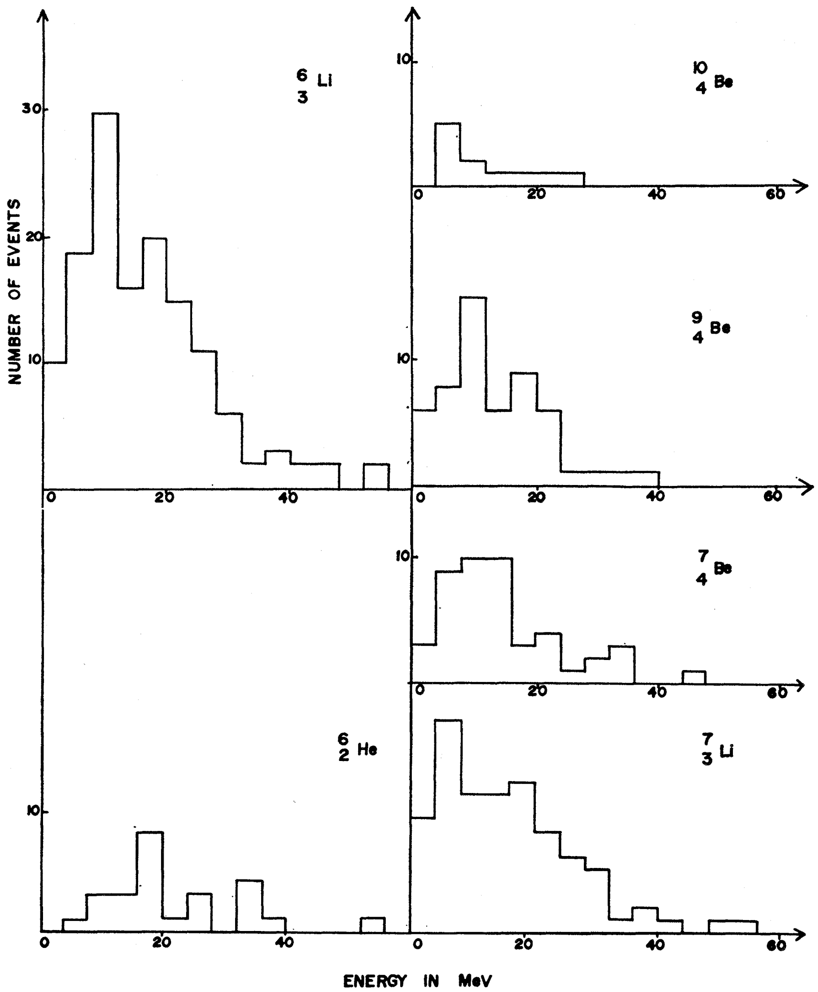

FIG. 5. Energy spectra of the fragments emitted in α+C, N, or O reactions.

B. Study of Reactions with 90-MeV Incident α Particles

There were 1570 measured interaction stars at a medium energy of 90 MeV. All the fragments emitted in those reactions are shown in Fig. 3.

The events with two emitted charged particles have not been measured; for that reason, the following reactions are not included in our results:

$$\alpha + {}^{12}\text{C} \rightarrow n + \alpha + {}^{11}\text{C},$$

$$\alpha + {}^{14}\text{N} \rightarrow n + \alpha + {}^{13}\text{N}.$$

Nevertheless, as these emitted fragments are of interest for astrophysicists, we shall give the lower limit for the corresponding cross sections.[10]

Table III summarizes all the measured cross-section values. For reasons given above, we have not calculated the values for the oxygen target.

For incident α particles there is no possibility of comparison with other results, and in discussing them we shall make the same assumptions as for incident protons.

As we pointed out previously, fragments with low energy are not detected; but that kind of fragment must be very rare, as indicated by Figs. 4–6, which show a decrease of the number of events toward lower energies for both light and heavy emitted fragments. The drift of the center of mass may explain the decrease in energy drift that appears also in the angular distributions of the events. An example is given for ^{6}Li and ^{7}Li fragments in Figs. 7 and 8. Thus, the loss of fragments of very low energy does not affect our values.

