OBSERVATION OF α–t CONTINUUM STATES WITH RELATIVE ENERGIES OF 0–2 MeV IN ^{7}Li BREAKUP REACTIONS

H. UTSUNOMIYA, R.P. SCHMITT, Y.-W. LUI, D.R. HAENNI, H. DEJBAKHSH, L. COOKE, P. HEIMBERG, A. RAY [1]

Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA

T. TAMURA and T. UDAGAWA

Department of Physics, University of Texas, Austin, TX 78712, USA

Received 9 February 1988

The breakup of ^{7}Li at 63 MeV was studied in an α–t coincidence experiment using an Enge split pole spectrograph. For the first time, the entire spectrum of the α–t continuum states of ^{7}Li was observed in the range of the relative energy ε from zero to 2 MeV. A pronounced bump was found at $\varepsilon \approx 0.4$ MeV. The astrophysical implications of the data are discussed.

A new technique has been developed to measure correlations between two particles that are emitted at the same angle in the laboratory frame. This technique, which utilizes a magnetic spectrograph with a large momentum acceptance, allows one to observe small relative energies without energy threshold. This threshold is inevitable with particle telescopes, regardless of their number and geometrical arrangement because it results from the finite angles between the detectors [1,2]. For example, in ref. [1], in spite of efforts to place a pair of telescopes in close proximity, the threshold was still 290 keV. We have applied the new method to ^{7}Li breakup reactions. Here we report results of α–t coincidence measurements that are completely free from the detection threshold at small relative energies.

A 63 MeV ^{7}Li beam (50–200 e nA) from the Texas A&M 88-inch cyclotron was used to irradiate self-supporting ^{208}Pb, ^{144}Sm, ^{120}Sn, and ^{58}Ni foils with areal densities ranging from 4.6 to 11 mg/cm^2. As illustrated in fig. 1, α–t breakup pairs emitted within the solid angle subtended by an Enge split pole spectrograph (5.3 msr) were analyzed according to the magnetic rigidity and were focused at different posi-

ENGE SPLIT POLE SPECTROGRAPH

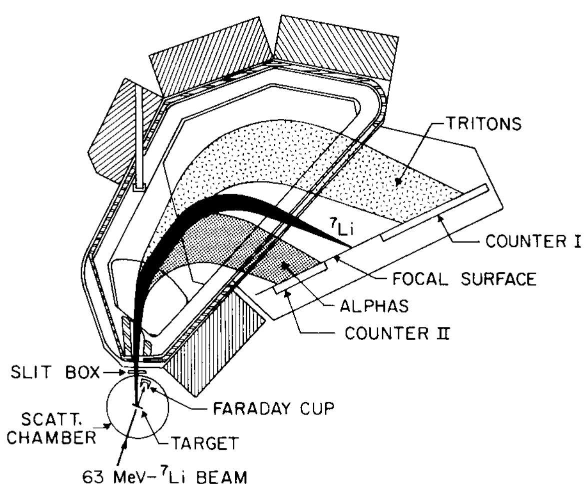

Fig. 1. Schematic of the experimental set-up.

tions along the focal plane. The set-up preferentially selected forward-going tritons and backward-going alphas in the rest frame of ^{7}Li*. Both counters were single wire proportional counters (SWPC) backed by plastic scintillators. Elastically scattered ^{7}Li* caused no interference in the coincidence measurements because they impinged on the focal plane between the two counters. The focal plane counters were cali-

[1] Present address: Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA.

0370-2693/88/$ 03.50 © Elsevier Science Publishers B.V. (North-Holland Physics Publishing Division)

brated using $^{12}C(\alpha, \alpha')^{12}C$ and $^{27}Al(\alpha, t)^{28}Si$ reactions. The energy of the α beam was determined by the crossover method with $^{12}C(\alpha, t)^{13}N$ and $^{12}C(\alpha, d)^{14}N$ reactions. Absolute energies were determined within 1%. Uncertainties in the absolute cross-sections are estimated to be about 15%. A detailed description of the experiment and the analysis will be presented elsewhere [3].

Fig. 2 shows a two-dimensional plot of the α–t coincidences along with the projected spectra for the ^{208}Pb target. One can see a concentration of data along a line of $E_\alpha + E_t = C$ (C=constant). This corresponds to elastic breakup, in which the target stays in the ground state. The line consists of two components which are more clearly seen in the projected spectra. One is a sharp peak resulting from the $7/2^-$ state of ^7Li at 4.63 MeV. The other is a broad bump in the relative energy range $\varepsilon \cong 0$–2 MeV. Intense elastic breakup was also observed for ^{144}Sm and ^{120}Sn targets. However, at 12° with a ^{58}Ni target the data are dominated by inelastic breakup which leaves the target in the 2^+ state at 1.45 MeV.

