Breakup of ^{8}B at sub-Coulomb energies

J. J. Kolata, V. Guimarães,* D. Peterson,† P. Santi,‡ R. H. White-Stevens, and S. M. Vincent§
Physics Department, University of Notre Dame, Notre Dame, Indiana 46556-5670

F. D. Becchetti, M. Y. Lee, T. W. O'Donnell, D. A. Roberts, and J. A. Zimmerman‖
Physics Department, University of Michigan, Ann Arbor, Michigan 48109-1120
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Energy distributions for outgoing ^{7}Be fragments from breakup of ^{8}B on a ^{58}Ni target have been measured at an incident energy of 25.75 MeV, which is below the Coulomb barrier. The data are compared with coupled-channels calculations that include higher-order couplings in the continuum.

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In a recent Letter [1], we presented an angular distribution for sub-Coulomb dissociation of ^{8}B on a ^{58}Ni target and compared our results with theories [2,3] that incorporate higher-order effects in the reaction mechanism. These calculations, both of which were in excellent agreement with the experimental data, had several common features, including Coulomb-nuclear interference at very large distances, well outside the normal range of the nuclear force, and the need to account for the extended size of the valence-proton wave function in computing the breakup yield. Both these effects are directly attributable to the exotic ''proton-halo'' structure of ^{8}B. However, because we detected only the outgoing ^{7}Be fragment, the experimental angular distribution could not be exactly transformed into the center-of-momentum frame of the residual $^{7}\mathrm{Be}+p$ system in which the theoretical calculations [2,3] are expressed. Instead, we used an approximate Jacobian derived for ^{8}B elastic scattering. This in principle might lead to ambiguities in the interpretation of the data, and obscure the meaning of the observed excellent agreement between theory and experiment. An explicit calculation of three-body observables in the laboratory frame was needed, and has now become available [4]. These observables include the energy distributions of the ^{7}Be fragments as a function of the angle of observation, which were recorded in the experiment [1] but never published because they lacked a theoretical interpretation. It has now been shown [4] that the information content of the energy distributions is quite high, and that the influence of higher-order interference effects, for example, is revealed even more significantly in them. We report these distributions in the present contribution.

*Present address: Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo 05389-970, Brazil.

†Present address: Dept. of Chemistry, Oregon State University, Corvallis, OR 97331-5903.

‡Present address: Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824-1321.

§Present address: Dept. of Physics, University of Surrey, Guildford, Surrey GU2 7XH, U.K.

‖Present address: Dept. of Chemistry, University of Wisconsin-Marinette, Marinette, WI 54143.

The technical aspects of this experiment, which was carried out at the Nuclear Structure Laboratory of the University of Notre Dame, have been previously discussed [1]. A portion of this discussion will be repeated here. The ^{8}B beam was produced via the *TwinSol* radioactive ion beam facility [5], using the $^{6}\mathrm{Li}(^{3}\mathrm{He},n)^{8}\mathrm{B}$ direct-transfer reaction. A 2.5-cm-long gas target containing 1 atm of ^{3}He, was bombarded by a high-intensity (up to 300 particle-nA), nanosecond-bunched primary ^{6}Li beam at an energy of 36 MeV. The entrance and exit windows of the gas cell were 2.0-μm Havar foils. The secondary beam was selected and transported through the solenoids, and then focused onto a 924-$\mu\mathrm{g/cm}^2$ thick, isotopically enriched ^{58}Ni secondary target. The laboratory energy of the ^{8}B beam at the center of this target was 25.75 MeV, with an overall resolution of 0.75-MeV full width at half maximum (FWHM) and an average intensity of 2.5×10^{4} particles per second. The beam had a maximum angular divergence of $\pm4°$ and a spot size of 4-mm FWHM. Pulse-pile-up tagging with a resolving time of 50 ns was used to eliminate pile-up events. The ^{8}B breakup events, and also elastically-scattered particles, were detected with two telescopes consisting of 25- and 30-μm Si ΔE detectors, backed by thick Si E detectors. These were placed on either side of the beam at $\Theta_{\mathrm{lab}}=20°$, 30°, 40°, 45°, 50°, and 60°. Each telescope had a circular collimator that subtended a solid angle of 41 msr, corresponding to an overall effective angular resolution of 10.9° (FWHM), computed by folding in the acceptance of the collimator with the spot size and angular divergence of the beam. Unambiguous separation of the ^{7}Be fragments resulting from ^{8}B breakup from ^{7}Be contamination in the direct beam elastically scattered by the ^{58}Ni target was achieved using time-of-flight (TOF) techniques. The TOF of the particles was obtained from the time difference between the occurrence of an E signal in a telescope and the radio frequency timing pulse from the beam buncher. The time resolution of better than 3 ns (FWHM) was adequate to separate ^{7}Be from ^{8}B.