To illustrate the second remark, we have plotted in Fig. 9 our cross-section results in terms of ΔT_3. The largest one is at $\Delta T_3 = 0$ rather than at $\Delta T_3 = +\frac{1}{2}$. The values for negative ΔT_3, which correspond to fragments deficient in neutrons, are lower than the corresponding ones for positive ΔT_3.

In conclusion, we should stress that our cross sections for $\Delta T_3 < 0$ suffer from the omission of the reactions

[10] M. Jung, thesis, University of Strasbourg, 1968 (unpublished).

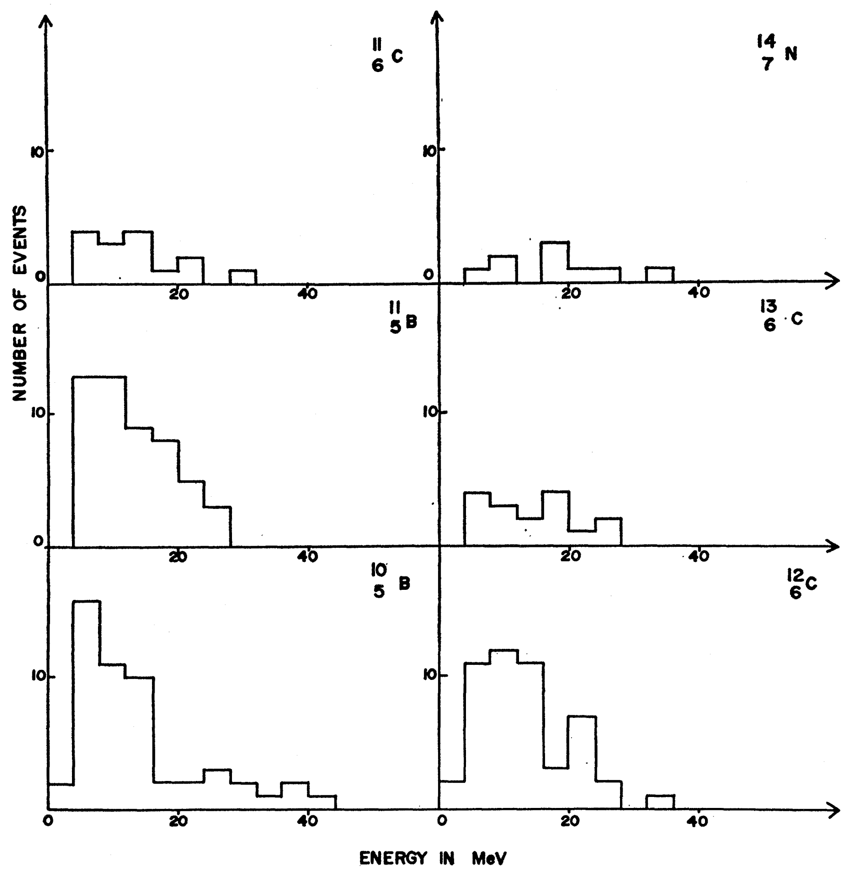

FIG. 6. Energy spectra of the fragments emitted in α+C, N, or O reactions.

TABLE II. Our results compared with those found by other authors for p+C and p+N reactions at 125 MeV.

Target	Fragment	a $P=0$	$P=0.4$	Our results (mb)	Other results (mb)	References
^{12}C	^{6}Li	12.6	9.9	8.3±2.1	9.8±1.8 155 MeV	b
	^{7}Li	7.8	8.6	6.5±1.9	7.8±1.6 155 MeV	b
	^{7}Be	12.1		4.0±1.4	12.1±1.2 155 MeV	c
	^{7}Li/^{6}Li	0.62	0.87	0.78±0.24	0.75±10%	d
					0.8±10%	b
	(^{7}Li+^{7}Be)/^{6}Li	1.5	1.85	1.26±0.35	2.0	e
	^{10}Be	0.9		0.4	1.8±0.6	f
^{14}N	^{6}Li			12.7±4.9	9.3±3 155 MeV	g
	^{7}Li			9.5±4.2		
	^{7}Be			1.6±1.6	4.4±1.1	g
					6.5±1	h
	^{7}Li/^{6}Li			0.75±0.40		
	(^{7}Li+^{7}Be)/^{6}Li			0.86±0.44		
	^{10}Be			1.6±1.6	4±2	f

