THE FORMATION OF Li, Be, B ISOTOPES BY THE SPALLATION OF CNO

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In 1955 Fowler *et al.* (1955) suggested that the elements Li, Be and B could be produced at the surface of some stars by the spallation of CNO induced by electromagnetically accelerated particles.

Since that time many observational data were gathered, not only on the lithium elemental abundance (Hunger, 1957; Bonsack and Greenstein, 1960), but also concerning the isotopic ratio ^{7}Li/^{6}Li (Herbig, 1964; Wallerstein, 1965). Then, the abundance of beryllium in many stars was measured (Bonsack, 1960; Conti and Danziger, 1966; Merchant, 1966) and the problem was, and still is to explain both ^{7}Li/^{6}Li and Li/Be ratios. In addition to spallation, different possibilities may be invoked, such as the inheritance from galactic gas enriched with matter remaining from a previous generation of stars, or from the big bang; but which can be checked most easily at the present time is the spallation assumption. Indeed, simultaneously with the development of the observations on stars, a program for measuring and calculating the production rates of the light elements has been in progress at Orsay. In 1960 the first experimental result concerning the production of ^{6}Li in ^{16}O by 156 MeV protons was obtained. But it was only in 1965 that the number of experimental and theoretical data on spallation was sufficient to make a valid comparison with abundances observed on the stars as well as in the solar system or in cosmic rays.

Below I shall present recent measurements on the production of beryllium and boron.

Table 1 shows the experimental results obtained by Bernas *et al.* (1965) for lithium and by Yiou *et al.* (1968) for beryllium and boron at various energies.

The cross-sections of Table 1 have been measured by mass spectrometry. This technique, combined with the isotope dilution method, allows one to determine very small amounts (down to 10^{-14} g or 10^{-12} g) of the Li, Be, B isotopes, although difficulties arising from the need of a high sensitivity and from contamination have to be overcome. The details of the procedure are described in the original papers.

While experiments were slowly progressing, we have performed theoretical calculations which could describe the spallation reactions on light targets and thus obtained the needed cross-sections. These calculations are based on the idea that when the incident proton is striking the nucleus, the reaction takes place in two steps (Serber, 1947). The first step is the so-called intranuclear cascade, where a few nucleons are knocked out of the target nucleus. The residual nucleus is left excited and will disintegrate. This disintegration is the second step of the reaction. Details concerning the calcula-

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Table 1

Experimental cross-section in millibarns

Target	^{12}C				^{16}O		
Ep (MeV)	44	50	156	550	156	600	19 GeV
^{6}Li [a]	10·6	9·2	9·8	7·4	10 ± 2	13·6 ± 3·5	
^{7}Li [a]	10·8	7·2	7·8	5·6	8·5 ± 2·5	12·4 ± 2·5	
^{7}Be [b]	22	25·5	12·1	11	5·4 ± 1	6·5 ± 2	6·5 ± 2
^{9}Be			0·8 [c]		1·7 ± 0·5	2·4 ± 1·2	2·2 ± 1·1
^{10}Be			0·3 [c]		0·4 ± 0·2	0·6 ± 0·4	0·6 ± 0·5
^{10}B [d]					11 ± 3	12 ± 5	
^{11}B [d]					25 ± 8	25 ± 12	
$^{11}B/^{10}B$ [d]					2·3 ± 0·4	2·1 ± 0·6	

[a] Accuracy: 20% for Li in ^{12}C.
[b] ^{7}Be in ^{12}C is reproduced from Cumming (1963).
[c] Preliminary results.
[d] ^{10}B and ^{11}B include contributions from ^{10}C and ^{11}C respectively.

tions of the cascade may be found in Rudstam (1956) or Metropolis *et al.* (1958).

The disintegration of the excited residual nucleus can be calculated by the 'evaporation model' as in Rudstam (1956) or Dostrovsky *et al.* (1958), or by the 'break-up model'. For light targets such as carbon and oxygen only the break-up model has been used. Table 2 shows results obtained by Epherre and Gradsztajn (1967).

Now, if we compare the calculated results with the available experimental data we see that the agreement is fairly good and that the calculated data may be used with some confidence when experimental cross-sections are missing.

