

CROSS SECTIONS FOR He, Li AND Be ISOTOPES PRODUCED IN THE $\alpha + \alpha$ REACTION AT 198.4 MeV

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Cross sections for the $\alpha(\alpha, pn)^6\text{Li}$, $\alpha(\alpha, p)^7\text{Li}$ and $\alpha(\alpha, n)^7\text{Be}$ reactions, as well as $\alpha + \alpha$ elastic scattering, have been measured at 198.4 MeV. These measurements are relevant to the understanding of light-element nucleosynthesis in galactic cosmic ray interactions with the interstellar medium.¹ The experiments were performed at the Indiana University Cyclotron Facility with a beam of 198.4-MeV ^4He ions. A gas target cell similar in design to that used in Ref. 2 was operated at a pressure of 267 torr. A four-element detector telescope was employed for mass, charge and energy identification of ^4He , ^6He , ^6Li , ^7Li and ^7Be ions. This telescope consisted of three surface-barrier silicon detectors of thicknesses 50 μm , 1 mm and 2 mm, followed by a 5-mm Si(Li) detector, tilted at 60 deg in order to stop elastically scattered ^4He ions.

The center-of-mass differential cross section for the two-body final state reactions are shown in Fig. 1, along with curves representing experimental data obtained at lower energies.² The measured total cross sections for all processes leading to the formation of A = 6 and 7 isobars are listed in Table I. These values are combined with lower-energy data, summarized in Ref. 3, to yield the excitation functions for ^6Li , ^7Li and ^7Be production in the $\alpha + \alpha$ reaction shown in Fig. 2. Of particular significance to the objectives of this research, it is observed that the $\alpha(\alpha, pn)^6\text{Li}$ reaction continues to dominate ^6Li production at high energies, but that this cross section decreases with increasing energy, as indicated by the data of Ref. 2. This result suggests that, unlike reactions on more complex light nuclei, the three-body final state