[a] Values calculated by E. Gradsztajn assuming probabilities of $P=0$ and $P=0.4$ for the collision of the proton with an α cluster.
[b] Reference 4.
[c] Reference 5.
[d] Reference 6.
[e] Reference 7.
[f] Reference 3.
[g] Reference 8.
[h] Reference 9.

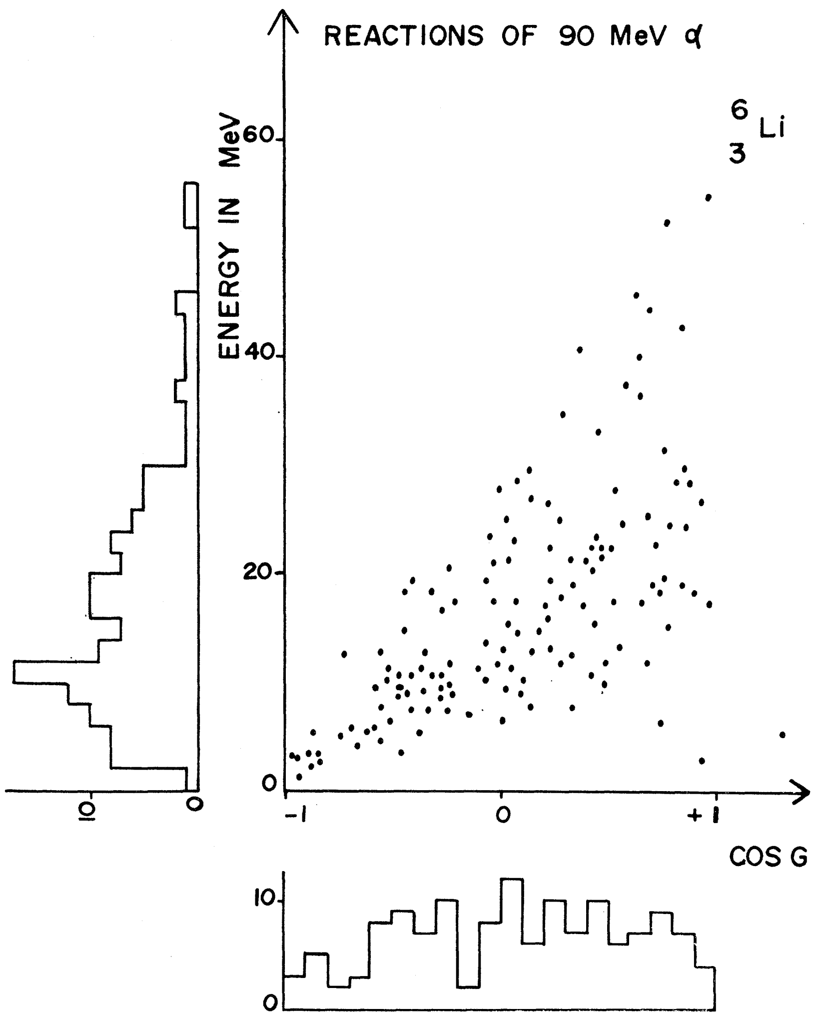

FIG. 7. Energy versus emission angle in the (c.m.) system of the target nuclei and the incident particle.

with several neutrons, and must be taken as lower limits.

III. (Li, Be, B) GROUP

During the evolution of stars, elements such as d, ^{3}He, Li, Be, and B, are generated in the period of hydrogen fusion.

