Breakup of ^{11}Be: Prompt or Delayed?

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The disintegration of a secondary beam of ^{11}Be has been studied in the Coulomb plus nuclear field of Au and Be targets. The vector momentum (longitudinal and transverse components) was measured with a magnetic spectrograph with sufficient precision to detect previously reported differences in the velocity of the ^{10}Be fragments and the incident beam. Coincident γ rays, detected by an array of BaF_2 scintillators surrounding the target, were used to identify events in which the target was simultaneously excited. No evidence for the previously suggested velocity difference was observed. [S0031-9007(98)06500-4]

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In the past decade there has been much interest in nuclei near the proton and neutron drip lines that have anomalous large matter radii in their ground state, the so-called "halo" systems. The matter distribution in these nuclei can be viewed as a tightly bound core with the remaining loosely bound nucleon's wave functions extending to a much larger radius, considerably beyond the extent of the nuclear potential. The low density region occupied by the valence nucleons can be considered as a new form of nuclear matter, whose properties have stimulated a great deal of theoretical and experimental interest, including the study of unusual new modes of excitation [1].

As an example, the significant difference in the radial wave functions for neutrons and protons in such systems can induce low energy dipole strength, which would be suppressed in normal systems. Millener *et al.* [2] used this argument to explain the very strong $E1$ transition observed between the ground and first excited state of ^{11}Be. Hansen and Jonson [3] later applied this idea to the dissociation of halo systems in the Coulomb and/or nuclear field of a target, suggesting that breakup could follow a dipole transition to the continuum. The dissociation could either involve a resonant intermediate state or proceed directly to the continuum. In both cases, the presence of significant low-lying $E1$ strength is important, but the two mechanisms have potentially different predictions for the time dependence of the breakup process.

The time scale of these reactions can be probed directly by measuring the change in electrostatic potential energy as the projectile and fragment move along their trajectories with known velocities. At one extreme, breakup is at the distance of closest approach and results in a final fragment velocity greater than that of the beam: the lighter fragment is accelerated more on the way out than the projectile was decelerated on the way in. This phenomenon is often referred to as "postacceleration," or "reacceleration." In contrast, if the breakup occurs long after the fragment has left the strong Coulomb field near the target, the deceleration and acceleration are the same, and the fragment velocity is the equal to that of the beam.

Despite an intense level of theoretical and experimental interest, a definitive understanding of the postacceleration phenomenon has yet to emerge. On the theoretical side, numerous papers have argued that reacceleration effects should be small; this point of view is, for example, advanced as a "general consensus from a theoretical point of view" by Anne *et al.* [4]. The basic argument is that the collision time is much less than the characteristic time for disintegration of the halo; this latter time should be related to the frequency of relative motion between the neutron(s) and the core. Because this frequency approaches zero with the binding energy (think of the motion in the ground state of a square well potential) a halo system would be expected to have a relatively long response time to the impulse delivered by the Coulomb force as it moves past the target. The validity of this quasiclassical argument has been questioned in a recent paper by Esbensen, Bertsch, and Bertulani [13] who, in a three-dimensional quantum mechanical calculation, find a magnitude for the reacceleration effect "similar to the classical value assuming instantaneous breakup at the distance of closest approach."

On the experimental side, the available sparse evidence appears to favor the instantaneous breakup picture. For

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example, the pioneering Michigan State University experiments [6,7] on the breakup of ^{11}Li observed a clear difference from zero in the final relative velocity of the ^{9}Li fragment and the two neutrons. Attempts to correlate the observed effect with a time scale inferred from the width in energy of the peak in the cross section were unsuccessful. More recent calculations [8] have shown that resonant states in such loosely bound systems would have a shorter lifetime than one would naively expect from the width of the dipole strength. A fundamental problem in exploring the ^{11}Li system is the three body nature of the final state: the theoretical analyses of the breakup mechanism for the most part make the (drastic) simplifying assumption of treating the two neutrons as a point dineutron. This would seem problematic, as experimental searches for the neutron-neutron correlations required by such a picture have been unsuccessful [9].

This latter problem can be addressed by focusing on the simpler system ^{11}Be, which is characterized by a single halo neutron weakly bound ($S_n = 0.504$ MeV) to a ^{10}Be core, as a model system, thereby removing complications from interactions among the halo neutrons. Accordingly, the recent report [10] of a significant reacceleration effect in the breakup of ^{11}Be on a Pb target has generated much interest [8,11–5]. In this experiment, a clear dependence on scattering angle of the longitudinal momentum of the ^{10}Be was observed. Because of the connection between scattering angle and the classical impact parameter for the assumed motion along a Rutherford trajectory, varying the angle of observation changes the electrostatic potential energy at the distance of closest approach. The resulting dependence of momentum on angle was found to agree with the classical calculation of Baur, Bertulani, and Kalassa [14], while contradicting the time-dependent, three-dimensional Schrödinger calculation of Kido, Yabana, and Suzuki [11]. Because of systematic uncertainties in the absolute momentum calibration of their spectrograph, Nakamura *et al.* [10] could not state whether the ^{10}Be fragments showed an absolute shift of velocity. Likewise, the measurements of the neutron momentum distribution from the fragmentation of ^{11}Be in Ref. [4] are not sufficiently precise to add anything regarding the reacceleration effect.

