Breakup of ^{7}Li near the α-t Threshold and a Possible Probe of Radiative-Capture Processes

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Breakup of 63-MeV and 42-MeV ^{7}Li near the α-t threshold is examined from the astrophysical point of view. A new approach is made to extract indirectly astrophysical S factors. The S factors are compared with those deduced from radiative-capture measurements. It is shown that the energy dependence favors the recent capture data of Schröder *et al.*

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Direct measurements of radiative-capture cross sections, $a(b,\gamma)c$, have generally provided basic data for nuclear astrophysics only by *extrapolation* since the astrophysical environments of big-bang expansion and the interior of massive stars cannot be replicated in the laboratory. An innovative method proposed by Baur, Bertulani, and Rebel[1] for overcoming this principal difficulty uses the reciprocity theorem to relate radiative capture and nuclear photodisintegration. In principle, this approach reduces the principal difficulty of the direct measurements to the technical problem of observing astrophysical energies in two-particle correlation experiments. Very recently, a technique[2] that utilizes a broad-range magnetic spectrograph has been devised to observe two particles emitted in extremely close proximity.

Breakup of ^{7}Li near the α-t separation energy was studied with the spectrograph technique at the Cyclotron Institute of Texas A&M University[3] and at the Holifield Heavy Ion Research Facility of Oak Ridge National Laboratory at bombarding energies of 63 and 42 MeV, respectively. Detection-threshold-free measurements of α-t correlation cross sections were made for a wide range of impact parameters (detection angles) and for different intensities of the Coulomb field (targets). These data taken for a variety of experimental conditions (i.e., two bombarding energies, five targets ranging from ^{27}Al to ^{208}Pb, and many different detection angles) provide a test of the indirect method proposed by Baur, Bertulani, and Rebel. It is shown that a modified version of the method may be feasible in the present energy domain where the Coulomb and the nuclear interactions behave similarly in exciting the α-t continuum states.

Figure 1 shows several α-t relative-energy distributions. The intensity of α-t correlations continuously changes in the relative-energy range (ε=0–1.0 MeV) of astrophysical interest. These spectra were generated from an event-by-event kinematical transformation.[3,4] In the data processing, the effects of the finite spectrograph aperture and the finite target thickness were taken into account. An extensive examination was made of the spectra to locate the spectral minimum corresponding to zero relative energy. No strong shifts were found in the

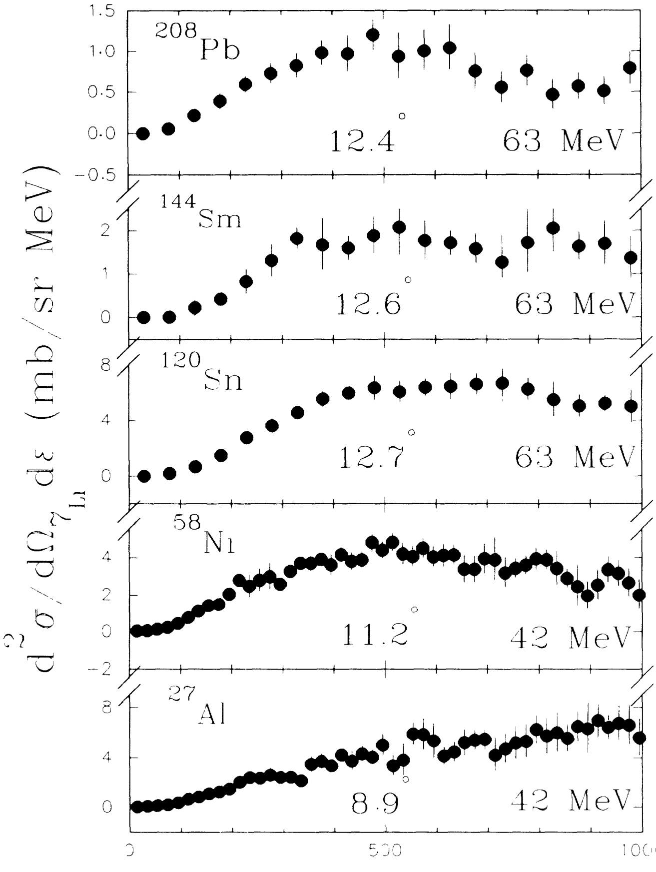

FIG. 1. Distributions of α-t relative kinetic energies observed in the breakup of ^{7}Li at 63 and 42 MeV.

location of these minima due to possible postbreakup Coulomb acceleration, limiting the postacceleration effects to about 0.3 MeV per unit charge.[3] Corrections were made at this level. The error bars displayed in Fig. 1 reflect the combined uncertainties due to all three effects as well as the counting statistics.