If one considers the universal-abundance curve of the elements (Fig. 10), it appears that the (Li, Be, B) group is separated by a factor 10^7–10^9 from the most abundant elements. To explain this anomaly, Burbridge *et al.*[11] suggest a theory which is unusual in the nucleosynthesis of elements. They consider the large (p, α) cross sections of the elements Li, Be, and B, and deduce they are destroyed at the high temperature which exists inside the stars. They based their theory also on spallation reactions of particles accelerated to a few tenths of a MeV with medium-nuclei targets like C, N, and O. The more appropriate particles to induce such reactions are the more abundant ones: protons and α particles. Fowler *et al.*[11] calculated the production rate of Li, Be, and B on the basis of the above-mentioned theory using known experimental spallation cross-section values. They found quite different values from those observed in stars, and concluded that it was necessary to introduce a second destruction mechanism able to adjust the observed values for stars to agree with those calculated in the spallation-reaction theory.

A. Observed Abundances in the Stars

Table IV[7,12–14] gathers some abundance ratios n_L/n_H of Li, Be, and B to hydrogen for the solar system and

[11] E. M. Burbridge, G. Burbridge, W. Fowler, and F. Hoyle, Rev. Mod. Phys. **29**, 547 (1957); W. Fowler, J. L. Greenstein, and F. Hoyle, Geophys. J. **6**, 148 (1962).

[12] G. M. Herbig, Astrophys. J. **141**, 588 (1965); P. S. Conti and I. J. Danziger, *ibid.* **146**, 383 (1966); W. Fowler, G. Burbridge, and E. M. Burbridge, Astrophys. J. Suppl. **2**, 167 (1955).

[13] G. M. Comstock, C. Y. Fan, and J. A. Simpson, in *Proceedings of the Ninth International Conference on Cosmic Rays, London, 1965* (The Institute of Physics and the Physical Society, London, 1966).

[14] C. Y. Fan, G. Gloeckler, and J. A. Simpson, in Tenth International Cosmic Ray Conference Calgary, Canada, 1967 (to be published).