The location of the bottom of the valley in the continuum is very sensitive to the post-acceleration in the Coulomb field of the target [4,5]. Since the valley of the continuum was observed without a detection threshold, one can evaluate the effect of the Coulomb acceleration as follows. The particle energies at the bottom of the valley are given by $E_\alpha = 4C/7 + 2V_c/7$ and by $E_t = 3C/7 - 2V_c/7$, where V_c is the Coulomb potential per unit charge at the point of the ^7Li breakup. A shift due to the Coulomb distortion amounts to $2V_c/7$. The acceleration is stronger for α particles than tritons because of the larger charge to mass ratio.

The bottom position without the Coulomb distortion ($V_c = 0$) is indicated by $\varepsilon = 0$ at the top of the projected spectra (in fig. 2), which seems to correspond with the minima in the spectra. This was observed at all angles and for all targets studied, indicating that the Coulomb distortion effect is weak. More quantitatively, if the breakup of ^7Li occurs at the nuclear surface of the target, V_c should be about 10 MeV, which would cause a shift of 3 MeV in the bottom of the valley. Since this is clearly not the case, the possibility of *direct breakup* at the time the projectile and the target overlap seems to be excluded.

Fig. 3 shows relative energy distributions $d^3\sigma/d\Omega_{Li} d\varepsilon\, d\Omega_{\alpha-t}$ for the elastic breakup of ^7Li. It is remarkable that a structure with a bump at $\varepsilon = 0.4$ MeV is observed. In fact, essentially the same bump struc-

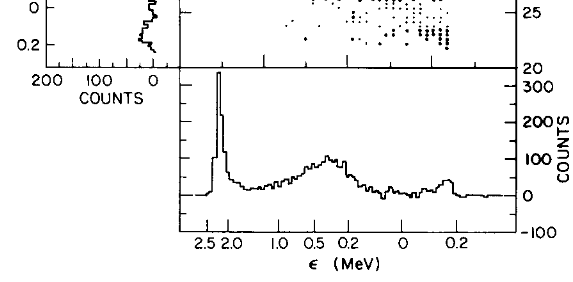

Fig. 2. A two-dimensional plot of the α–t coincidences at 15° in the $^7Li + ^{208}Pb$ reaction at 63 MeV. Projected spectra of α particles and tritons are also presented with relative energy scales neglecting Coulomb distortion (see text).

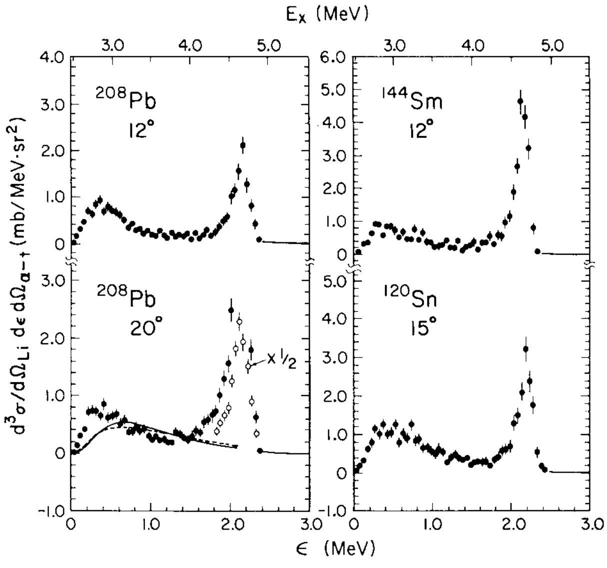

Fig. 3. Representative relative energy distributions, $d^3\sigma/d\Omega_{Li} d\varepsilon\, d\Omega_{\alpha-t}$, for elastic breakup of 63 MeV ^7Li. The excitation energy, E_x, is given at the top of the figure. $E_x = \varepsilon + 2.47$ in MeV, where 2.47 MeV is the α–t threshold energy. The curves represent the classical E1 Coulomb excitation calculations (see text).

ture has been observed for all the detection angles and all the targets. The kinematical transformation followed ref. [6] and assumed no Coulomb distortion. The kinematical effect of the finite angle subtended by the spectrograph on the spectral shape was investigated and was found to be unimportant [3]. Note that the width (about 200 keV) of the observed peak corresponding to the $7/2^-$ state is considerably larger than that (≈ 93 keV) reported in a study of the ^{6}Li(d, p)^{7}Li reaction [7]. This is due mainly to the target thickness and the finite solid angle.