The number of ^{8}B ions per integrated charge of the primary beam was determined in a separate run by placing a telescope directly into the secondary beam after reducing the primary beam current by three orders of magnitude. The differential cross sections were normalized using the information on solid angle, target thickness, and integrated charge

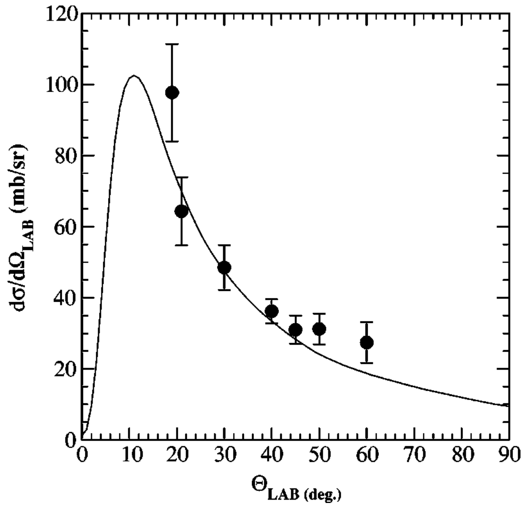

FIG. 1. Experimental angular distribution for ^{8}B breakup as a function of the laboratory angle of the outgoing ^{7}Be fragment. The data are compared with the calculations given in Ref. [4].

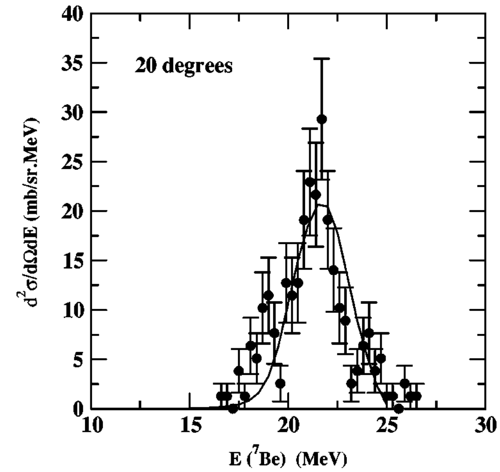

FIG. 2. Experimental energy distribution for ^{7}Be from ^{8}B breakup at a laboratory observation angle of 20°. The data are compared with the calculations given in Ref. [4].

for each run, and verified by a measurement of ^{8}B elastic scattering that is expected to be purely Rutherford at forward angles. The systematic error in the absolute normalization is about 10% because of the uncertainty in the intensity of the secondary beam. The ^{8}B beam had a 1° angular offset from the center axis set for the telescopes. This shift, evaluated by analyzing the observed asymmetry in the elastic scattering of ^{8}B, had a strong effect on the differential cross section at forward angles. Thus, at the most-forward angle setting of the telescopes, we computed the differential cross sections obtained at $\Theta_{\rm lab}=19°$ and 21° separately. At backward angles, where the cross section does not change rapidly with angle, we have taken the average of the yield measured in the two telescopes.

The experimental angular distribution (Fig. 1) is the same as that given in Ref. [1], but in the laboratory frame. Comparison is made with the theoretical calculation of Ref. [4]. It can be seen that the agreement is excellent, in support of the conclusions of Ref. [1]. The description is much better than that shown in our previous work, due in part to the effects of a third-order term in the multipole expansion of the ^{7}Be core and valence-proton interactions with the target. This $q=3$ term is important at large angles; higher-multipole terms have, however, been shown to be negligible [4]. We have previously suggested [1] that the discrepancy between theory and experiment at large angles was because of the neglect of nucleon transfer from the projectile to the target in the breakup calculations. This discrepancy is much reduced in the comparison shown in Fig. 1. On the other hand, a truly consistent three-body calculation will include most or all of the transfer yield in the multipole expansion of the projectile-target interaction.

An energy distribution for the outgoing ^{7}Be fragment, observed at a laboratory angle of 20°, is illustrated in Fig. 2. (This is actually the average of the distributions at 19° and 21°.) The agreement between theory and experiment, both as to the centroid and width of the distribution, is very good. These quantities, as well as the overall shape of the distribution, have been shown to be very sensitive to interference between $E1$ transitions to even partial waves and $E2$ transitions to odd partial waves. However, the higher-order couplings induce an almost complete suppression of what would otherwise be a very large $E2/E1$ interference asymmetry in the energy distribution, producing the almost perfectly symmetric result shown in Fig. 2. See Ref. [4] for a complete discussion of these very interesting effects.

