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Measurements of discrete nuclear reactions induced by a radioactive ^{8}Li beam

F. D. Becchetti, W. Z. Liu, D. A. Roberts, and J. W. Jänecke
Department of Physics, The University of Michigan, Ann Arbor, Michigan 48109

J. J. Kolata, A. Morsad, X. J. Kong, and R. E. Warner*
Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556
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Energy- and angle-resolved nuclear reactions, primarily one-nucleon stripping, have been observed for targets of CD_2, Be, and C, using a radioactive ^{8}Li beam ($T_{1/2}=842$ ms) at $E=14.3$ MeV. The (^{8}Li,^{7}Li) neutron transfer reaction populating discrete final states was identified and angular distributions were obtained. This direct-reaction channel has large cross sections (10–100 mb/sr) due, in part, to the unique nuclear properties of ^{8}Li. Implications for astrophysical abundances of Li isotopes may be significant.

The production and use of unstable, radioactive nuclear ion beams is of considerable interest.[1–3] In explosive nucleosynthesis, even nuclei which are "stable" for only fractions of a second are nonetheless critically involved in the production of the elements.[4] Few, if any, of the nuclear reaction rates involving unstable nuclei such as ^{6}He, ^{8}Li, ^{7}Be, etc., which are necessary for accurate theoretical modeling, are experimentally known, yet there are about five times as many nuclei with $0.1<T_{1/2}<1$ s than with $T_{1/2}>1$ s. Extrapolations of reaction rates for radioactive nuclei from rates observed with stable nuclei may well be in error since (a) reactions involving radioactive nuclei are often *very* exothermic ($Q\gg 0$); (b) radioactive nuclei are often loosely bound with respect to breakup and direct transfer channels; (c) radioactive nuclei often have high ground-state (g.s.) spin and isospin; and (d) many radioactive nuclei can be highly deformed.

Hence, due to (a)-(d) certain types of reactions, e.g., direct in addition to compound-nuclear, may be significant even at the low energies of astrophysical interest, viz., $E_{\mathrm{c.m.}}<5$ MeV.

^{8}Li-induced reactions can have important consequences for the abundances of ^{6,7}Li and other light nuclei.[4,5] The latter abundances are often used to infer, via modeling of nuclear reaction rates, the conditions present during the early stages of the evolution of the Universe, e.g., the total baryon density. Since most of the mass necessary to close the Universe appears to be missing, knowledge of the present total baryonic mass is critical. The latter is normally constrained to limits set via nucleosynthesis calculations[4] by the observed ^{1}H/Li, ^{2}H/Li, and ^{3}He/Li abundances. The implication is that most of the missing mass in the Universe is nonbaryonic.

However, unlike reactions involving ^{6}Li and ^{7}Li $[(J^\pi,T,T_z)=(1^+,0,0)$ and $(\frac{3}{2}^-,\frac{1}{2},\frac{1}{2})$, respectively] those involving ^{8}Li $(2^+,1,1)$ usually have $Q\gg 0$ and in addition can have large spin, angular-momentum, and isospin transfers. Since $J^\pi_{\mathrm{g.s.}}(^8\mathrm{Li})=2^+$, the nuclear reaction selection rules are also considerably different for ^{8}Li compared to other light, stable nuclei. Thus one would like observation of reactions to *discrete* final nuclear states, i.e., those with definite J^π, T, and T_z.

Unfortunately, most previous attempts[1,2,5] to measure radioactive-beam-induced reactions to discrete states have been hampered by the large backgrounds of unwanted particles inherent with conventional ion-optical systems. However, a device[6,7] which appears to be well suited for the production, filtering, and refocusing of radioactive ion beams[8,9] is the superconducting solenoid lens. We have used a 3.5 T, 20 cm bore, 35 cm long air-core superconducting solenoid[7] which has been configured[8,9] as a radioactive-beam lens ($d\Omega=90$–110 msr; $\theta=5°$–$11°$) on a dedicated beam line at the University of Notre Dame three-stage Van de Graaff accelerator. The use of a yokeless air-core magnet together with an iron-free environment insures that the solenoid field is highly uniform and axially symmetric. This permits precise blocking of the high-intensity ($\geq 10^8$/s) elastically scattered incident ^{7}Li beam. This design also permits operation in a highly asymmetric mode, which is necessary to keep the secondary beam divergence small ($\pm 4°$).