The lifetime of the continuum bump can be estimated from its full width at half maximum (FWHM). After incoherently subtracting the contribution associated with the experimental set-up, the FWHM is approximately 570 keV. The implied lifetime of the continuum is 350 fm/c. If it is assumed that the excitation of the continuum states occurs in the vicinity of the target and that the reaction takes place along the classical grazing trajectory, then the excited ^{7}Li with the lifetime of 350 fm/c decays at about 45 fm from the ^{208}Pb target. The associated Coulomb distortion effect, which shifts the bottom of the valley by $2V_c/7 \cong 0.7$ MeV, is not incompatible with the present observations. Thus, while the excitation itself could take place nearby the target, the ^{7}Li excited to the continuum states is most likely to decay at a significant distance from the target.

Fig. 4 shows the experimental angular distributions, $d\sigma/d\Omega_{Li}$, for the excitation of the continuum as well as the $7/2^-$ state for the ^{208}Pb and the ^{120}Sn targets. No polarization of ^{7}Li* (i.e., an isotropic emission of α and t in their rest frame) was assumed so that the integration over $\Omega_{\alpha-t}$ was equivalent to multiplying by 4π. The experimental angular distributions for the continuum and the $7/2^-$ state are very different. While the former distributions are rather structureless and forward peaked, the latter exhibit strong oscillatory behavior.

Putting aside the discussion of a possible origin of the bump, we have first attempted to see to what extent straightforward DWBA calculations explain the difference in the angular distributions of the $7/2^-$ and the continuum bump. The DWBA calculations took into account both Coulomb and nuclear excitations [9]. An optical potential with parameters that are essentially those of Chua et al. [10] was used. The derivative of the optical potential provided the collective

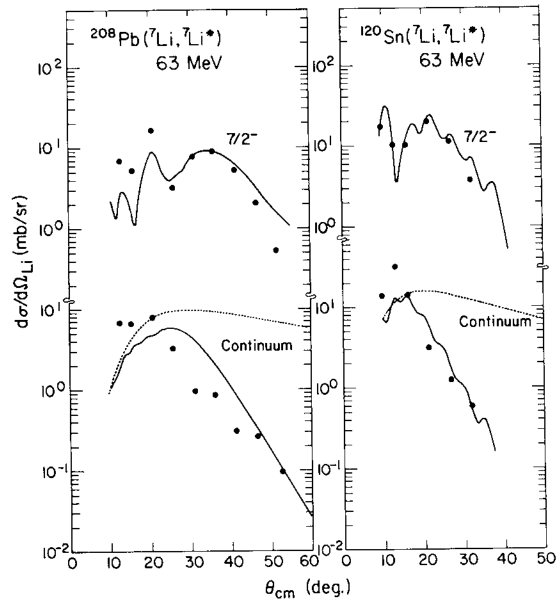

Fig. 4. Angular distributions, $d\sigma/d\Omega_{Li}$, for the excitation of the continuum and the $7/2^-$ state at 4.63 MeV in the reactions of ^{208}Pb and ^{120}Sn with 63 MeV ^{7}Li. The statistical errors are within the data points. The solid curves represent the DWBA calculations. The dotted curves are the results of the E1 Coulomb excitation calculations with the reduced transition probability corresponding to $S = 0.065$ keV b [8].

form factors in the usual way. The continuum was assumed to be of an $S_{1/2^+}$ nature, since studies [11,12] of the radiative capture reaction, $\alpha(t, \gamma)^7$Li, indicate that E1 contributions dominate. The results of the calculations are shown by the solid curves in fig. 4. It is clearly seen that different angular distributions were produced for the $7/2^-$ state and the continuum, which are, respectively, due to E2 and E1 transitions. The theoretical angular distributions are in reasonably good accord with experiment for both states and both targets.

Previously, a similar continuum bump was reported by Shotter et al. [13]. However, the previous results (fig. 3b in ref. [13]) show a large depression in the yield centered at 290 keV, while the present data actually peaks near 300 keV. This results from differences in the sensitivity at small ε in the two detection methods and also the finite detection threshold in the previous measurements. In the telescope study [13], the coincidence phase space for small ε favors the emission of α particles and tritons near

$\Phi = \pm 90°$ in the rest frame of ^{7}Li*. This combined with the large opening angle of each telescope [13] is the reason for the poor sensitivity. In contrast, the sensitivity is maximized with the present method [3] since the detected tritons and α particles are emitted essentially at $\Phi = 0°$ and $\Phi = 180°$, respectively. The present sensitivity can be seen in fig. 2 from the fact that a change in ε from zero to 200 keV results in a 3 MeV difference in the α energy.

Also shown in fig. 4 are classical E1 Coulomb excitation calculations (dotted curves) of the type presented previously [13,14]. The discrepancy at backward angles can be attributed to the nuclear absorption effect. However, the current calculations and data also indicate significant discrepancies at forward angles. The dominance of Coulomb excitation inside the grazing angle [13] does not seem to be justified.