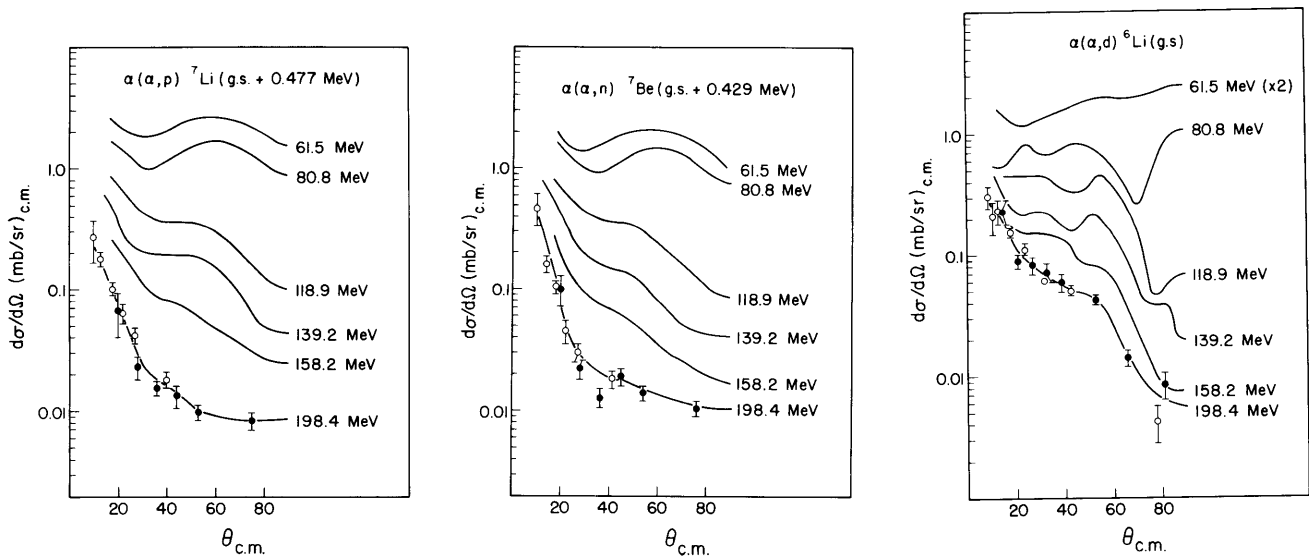


Figure 1. Center-of-mass angular distribution of ^7Li and ^7Be (ground state plus first excited state) and $\alpha(\alpha, d)^6\text{Li}$ (ground state) from the $\alpha + \alpha$ reaction at 198.4 MeV. Solid points refer to forward (c.m.) hemisphere and open points to backward hemisphere data. Solid lines summarize lower-energy data from Ref. 2 except lower line, which is to guide the eye through the present data.

Table I

Total cross sections for A = 6 and 7 isobars from the $\alpha + \alpha$ reaction at 198.4 MeV.

| $(\alpha, 2p)^6\text{He}$ | $(\alpha, d)^6\text{Li}$ | $(\alpha, pn)^6\text{Li}$ | total ^6Li | $(\alpha, p)^7\text{Li}^a$ | $(\alpha, n)^7\text{Be}^a$ |
|---------------------------|--------------------------|---------------------------|---------------------|----------------------------|----------------------------|
| $\sigma(\text{mb}) < 0.2$ | 0.6 ± 0.2 | 2.8 ± 0.7 | 3.4 ± 0.8 | 0.25 ± 0.06 | 0.35 ± 0.08 |

a - Ground state + first excited state

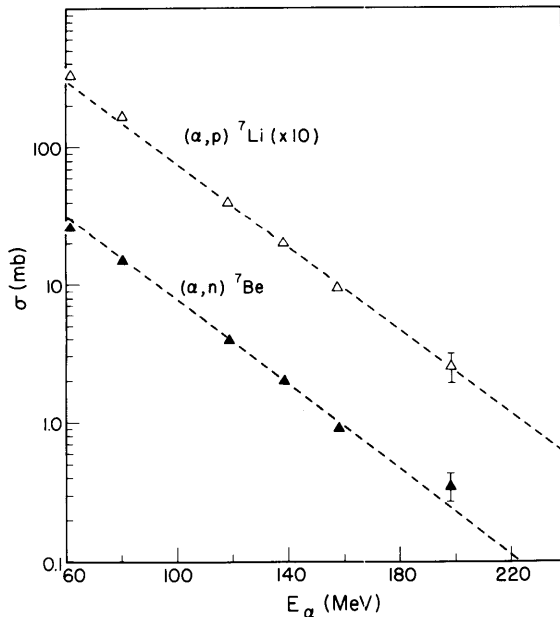
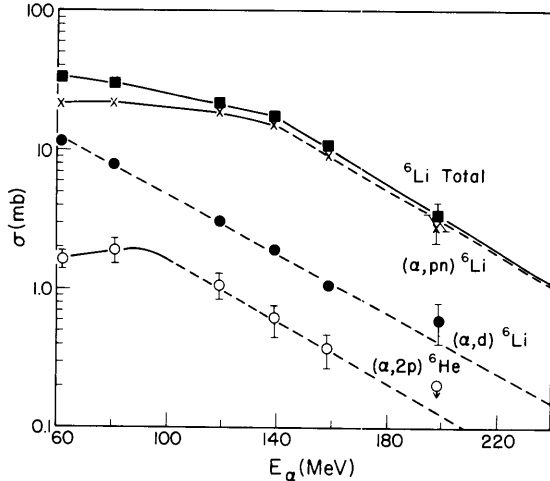


Figure 2. Excitation functions for A = 6 and 7 production in the $\alpha + \alpha$ reaction. Symbols are as follows: Δ - ^7Li ; \blacktriangle - ^7Be ; \circ - $\alpha(\alpha, 2p)$; \bullet - $\alpha(\alpha, d)$; \times - $\alpha(\alpha, pn)$, and \blacksquare - total A = 6. Dashed lines are Eqs. (1)-(4), respectively. Solid lines are to guide the eye.

reaction in $\alpha + \alpha$ collisions follows the same exponential decrease at high energies as do the two-body final states.