We have produced usable beams of ^{8}Li and ^{6}He via the production reactions ^{9}Be(^{7}Li,^{8}Li)^{8}Be, and ^{9}Be(^{7}Li, ^{6}He)^{10}B at $E_{\mathrm{lab}}(^7\mathrm{Li})=17$ MeV. The ^{9}Be metal production target permits the use of the maximum obtainable primary beam intensity which was limited by the ion source to 30 particle nA. The production reaction leading to the $^8\mathrm{Be}_{\mathrm{g.s.}}$ yields[8,9] a well-defined ^{8}Li peak at $E\simeq 14.3$ MeV with reasonable yield in the range $\theta=3°$–$11°$. ^{8}Li has no long-lived particle-stable excited states. The $J^\pi=1^-$ level in ^{8}Li at $E_x=0.98$ MeV, while particle stable, quickly decays by γ-ray emission ($T_{1/2}\sim 8$ fs) and the resulting ^{8}Li ion, since it is shifted in energy, can be mostly filtered out by the magnet. The ^{8}Li ions are refocused on the secondary target. Since ^{8}Li (and ^{6}He) ions are more magnetically rigid than the intense, elastically scattered ^{7}Li ions, the latter are removed with a blocking aperture located at the ^{7}Li focal point in the intermediate vacuum chamber. The flight path through the solenoid is about 2 m. Hence, radioactive beams with half lives as short as a few hundred ms (such as ^{8}Li and ^{6}He) can be collected without significant beam losses.

A 12.7 μm (2.3 mg/cm^2) thick ^{9}Be production target and an incident 17 MeV $^7\mathrm{Li}^{3+}$ beam of intensity 100 nA (electrical) produce a secondary 14.3 MeV ^{8}Li beam of approximately 5×10^4 ions/s focused to a spot 5 mm in diameter with an energy resolution of 600 keV FWHM. The corresponding conversion efficiency is 10^{-7}. The beam consists of $\sim$70% ^{8}Li ions together with alpha particles, protons, deuterons, and ^{6}He ions at the same magnetic rigidity.[8,9] Trace amounts ($<5\%$) of other ions including ^{7}Li are also present, but they are usually the result of multiple scattering in the solenoid and hence appear only at low energies. (See Refs. 8 and 9 for details of the ^{8}Li beam production and calibration). Since the reaction Q values for secondary reactions induced by ^{8}Li and ^{6}He beams are generally very positive, identification of reactions involving these ions is usually unambiguous.

The secondary target chamber consists of an entrance collimator, a target ladder, and a rotatable ΔE-t-E-XY position-sensitive counter telescope. This detector consists of a 450 mm^2, 28 μm thick planar Si detector, backed by a 25×25 mm, 200 μm thick boron-implanted Si detector[10] having a two-dimensional resistive cathode consisting of up or down and left or right electrodes.

Our initial experiments[8,9] consisted of measurements of the reactions from the production target, verification of the ion optics, and measurement of the radioactive beam intensity and characteristics. Targets of CH_2 (1.4 mg/cm^2), CD_2 (1.9 mg/cm^2), beryllium (1.8 mg/cm^2), carbon (1.0 mg/cm^2), aluminum (1.3 mg/cm^2), and gold (1.0 mg/cm^2) were then used to observe various ^{8}Li (and ^{6}He) induced reactions. In addition to elastic scattering, which was observed to $\theta\simeq45°$, several discrete nuclear reactions were identified in the ΔE-E spectra and confirmed by target-in or target-out runs together with the use of the unique, positive-Q-value signatures which lead to isolated groups of particles at energies well above the secondary ^{8}Li beam energy (Fig. 1).

Except for elastic and inelastic scattering,[8,9,11] the most prominent reaction observed at forward angles on most of the lighter targets is the single nucleon (^{8}Li, ^{7}Li) transfer reaction which typically has $Q=+0.2$ to $+5.6$ MeV (Figs. 1 and 2). The g.s.$\rightarrow$g.s. transition was observed for ^{2}H, Be, and C targets, and transitions to excited states were observed for the Be and C targets. Although the ^{7}Li ejectile may also be produced in its particle-stable first excited state ($J^\pi=\frac{1}{2}^-$, $E_x=0.47$ MeV), the energy spectra (Fig. 2) indicate that most of the (^{8}Li, ^{7}Li) cross section results in production of the ^{7}Li g.s. ($J^\pi=\frac{3}{2}^-$). The ^{12}C(^{8}Li,^{7}Li)^{13}C$_{\rm g.s.}$ cross section has been verified by measurement of the time reversed reaction ^{13}C(^{7}Li,^{8}Li)^{12}C$_{\rm g.s.}$ at the appropriate $E(^7$Li).