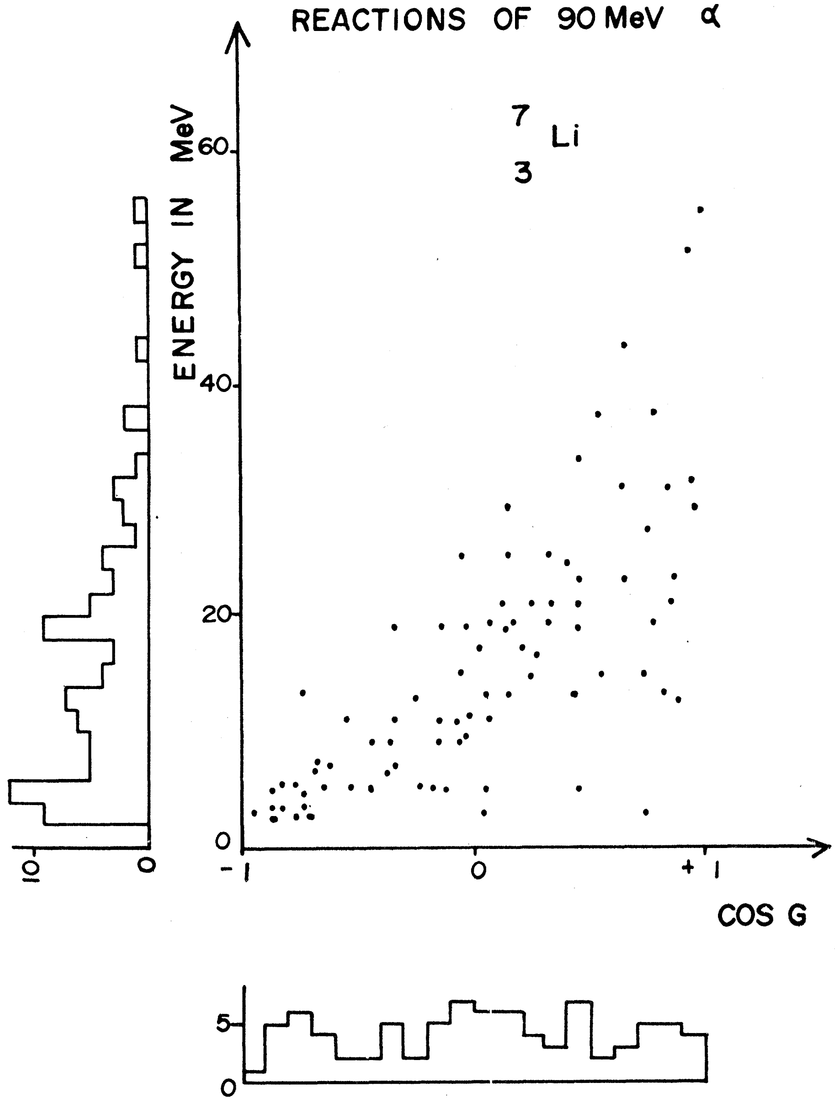

FIG. 8. Energy versus emission angle in the (c.m.) system of the target nuclei and the incident particle.

TABLE III. Cross sections (in mb) and isotopic ratios of different elements emitted in α+C and α+N reactions at 90 MeV.

Fragments	α+C reactions	α+N reactions
^{6}He	5.4±1.9	13.2±6.3
^{6}Li	45.2±6.8	46.3±13.2
^{7}Li	26.5±5.9	39.7±15.8
^{7}Li/^{6}Li	0.59±0.10	0.86±0.22
^{7}Be	16.7±4.2	14.9±7.1
(^{7}Li+^{7}Be)/(^{6}Li+^{6}He)	0.85±0.16	0.92±0.22
^{9}Be	15.2±3.9	28.1±13.5
^{10}Be	<0.5	13.2±6.3
^{10}B	11.8±3.2	38.0±15.1
^{11}B	11.8±3.2	34.7±13.8
^{11}B/^{10}B	1.00±0.28	0.91±0.29
^{12}B	1.0±0.7	<1.6
^{10}C	>0.5	3.3±2.5
^{11}C	>2.5	9.9±5.1
(^{11}B+^{11}C)/(^{10}B+^{10}C)	>1.2	1.08±0.31

some stars. These values are taken from Reeves's lectures.[15]

Inasmuch as in the zone of hydrogen fusion the elements Li, Be, and B are destroyed, the only regions where these elements can be produced are the stellar atmospheres and gaseous nebulae. In such regions, nuclear reactions can only be induced by particles accelerated by nonthermal processes.

The T Tauri stars are in their first stage of gravitational contraction and have not yet reached the main sequence. Bonsack and Greenstein[16] have measured a lower rate for Li in the nebula surrounding the star than in the star itself. From that, they have deduced that there was no lithium in the initial gas cloud, but

[15] H. Reeves, Summer School Report, Tarbes, 1966 (unpublished).

[16] W. K. Bonsack and J. L. Greenstein, Astrophys. J. 131, 83 (1960).