Also shown in Fig. 2 are fits to the high-energy portion of each excitation function (dashed lines) leading to A = 6 and 7 formation. These are given by:

$$\sigma(^6\text{He}) = 20 e^{-0.025E_{\text{mb}}}; (E > 100 \text{ MeV}) \quad (1)$$

$$\sigma(^6\text{Li}_{2\text{-body}}) = 59 e^{-0.025E_{\text{mb}}}; (E > 60 \text{ MeV}) \quad (2)$$

$$\sigma(^6\text{Li}_{pn}) = 500 e^{-0.025E_{\text{mb}}}; (E > 140 \text{ MeV}) \text{ and} \quad (3)$$

$$\sigma(^7\text{Li}, ^7\text{Be}) = 260 e^{-0.035E_{\text{mb}}}; (E > 60 \text{ MeV}), \quad (4)$$

where E is the bombarding energy for ^4He in the laboratory system.

In terms of Li nucleosynthesis these results reinforce the previous conclusion that beyond ^4He energies of about 250 MeV, the $\alpha + \alpha$ reaction does not contribute significantly to ^6Li and ^7Li synthesis.^{1,2} Further, the excitation functions of Fig. 2 demonstrate that any non-thermal mechanism which employs conventional H/He/CNO abundances cannot reproduce the $^7\text{Li}/^6\text{Li}$ abundance ratio of 12.6. The exception to this would be a monoenergetic flux spectrum with a very narrow energy window ($< 1 \text{ MeV}$) near the $\alpha + \alpha$ threshold.⁴

These measurements also provide elastic scattering differential cross section data for the $\alpha + \alpha$ system. These data have been fit with a nine-parameter optical model which, in addition to standard real and imaginary parts, includes a second real part (V_2) to allow more flexibility in the shape of the potential.⁵ These

parameters are listed in Table II, where they are compared with parameters derived in Ref. 5 for 158.2-MeV $\alpha + \alpha$ elastic scattering. Given the lower statistical quality of the present results and the absence of data between center-of-mass angles 70 to 90 degrees, the values are in good agreement, except for the increased magnitude of the imaginary potential at 198.4 MeV. A chi-squared value of 2.0 per point was obtained for the best fit.

Also tabulated in Table II are the values of the volume integrals for the real and imaginary potentials. Based on Ref. 5, it was suggested that both volume

integrals exhibited a linear dependence on bombarding energy, the real integral decreasing and the imaginary integral increasing with energy. The present results are more consistent with a real volume integral that is constant in the range of $J_R/4A \approx 420\text{-fm}^3$ over the laboratory energy range from 100 to 200 MeV. In contrast, the imaginary volume integral obtained at 198.4 MeV supports a continued linear increase with energy for this quantity with a slope of $\sim 1.7 \pm 0.2$ MeV-fm³/MeV. This slope is somewhat larger than the value of 1.2 ± 0.2 MeV-fm³/MeV quoted in Ref. 5 and 1.3 ± 0.7 in Ref. 6.

Table II

Optical-model parameters used to fit $\alpha + \alpha$ elastic scattering data compared with values for 158.2 MeV, as quoted in Ref. 5. Potentials V and W are in MeV and half-radii r and difference parameters a are in fm.

| E_α (MeV) | V_1 | r_1 | a_1 | W | r_I | a_I | V_2 | r_2 | a_2 |
|--|-------|-------|-------|------|-------|-------|-------|-------|-------|
| 198.4 | 59.2 | 1.505 | 0.694 | 30.1 | 1.654 | 0.472 | 55.8 | 0.804 | 0.047 |
| 158.2 | 53.8 | 1.628 | 0.613 | 9.6 | 2.094 | 0.467 | 44.0 | 0.545 | 0.142 |
| $J_R/4A = 418 \text{ MeV-fm}^3/\text{MeV}$ | | | | | | | | | |
| $J_I/4A = 188 \text{ MeV-fm}^3/\text{MeV}$ | | | | | | | | | |
| $\chi^2/N = 2.0$ | | | | | | | | | |

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