Spectra from ^{9}Be and CD_2 targets are shown in Fig. 2. Even for minimal statistics each spectrum typically requires 8–16 h of running time. Angular distributions are displayed in Fig. 3 together with finite-range distorted-wave Born approximation (FRDWBA) calculations assuming a *direct* neutron capture. The parameters needed for these calculations have been adopted from those used by Schumacher *et al.*[12] in the analysis of ^{6,7}Li+^{12,13}C reactions at E(Li)=34 and 36 MeV. The general characteristics of the observed (^{8}Li,^{7}Li) cross sections (shape and magnitude) are reproduced using spectroscopic factors comparable to those from nuclear shell model calcula-

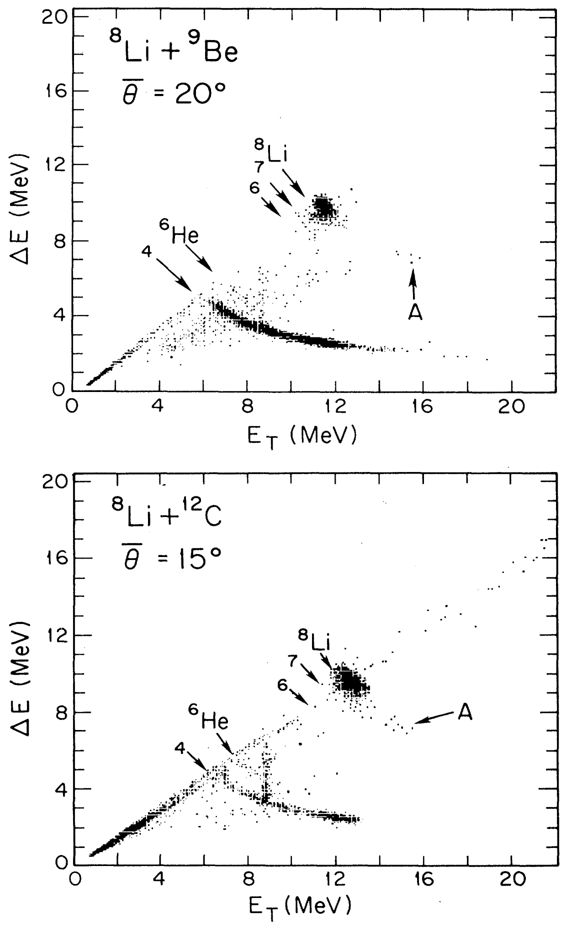

FIG. 1. ΔE-E particle spectra observed for ^{8}Li, etc., incident on a 1.8 mg/cm^2 Be target (top) and on an $\sim$1 mg/cm^2 C target (bottom). Group "A" represents the ^{7}Li group from the (^{8}Li,^{7}Li) reaction. (The vertical band of particles at $E\simeq9$ MeV is due to temporary surface contamination of the ΔE detector from a ThC′ α-calibration source.)

tions.[13] An exact quantitative FRDWBA analysis must await information on the appropriate ^{8}Li optical model potentials. (More detailed measurements of ^{8}Li elastic and inelastic scattering are in progress.)

As noted previously, the relatively large direct-reaction cross sections (10–100 mb/sr) apparently observed for the (^{8}Li,^{7}Li) reaction result from (a) the small binding energy of the last neutron in ^{8}Li, (b) the large positive Q values (which facilitate momentum matching), and (c) the $J^\pi_{\rm g.s.}=2^+$ of ^{8}Li, which permits multiple l transfers.

As noted, the reactions of ^{8}Li+^{1}H and especially ^{8}Li+^{2}H (using CH_2 and CD_2 secondary targets) are of astrophysical interest[4,5] as they help to determine the abundances of the stable Li ions (^{6,7}Li) which are used to infer the temperature and baryon density in the early Universe.[4] These reactions may also serve to produce ^{9}Be in nonstandard big-bang scenarios and thus circumvent the gap in nucleosynthesis due to the instability of ^{8}Be.