Upon close inspection, it appears that there may be structure in the data that is not reproduced by the theory. In particular, the distribution seems to consist of three peaks; two of which are nearly symmetrically placed about a central maximum. Such a structure could be due to resolved longitudinal vs transverse decay of the excited projectile. The former produces an energy shift in the recoiling residue that is positive or negative depending on the direction of the proton. The latter produces only an angular deviation. However, the distributions at other angles (Fig. 3) do not show this effect, though there is weak evidence for structure in some of them. Another possibility (though perhaps remote) is proton transfer to high-lying states in ^{59}Cu, well above the proton separation energy. Since this is a two-body reaction, it would display a unique-energy peak that shifts according to the appropriate kinematics. In fact, the lowest-energy group in

TABLE I. Experimental energy shift (ΔE_{exp}), and the shift in the calculation of Ref. [4] (ΔE_{theor}), compared with the Coulomb post-acceleration (ΔE_{coul}) computed at the distance of closest approach ρ along the orbit for a particular laboratory scattering angle.

$\Theta_{\rm lab}$ (deg)	ρ (fm)	ΔE_{coul} (MeV)	ΔE_{theor} (MeV)	ΔE_{exp} (MeV)
20	27	0.56	0.57	0.60 (0.34)
30	20	0.77	0.98	1.32 (0.35)
40	16	0.94	1.37	1.30 (0.25)
45	15	1.02	1.57	0.64 (0.30)
55	13	1.15	1.62	1.34 (0.25)

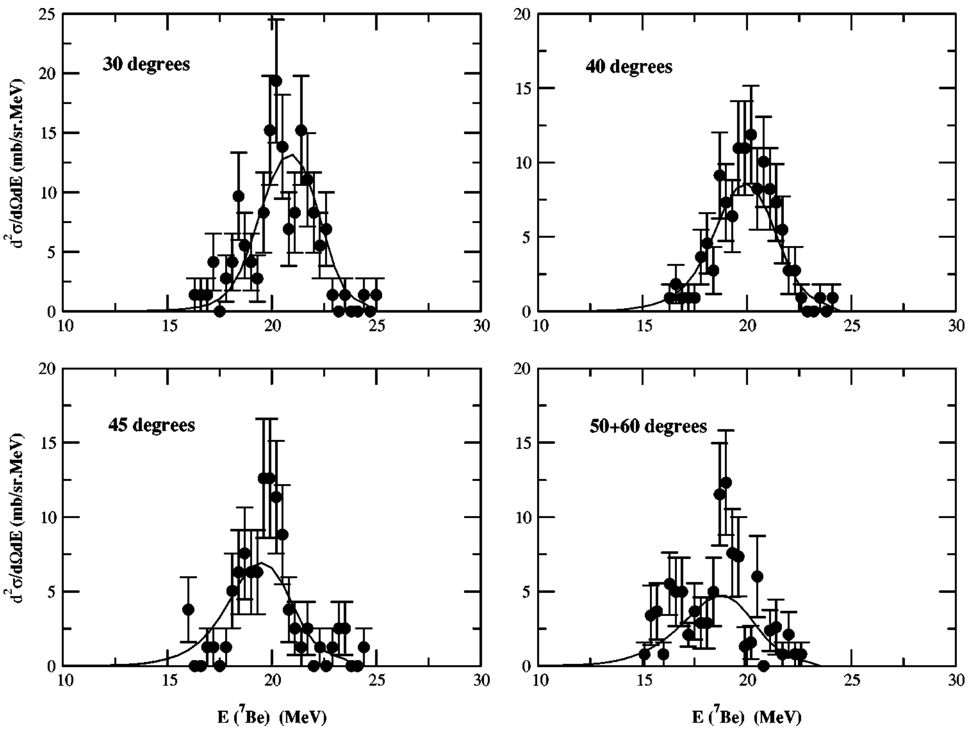

FIG. 3. Experimental energy distributions for ^{7}Be from ^{8}B breakup at the indicated laboratory observation angles. The data are compared with the calculations given in Ref. [4].

Fig. 2 can be traced in this way (but with low statistical accuracy) through the distributions in Fig. 3. It is, however, clearly premature to speculate on the interpretation of these peaks based only on the current experimental data.

Another interesting feature of the data is the shift in the centroids of all the distributions (Table I) from 7/8 of the energy for ^{8}B elastic scattering at a given angle. This shift is usually discussed in terms of postacceleration of the fragment in the Coulomb field of the target [6], which reduces the asymptotic ^{7}Be energy if the reaction occurs in the vicinity of the ^{58}Ni. Interpreted in this way, the data are consistent with the maximum expected Coulomb acceleration, suggesting a time scale for the breakup process that is of the order of the collision time of about 100 fm/c. It should be noted, however, that the energy shifts from the theoretical calculation [4] are greater than the Coulomb shifts, except at the smallest angle where the effect of the nuclear force is small. At this angle, the agreement between the experimental shift and both calculations is excellent.

In summary, we have presented angular and energy distributions for sub-Coulomb breakup of ^{8}B on a ^{58}Ni target. The data have been compared with coupled-channels calculations due to Tostevin, Nunes, and Thompson [4], and the agreement is found to be excellent. This agreement supports the claims made in our earlier Letter [1]. The energy distributions contain a wealth of information regarding the influence of higher-order interference effects on the reaction mechanism, which is discussed in detail in Ref. [4].

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