It is of further interest to compare the classical Coulomb excitation calculations with the relative energy distributions presently measured down to zero energy. A comparison for the 20° data taken with the ^{208}Pb target is shown in fig. 3. We have determined the reduced transition probabiliby from two different kinds of the astrophysical S-factors, i.e., $S = 0.065$ keV b, which is consistent with the data of Griffiths et al. [8], and the energy dependent S-factor of Kajino, Bertsch and Kubo (KBK) [15]. The solid and the dotted curves represent the results obtained from the energy independent and dependent S-factors, respectively. Currently, there are large discrepancies (including about a factor of two difference in the $S(0)$ value) in the capture data [8,16]. Using the data of Schröder et al. [16] with an energy dependence similar to that of KBK multiplies the results shown in figs. 3 and 4 by about a factor of 1.5. The calculations and the data exhibit different behavior at small relative energies. Namely, the data continue to increase down to 400 keV then drop steeply. In contrast, the calculated cross sections begin to decrease gradually around 600 keV.

Baur, Rebel and Bertulani [17] have proposed using Coulomb breakup data to indirectly determine astrophysical S-factors, which cannot be accessed by the direct capture measurements. Since the present data include cross sections at the relative energies on the order of keV, they may contain important astrophysical information. However, the discrepancies between the data and the ingenuous Coulomb excitation calculations seem to indicate that a microscopic understanding of the bump is necessary. The method of the coupled discretized continuum channels developed by Kamimura et al. may play such a role [18].

We speculate that the bump contains contributions from a three-body effect especially at small ε. In other words, the α+t system may exhibit the resonance behavior when it is brought into the strong external field of another nucleus. This is based on the following observations. If the bump were due to an *intrinsic* property to ^{7}Li, e.g., a resonance, like the $7/2^-$ state, a similar bump should have been seen in earlier experiments of (p, p′), (e, e′), direct capture and so forth. To our knowledge, however, no evidence has been presented for this marked bump structure [8,16, 19,20].

One of the authors (H.U.) is very grateful to Dr. G. Baur and Dr. C.A. Bertulani for invaluable discussions about the astrophysical application of the breakup. This work was motivated by these discussions and supported by the US Department of Energy and The Robert A. Welch Foundation.

References

[1] A.C. Shotter et al., Phys. Rev. Lett. 46 (1981) 12.
[2] W.D. Rae et al., Phys. Lett. B 105 (1981) 417.
[3] H. Utsunomiya et al., to be submitted to Phys. Rev. C.
[4] M.A. Bernstein and W.A. Friedman, Phys. Rev. C 31 (1985) 843.
[5] J. Pochodzalla et al., Phys. Lett. B 175 (1986) 275.
[6] H. Fuchs, Nucl. Instrum. Methods 200 (1982) 361.
[7] C.P. Browne, Bull. Am. Phys. Soc. 2 (1957) 350.
[8] G.M. Griffiths et al., Can. J. Phys. 39 (1961) 1397.
[9] T. Kim, T. Udagawa, D.H. Feng and T. Tamura, Fortran program JPWKB, unpublished.
[10] L.T. Chua et al., Nucl. Phys. A 273 (1976) 243.
[11] T.A. Tombrello and P.D. Parker, Phys. Rev. 131 (1963) 2582.
[12] T. Kajino and A. Arima, Phys. Rev. Lett. 52 (1984) 739; T. Kajino, Nucl. Phys. A 460 (1986) 559.
[13] A.C. Shotter et al., Phys. Rev. Lett. 53 (1984) 1539.
[14] K. Adler et al., Rev. Mod. Phys. 28 (1956) 432.
[15] T. Kajino, G.F. Bertsch and K.-I. Kubo, Phys. Rev. C 37 (1988) 512.
[16] U. Schröder et al., Phys. Lett. B 192 (1987) 55.

[17] H. Rebel, Workshop on Nuclear reaction cross sections of astrophysical interest, unpublished Report, Kernforschungszentrum Karlsruhe, (February 1985);
G. Baur, C.A. Bertulani and H. Rebel, Nucl. Phys. A 458 (1986) 188;
G. Baur, private communications;
H. Rebel, private communications.
[18] Y. Sakuragi, M. Yahiro and M. Kamimura, Prog. Theor. Physics, Suppl. 89 (1986) 136;
Y. Sakuragi, private communications.
[19] R.M. Hutcheon and H.S. Caplan, Nucl. Phys. A 127 (1969) 417.
[20] D. Hasselgren et al., Nucl. Phys. 69 (1965) 81.