According to the originally proposed method,[1] the first step involves obtaining the reduced transition probability for exciting the α-t distribution by dividing the experimental cross sections $d^2\sigma/d\Omega_{\gamma\mathrm{Li}}d\varepsilon$ by the Coulomb excitation function $df/d\Omega(\xi,\theta)$. The latter quantity is dominated by $E1$ transitions in the present case. In the next step, the detailed balance theorem is applied to relate the reduced transition probability $B(E1;\varepsilon)$ to the radiative-capture cross sections $\sigma_{at}(\varepsilon)$ as follows:

$$B(E1;\varepsilon)=\frac{9}{16\pi^3}\hbar c\left(\frac{6}{7}\right)\frac{mc^2}{E_\gamma^3}\varepsilon\sigma_{at}(\varepsilon)\,. \tag{1}$$

Thus, the astrophysical S factors $S(\varepsilon)$ for the radiative-capture process are obtained from the definition

$$S(\varepsilon)=\varepsilon e^{2\pi\eta}\sigma_{at}(\varepsilon)\,. \tag{2}$$

Here, η is the Coulomb parameter, $\eta=Z_aZ_te^2/\hbar v$.

Let us examine the first step as applied to the present data, temporarily putting aside the question[3,5] of Coulomb-nuclear interference. Five sets of data representing different experimental conditions with sufficient counting statistics were chosen for this purpose. Their experimental conditions are listed in Table I. Dividing the data by the $E1$ Coulomb excitation function[6] yielded the results summarized in Fig. 2. It is remarkable that, for all the systems, the energy dependence of the reduced transition probability is nearly *universal.*

Now let us consider nuclear-Coulomb interference effects. It is quite plausible that nuclear breakup and Coulomb breakup coexist[3,5] over the energy region under consideration. The original proposal[1] of Baur, Bertulani, and Rebel requires a clean separation of the Coulomb and nuclear contributions. Under present circumstances, this decomposition, which can only be obtained with the help of direct reaction theories, is currently premature. On the other hand, one may be able to interpret the observed "universal" energy dependence as a signature that the nuclear and Coulomb interactions excite the continuum with the same ε dependence. We investigated the dependence of the Coulomb and nuclear excitation functions on the excitation energy (ε) within the framework of a distorted-wave Born approximation (DWBA). Assuming that the α-t continuum results from one-step $E1$ transitions from the ground state of ^{7}Li, the Coulomb and nuclear excitation functions were generated with the program[7] JPWKB which involves a collective form factor.[8] For the current experimental conditions, the DWBA analysis lends support to the *parallelism* in the ε dependence within the accuracy of ±5% in the range from 0 to 0.5 MeV and within ±10% in the range 0.5–1.0 MeV. At the present time, however, this result of the DWBA study should not be regarded as evidence for the observed universal energy dependence. The proof must await thorough theoretical investigations that

TABLE I. Various systems chosen for the nuclear-astrophysical application of the ^{7}Li breakup.

Data set	Targets	Laboratory bombarding energies (MeV)	c.m. angles (deg)
I	^{208}Pb	63	12.4
			15.5
			20.7
			25.8
II	^{144}Sm	63	12.6
III	^{120}Sn	63	9.6
			12.7
			15.9
IV	^{58}Ni	42	11.2
			16.9
V	^{27}Al	42	8.9
			12.7

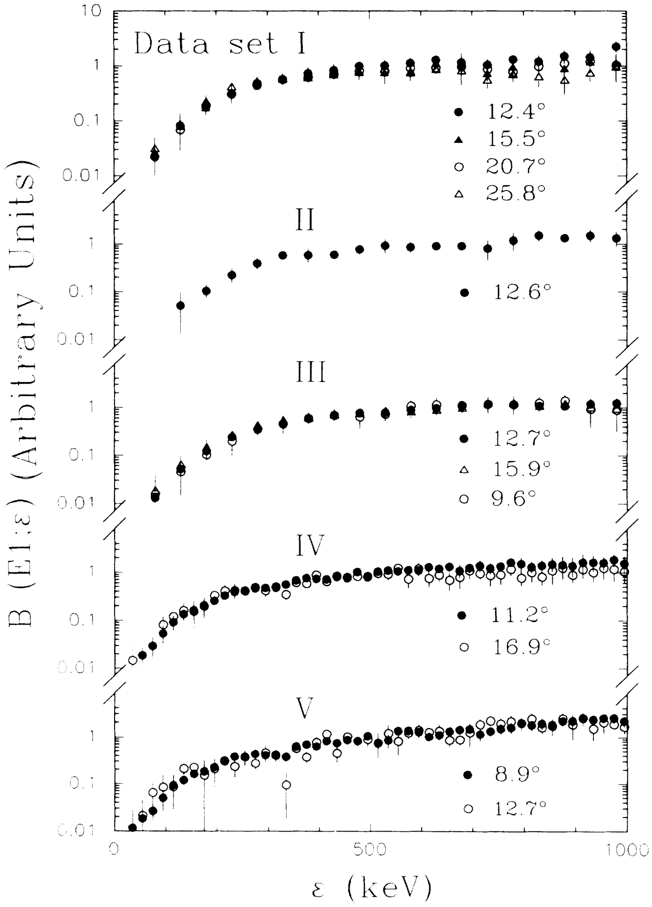

FIG. 2. The reduced transition probabilities deduced from the data sets listed in Table I.

should include studies of higher-order effects such as channel coupling between the $\frac{1}{2}^-$ (and/or the $\frac{7}{2}^-$) discrete state and the continuum.