Our present data for ^{8}Li+^{2}H are limited to large c.m. scattering angles since the reverse kinematics involved,

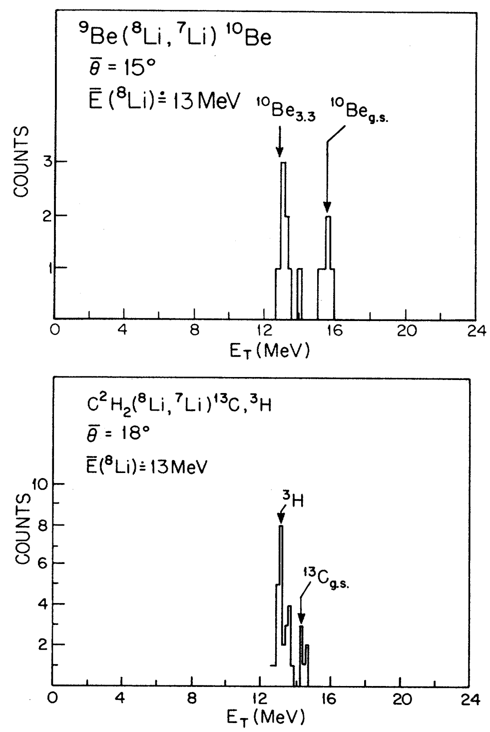

FIG. 2. Energy spectra from (^{8}Li,^{7}Li) reactions on ~2 mg/cm^{2} ^{9}Be and CD$_2$ targets. ($\bar{E}$ is the mean lab ^{8}Li energy in the target and $\bar{\theta}$ is the mean scattering angle in the ΔE-E-XY detector.)

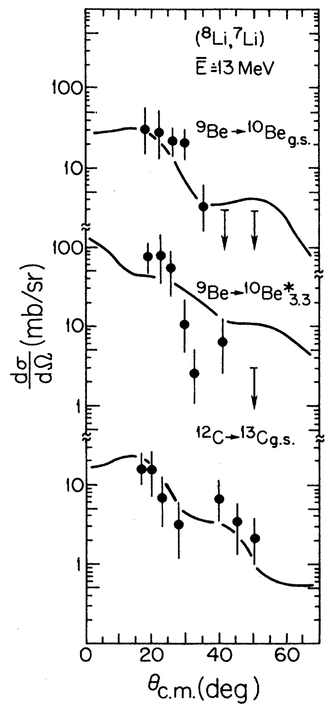

FIG. 3. Angular distributions for (^{8}Li,^{7}Li) compared with FRDWBA calculations. The optical-model parameters are adopted from Ref. 12 (set III). The magnitudes have been normalized by readjustments in the spectroscopic factors relative to shell-model values (Ref. 13).

viz., heavy projectile on a light target, results in ^{7}Li ejectiles produced close to $\theta=0°$ in the lab. These ions overlap the angular spread of the incident ^{8}Li secondary beam, which is too intense for the ΔE-E Si telescope. (New methods for measurement of this reaction near $\theta_{\rm lab}=0°$ are being developed.) The present data (e.g., Fig. 2, bottom) yield $d\sigma/d\Omega(\theta_{\rm c.m.}=36°)=14\pm4$ mb/sr and $d\sigma/d\Omega(\theta_{\rm c.m.}=45°)=4\pm1$ mb/sr for the ^{2}H(^{8}Li,^{7}Li)^{3}H reaction at $\bar{E}_{\rm lab}(^{8}{\rm Li})=13$ MeV and $\bar{E}_{\rm c.m.}=2.6$ MeV. The latter, relatively low $E_{\rm c.m.}$, which is necessary for reactions of astrophysical interest, is the result of using reverse kinematics, viz., a heavy beam on a light target (^{2}H). Most nucleosynthesis calculations involving low $E_{\rm c.m.}$ radioactive nuclei assume a nondirect, statistical (CN) reaction mechanism. Our (^{8}Li,^{7}Li) data [consistent with (a)-(c)] show that selective, *direct* nuclear reactions, e.g., neutron transfer or tunneling are significant and must be considered even at rather low energies.

Recently, a high-intensity, cesium-sputter ion source has been installed which yields more than one order-of-magnitude improvement in the secondary beam intensity and permits the measurement of discrete radioactive-beam (^{6}He, ^{8}Li, ^{7}Be, . . .) cross sections of a few mb/sr.

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*Permanent address: Oberlin College, Oberlin, OH 44074.

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