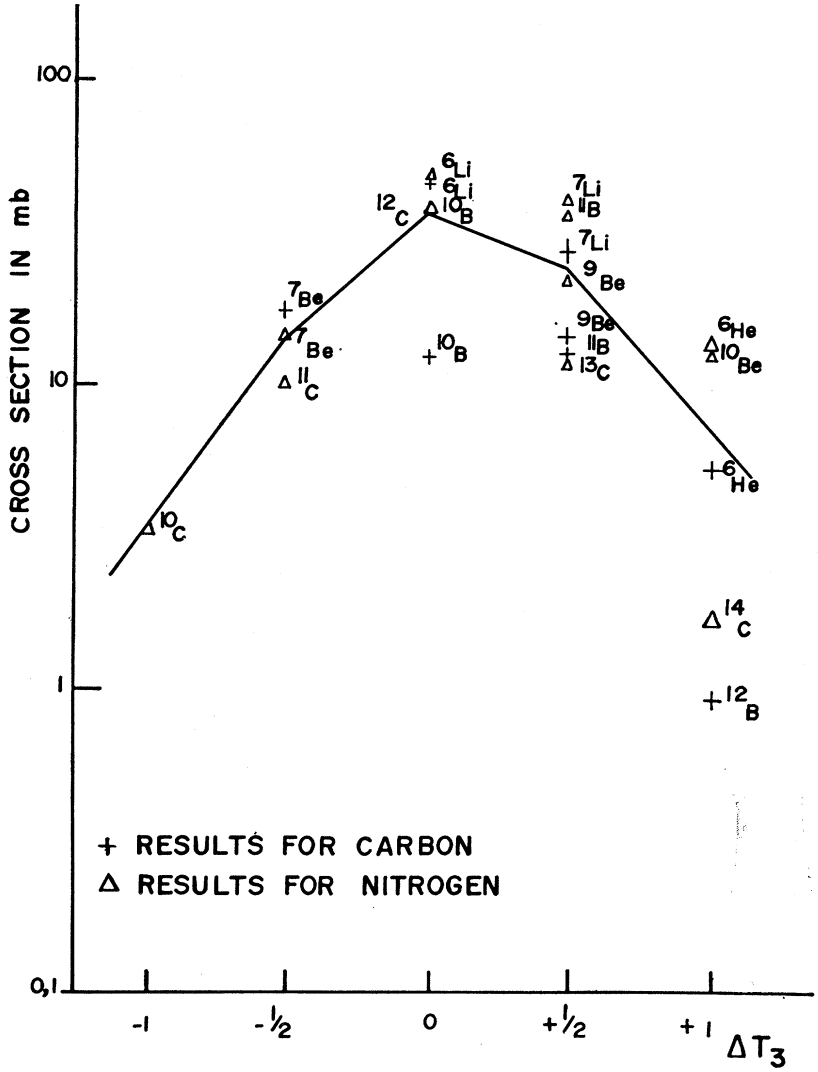

FIG. 9. Cross sections of the emitted fragments in α-particle-induced reactions plotted according to ΔT_3.

that the lithium was produced during the stage of contraction of the interstellar gas.

According to the Hayashi's calculations, all young stars such as T Tauri are convective and give signs of intense electromagnetic activity. Light particles may be accelerated at the surface of such stars by magnetic fields and bombard the nuclei present in the stellar matter (composed mainly of hydrogen but also of heavier nuclei). The synthesis of such elements occurred during the evolution of older stars and had been returned to the interstellar matter by eruptions or stellar explosions; afterwards new generations of stars could be formed from more and more contaminated interstellar gas. Consequently, the younger the star, the more important will be the contamination by heavy elements such as C, N, or O at the surface. As the most abundant medium-weight elements are C, N, O, and Ne, they must also be the most privileged targets for spallation reactions. The light-incident particles which we have to consider are the most abundant, i.e., protons and α particles.

For a set of stars of a given age, there is a great variation in the amount of lithium with their spectral class; the amount of Li decreases with increasing temperature at the surface of the stars.[15] There is also a correlation between the age of the star and its Li abundance; younger stars (T Tauri) are richer in lithium than older ones (the Pleiades and the Sun).

For the solar system, the Li abundance on the earth and meteorites is large by comparison to that measured in the sun. According to an accepted theory, this may be explained if one considers that the lithium was produced during the period of sun contraction when the earth, planets, and meteorites were a part of the same solar nebula, the lithium being destroyed in the sun during a second phase.

B. Isotopic Yields

The n_L/n_H yield ratios considered above include rather large errors. The isotopic ratios are better known, and their comparison with values measured in

TABLE IV. Different values of isotopic ratios observed on the earth, the sun, a few stars, and meteorites. Comparison with values observed in laboratory.

	Be/Li	B/Li	^{7}Li/^{6}Li	^{11}B/^{10}B	B/Be	^{10}B/^{7}Li	^{11}B/^{9}Be	n_{Li}/n_H	n_{Be}/n_H	n_B/n_H
Meteorites	0.02[a]	0.21	12	4	7	0.05	6	10^{-9}	2×10^{-11}	2×10^{-10}
Earth	0.2[f]	0.24	12	4	1.2	0.05	1	10^{-8}	5×10^{-9}	2×10^{-9}
Sun	20	<400	10		≤20			10^{-11}	2×10^{-10}	$<4\times10^{-9}$
Cosmic rays[b]	0.3	1.5			4					
Cosmic rays[c]	0.7	1.3			2					
Stars	0.05 to 10[d]		1.8 to ∞					10^{-9} to 10^{-12}	10^{-8} to 10^{-12}	
^{12}C[e]	0.5[f]	2.5[f]	2	3.2[f]	50[f]	0.9	39[f]			
^{16}O[e]	0.05[f]	1.5[f]	2	2[f]	30[f]	0.7	20[f]			
p+C[g]	0.13		1.3							
p+N[g]	0.14		0.8							
α+C[g]	0.16	>0.3	0.6	>1.2	>1.6	>0.3	>0.9			
α+N[g]	0.25	0.8	0.9	1.1	2.1	0.8	1.6			