From both experimental and theoretical values, we see that the production cross-section of ^{10}Be is much smaller that for ^{9}Be. This is very unfortunate, because, due

Table 2

Calculated cross-sections in millibarns

Target	^{12}C				^{16}O			
Ep (MeV)	70	100	156	200	70	100	156	200
^{6}Li	18	15·8	13·7	13·4	16·7	16	13·7	13
^{7}Li	10·3	10·1	9·9	11·1	5·5	7·5	8·4	8·8
^{7}Be	17·6	14·6	12·2	11·8	15·6	15	13·2	12·5
^{9}Be	2·7	2·9	2·9	3.1	3·5	4	3·6	3·9
^{10}Be	0·5	0·7	0·8	0·9	0·33	0·46	0·66	0·85
^{10}B [a]	28·6	24·4	24	23	22·8	22	16·4	17·2
^{11}B [a]	87·5	71	55	49	31·2	29·7	24·1	23·5

[a] ^{11}B and ^{10}B include contributions from ^{10}C and ^{11}C respectively; direct ^{11}B is calculated; ^{11}C is experimental (Cumming, 1963).

to its half life of a few million years, this isotope could have been used e.g. to determine the time of diffusion from the surface where spallation is supposed to take place, into the convective zone.

^{7}Be, on the contrary, has a short half life (54 days) but a higher cross-section than ^{9}Be. Using this fact Reeves (1967) has suggested that it may be possible to observe ^{7}Be if it is retained at the surface of the star for a certain time.

Now, since there are as yet no observations concerning boron, the interesting data are the ratios ^{7}Li/^{6}Li and Li/^{9}Be.

Combining the experimental and calculated values we obtain for the formation ratios at energies >50 MeV:

$$\begin{aligned} {}^7\mathrm{Li}/{}^6\mathrm{Li} &\approx 2 \\ \mathrm{Li}/{}^9\mathrm{Be} &\approx 15 \text{ for oxygen} \\ &\simeq 20\text{–}30 \text{ for carbon.} \end{aligned}$$

From 50 MeV to much higher energies (GeV), the cross-sections of interest change only very slightly, if at all, but below this range, the situation may be quite different. Indeed, the thresholds of the reactions producing ^{7}Li, ^{6}Li and ^{9}Be are different (25, 32 and 34 MeV, respectively in ^{12}C), so that if the energy spectrum of the protons at the surface of a star is concentrated in the low-energy region. This may lead to observations where ^{7}Li/^{6}Li can be higher than 2 and Li/Be higher than 30.

However, as suggested by many observational data, we may assume that Li and Be are produced at the surface of stars at high energies, with the well-defined values of these ratios, as given earlier, and then try to explain the observational data by looking for processes destroying the lithium.

Nevertheless one should remember that the possibility exists to produce any value of ^{7}Li/^{6}Li higher than 2 and Li/Be higher than 20 or 30. This doubt will probably be eliminated when observations on boron isotopes become available: indeed, as ^{11}B and ^{10}B are produced by reactions with thresholds different from Li and Be, this will give additional parameters needed to determine the proton spectrum of the observed star.

References

Bernas, R., Epherre, M., Gradsztajn, E., Klapisch, R., Yiou, F. (1965) *Phys. Rev. Letters*, **15**, 147.
Bonsack, W.K., Greenstein, J.L. (1960) *Astrophys. J.*, **131**, 83.
Bonsack, W.K. (1960) *Astrophys. J.*, **133**, 551.
Conti, P.S., Danziger, I.I. (1966) *Astrophys. J.*, **146**, 383.
Cumming, J.B. (1963) *Am. Rev. Nucl. Sci.*, **13**, 261.
Dostrovsky, I., Fraenkel, Z., Rabinowitz, P. (1958) *Phys. Rev.*, **118**, 791.
Epherre, M., Gradsztajn, E. (1967) *J. Phys.*, **28**, 745.
Fowler, W.A., Burbidge, G.R., Burbidge, E.M. (1955) *Astrophys. J.*, Suppl., **2**, 167.
Herbig, G. (1964) *Astrophys. J.*, **140**, 702.
Hunger, K. (1957) *Astron. J.*, **62**, 294.
Merchant, A. (1966) *Astrophys. J.*, **143**, 336.

Metropolis, N., Bivins, R., Storm, M., Miller, J. M., Friedlander, G., Turkevitch, A. (1958) *Phys. Rev.*, **110**, 185.
Reeves, H. (1967) Unesco Conf. on the Origin and Abundance of the Elements, Paris, May 1967.
Rudstam, G. (1956) Thesis, Uppsala.
Serber, R. (1947) *Phys. Rev.*, **72**, 1114.
Wallerstein, G. (1965) *Astrophys. J.*, **141**, 311.
Yiou, F., Baril, M., Dufaure de Citres, J., Fontes, P., Gradsztajn, E., Bernas, R. (1968) *Phys. Rev.*, **166**, 968.

DISCUSSION

Fowler: Those of us engaged in experimental nuclear research are filled with admiration for the beautiful work underway by the workers at Orsay. Their ability to detect submicroscopic amounts of non-radioactive materials is just fantastic and they deserve every accolade we can give them. *(Applause.)*

Conti: The highest Li/Be ratio observed in stars is of the order of 20 by number. This is in good agreement with the predicted spallation results. All values smaller than this could be interpreted as selective Li depletion in individual stars.