Radiative-capture cross sections σ_{at} have been measured by three independent groups: Griffiths *et al.*[9] in 1961 for ε down to 150 keV and Schröder *et al.*[10] and Burzynski *et al.*[11] in 1987 for ε down to 79 and 297 keV, respectively. The astrophysical S factors deduced from these data are summarized in Fig. 3. It is noted that the data of Schröder *et al.* exhibit a pronounced energy dependence below $\varepsilon = 300$ keV compared to the data of Griffiths *et al.*, while the third measurement by Burzynski *et al.* does not help differentiate between these two data sets because of a lack of cross sections in this energy region. The discrepancies at low energies are a serious problem in big-band nucleosynthesis because they give $S(0)$ values which differ by a factor of nearly 2.

Let us apply Eqs. (1) and (2) to the universal reduced transition probability. The S factors extracted from the breakup data are plotted in Fig. 3 after normalizing them to $S(\varepsilon) = 0.06$ keV b at $\varepsilon = 500$ keV. We see that the energy dependence favors the data of Schröder *et al.* This energy dependence, however, seems to be stronger than those of the most recent calculations,[12-16] which tend to support the data of Griffiths *et al.* Possibly the production rate[17] of primordial ^{7}Li needs to be modified.

There seems to be a systematic difference within 2σ between the results at 42 and 63 MeV in both the low- and high-energy regions. This may reflect effects of the final-state interactions (FSI) especially at low ε. FSI effects need to be studied theoretically in the future. The S factors obtained from the combined data are given in Table II. The individual values represent the simple average between the 42- and 63-MeV data, while the errors correspond to the total range spanned by the two data sets. It is added that below 100 keV, the extracted S factors even exceed 0.15 keV b with considerable uncertainties. This is at least partly because the measurements suffered from degradation of the energy resolution in this region.[2,3]

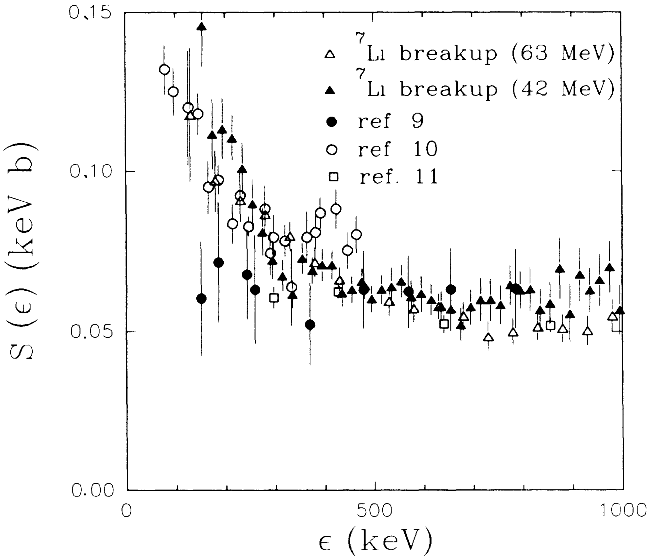

FIG. 3. Comparison of astrophysical S factors extracted from the present breakup data with those deduced from radiative-capture measurements. The data at 63 and 42 MeV, respectively, were averaged with weights inversely proportional to the uncertainties (in Fig. 1) associated with the individual measurements.

TABLE II. Astrophysical S factors obtained from the breakup data.

ε (keV)	$S(\varepsilon)$ (keV b)	Errors (+/−) (keV b)
80	0.35	0.14/0.13
130	0.15	0.04/0.05
180	0.11	0.01/0.012
230	0.095	0.007/0.010
280	0.082	0.011/0.010
330	0.071	0.014/0.012
380	0.069	0.008/0.006
430	0.064	0.007/0.006
480	0.063	0.006/0.005
530	0.060	0.003/0.005
580	0.059	0.004/0.005
630	0.057	0.005/0.004
680	0.054	0.005/0.004
730	0.053	0.007/0.009
780	0.056	0.009/0.009
830	0.055	0.007/0.007
880	0.054	0.007/0.007
930	0.056	0.011/0.010
980	0.059	0.009/0.009

In conclusion, projectile breakup near particle thresholds may provide indirect access to radiative-capture processes at astrophysical energies where extrapolation has been known to be the major cause of associated uncertainties. The theoretical aspects of this indirect approach need to be investigated. Another measurement of the radiative-capture cross section is also desired. Achieving sufficient energy resolution for the ^{7}Li system at its astrophysical energies (below 10 keV) requires particle-tracking capabilities within the aperture of the spectrograph.[2] However, it would be interesting to study the breakup of other nuclear species where such ultrasensitivity is not required.

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