[a] Reference 7.
[b] Reference 13.
[c] Reference 14.
[d] Reference 12.
[e] Values given by E. Gradsztajn for incident protons in Ref. 4.
[f] Theoretical values (see Refs. 4–7).
[g] Our results.

the laboratory gives more information. Let us first consider the ^{7}Li/^{6}Li ratio.

In addition to the abundance ratios previously discussed, Table IV summarizes some isotopic ratios for Li, Be, and B observed on the earth, in the sun, and in several stars and meteorites. We included also the laboratory experimental values as well as the theoretical results given by Gradsztajn.[4] Since ^{7}Be and ^{6}He are β emitters, the experimental yields we give correspond to the (^{7}Li+^{7}Be)/(^{6}Li+^{6}He) ratio.

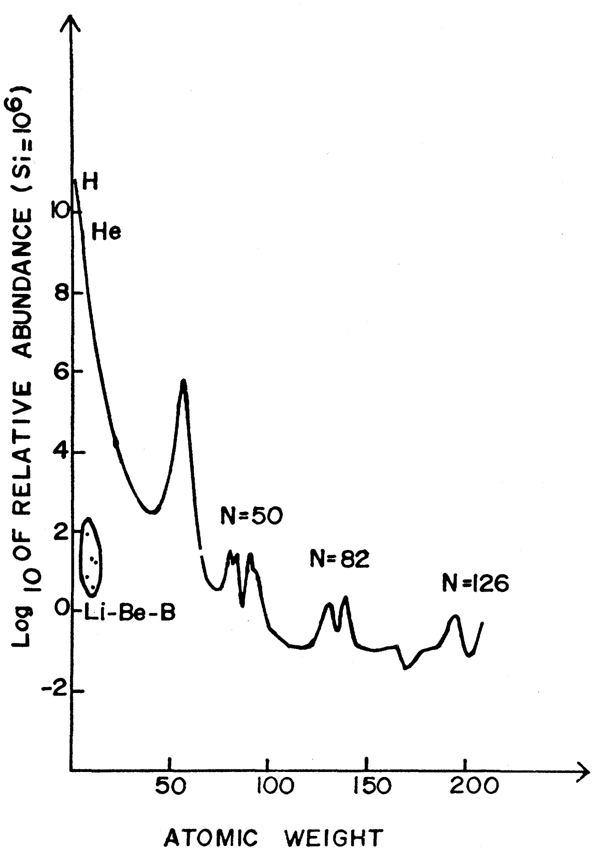

FIG. 10. Cosmic abundance curve of the elements (Suess and Urey).

The largest value we find for the ^{7}Li to ^{6}Li production ratio has an upper limit of 1.6 mb. Gradsztajn gives a value near 2, which is not very different from ours.

The ratios measured for stars are all higher than the production ratio; they rise from 1.8 up to very high values. This and the fact that young stars are richer in lithium than older ones, shows the necessity of introducing into the model a lithium destruction mechanism—more precisely, one with a preference for ^{6}Li destruction over ^{7}Li. For this, the (n,α) reactions and the (p,α) reactions must be considered.

Fowler, Greenstein, and Hoyle[11] proposed an alteration model for isotopic yields due to thermal neutrons. At temperatures around $10^{7\circ}$ K the (n,α) reactions destroy ^{6}Li and ^{10}B, and the consequences are as follows: an increase of the ^{7}Li/^{6}Li and ^{11}B/^{10}B ratios, and only a small variation of the B/Be, B/Li, and Be/Li ratios.

Appreciable destruction of light elements by thermal protons begins at temperatures 2×10^6 °K for Li, 3×10^6 °K for Be, and 4×10^6 °K for B. The half-life ratios for Li and B isotopes are $t(^7\mathrm{Li})/t(^6\mathrm{Li})=75$ and $t(^{11}\mathrm{B})/t(^{10}\mathrm{B})=0.25$.

For temperatures between 2 and 4×10^6 °K, the ^{7}Li/^{6}Li ratio increases but the ^{11}B/^{10}B ratio remains constant. The latter ratio decreases at higher temperatures. Thus, the three ratios Be/Li, B/Li, and B/Be might increase. Comparing these ratios with laboratory values gives information about the destruction mechanism modifying the production rate.

The Be/Li production ratios we find are larger than those given by Gradsztajn,[4] but on the whole are lower than the observed ratios on the sun and in the cosmic rays. This fact underlines the argument for preferential destruction of lithium as compared to beryllium. Thus the high Be/Li ratio measured in the sun (compared to the earth value) can be explained if one supposes that the sun, since its formation, has destroyed its lithium, whereas the destruction in the earth was stopped at the time of the earth's solidification. In conclusion, one may suppose that lithium has been destroyed continually (in the sun) since its formation, while for beryllium this destruction, if there is any, is very low.

Gradsztajn[4] explains the low value for B/Li ratios in the earth and meteorites on the hypothesis that boron, being more volatile than other elements, escaped at the time of the earth's solidification.

The $^{11}B/^{10}B$ ratios we find for incident α particles are somewhat lower than Gradsztajn's theoretical ones. Taking into account the lack of precision of the ratios measured in the solar system, we can conclude that the relative abundance of boron has not been altered but remains near its production ratio. This assertion excludes (n,α) reactions as a possible destruction mechanism for the elements Li, Be, and B.

IV. CONCLUSION

The abundance of the elements Li, Be, and B measured in the solar system may be explained by the following hypothesis: The Li, Be, and B produced by spallation reactions at the surface of the stars are drawn back to the base of the convective zone, where Li is destroyed by (p,α) reactions. The temperature in this region is supposed to be about 2×10^6 °K, a temperature which is sufficient to destroy lithium but not beryllium and boron. The products of the reactions are then drawn to the surface of the star, and the observable result is a strong increase of the $^7Li/^6Li$ ratio. Such a convective zone exists in all stars. For the sun, its depth is equal to about $\frac{1}{10}$ of the solar radius.

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Excitation of Collective States in Light Nuclei by Inelastic Scattering of 20.3-MeV Polarized Protons*

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Asymmetries and relative differential cross sections have been measured for elastic and inelastic scattering of 20.3-MeV polarized protons from light elements. The targets included C^{12}, O^{16}, Mg^{24}, Mg^{25}, Mg^{26}, Al^{27}, Si^{28}, and Ca^{40}. Significant differences have been observed in both the asymmetries and cross sections for transitions with a given angular momentum transfer. The shapes of the asymmetries for Al^{27} and Si^{28} show some disagreement with the weak-coupling model prediction. Coupled-channels and distorted-wave Born-approximation calculations (DWBA) have been performed for the first 2^+ and 4^+ states in Mg^{24} and Si^{28}, with several types of deformed spin-orbit potential. In principle, it should be possible with a coupled-channel analysis to distinguish between vibrational and rotational models, and between positive and negative deformations. In fact, there are differences between the predictions of these models. However, none of them gives a good account of the 2^+ and 4^+ asymmetries in Mg^{24} and Si^{28}, even when the full Thomas form of the spin-orbit potential is used. Microscopic- and macroscopic-model DWBA predictions of the 3_1^- and 5_1^- asymmetries in Ca^{40} yield fair agreement with the experimental data.

I. INTRODUCTION

MEASUREMENTS of the asymmetry in the inelastic scattering of polarized protons from medium-weight nuclei have now been reported at 18.6,[1] 20.3,[2] 30,[3] 40,[4] and 49 MeV.[5] Results for some light nuclei at several energies have also been pub-

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