Subsequent theoretical attempts to account for these interesting observations have met with only partial success. For example, Kido *et al.* [12] have appealed to the spin dependence of the force binding the halo neutron to the core. Their calculation is able to account for approximately half of the velocity difference reported in Ref. [10]. Because of the theoretical debate surrounding these results, it seemed essential to verify the experimental result of Nakamura *et al.*

The present experiment was designed to measure the momentum of the ^{10}Be core from the dissociation of ^{11}Be with sufficient precision to verify the previously reported postacceleration effect. The magnetic spectrograph facilitated the high-precision momentum measurement at four angles between 0° and 5°. Because of the present interest in relatively small higher order effects, the experiment was designed to minimize uncertainties in the reaction mechanism. To this end, we surrounded the target with a high-efficiency array of eight BaF_2 γ-ray detectors. These tag events in which the halo neutron is captured by the target, resulting in a cascade of γ rays.

The measured efficiency of the array for γ rays of energy about 1 MeV was 70%. Because typical heavy ion reactions at this energy have γ-ray multiplicity on the order of 10 [15], the detector array can identify such events quite reliably. On heavy targets, for example, removing these events from the data permits a more effective focus on the dominant Coulomb excitation mechanism.

A beam of 41.71 MeV/nucleon ^{11}Be ions with an intensity of 3×10^4 pps was obtained by fragmentation of a ^{13}C primary beam from the K800 cyclotron and separated by the A1200 Projectile Fragment Separator at the National Superconducting Cyclotron Laboratory. The energy spread in the beam was approximately 2%. The number of incident particles was measured using a thin scintillator upstream of the final bend in the beam line, which also provided time of flight information. Transmission calibration measurements were made by replacing the target with another plastic scintillator and measuring the fraction of particles that reached the target position. Background measurements made both with the target ladder fully retracted and with empty target frames indicated negligible events from sources other than the target. The two targets used were gold and beryllium, chosen to have a thickness corresponding to an energy loss of 10 MeV.

We illustrate the importance of the γ-ray tag for obtaining a momentum distribution characterized by a single reaction mechanism in Fig. 1. This exhibits the cross section as a function of transverse momentum for the

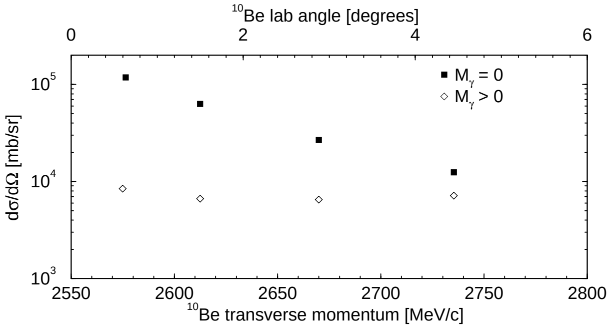

FIG. 1. Angular distribution of the ^{10}Be fragments from the breakup of ^{11}Be on a Au target without (solid squares) and with (open diamonds) the coincident detection of one or more γ rays. The much flatter angular distribution for the latter suggests that they originate from nuclear as opposed to Coulomb excitation.

^{10}Be fragments from the breakup of ^{11}Be on a Au target separately for the events with and without accompanying γ rays. The falloff with transverse momentum over the range studied differs by approximately a factor of 10 for the two types of events. At the largest angle measured, the events with γ rays constitute an appreciable fraction of the total. The condition that no γ rays be present was placed on all of the momentum spectra used in the analysis presented below.

A principal goal of the measurements was to make a precise determination of the fragment momentum as a function of scattering angle. Thus, the spectrograph magnetic field was kept constant, and the ^{10}Be core momentum spectrum of each target at each angle was measured in sequence. Only then was the field changed (including recycling to minimize hysteresis) to accept the more rigid ^{11}Be quasielastically scattered beam in order to measure the difference between the fragment and beam velocity. The same sequence of measurements was then repeated for the ^{11}Be beam.

The S320 focal plane detectors used in this experiment consisted of two wire detectors and a stopping plastic scintillator, which provided the trigger, the timing stop signal, and a full energy measurement used in particle identification. We measured the flight time of the projectile from the upstream thin scintillator to the target combined with the flight time of the fragment from the target to the focal plane. This measurement permitted rejection of background events associated with contamination of the beam, resulting in very clean spectra. The wire detectors provided the precision measurement of the momentum. Calibration of the S320 was performed by scanning a fixed energy beam across the focal plane by changing the S320 settings. Confirmation was provided by measuring the position of different energy beams from the A1200 across the focal plane with a fixed S320 setting. The two methods of calibration differed by approximately 1.5 MeV/c, varying slowly with position along the focal plane. This difference is attributed to differential hysteresis resulting from changing the spectrograph magnetic field. Further evidence of this problem is the fact that an attempt to repeat a point immediately following the first calibration, including recycling the magnetic field, showed an even bigger change (4 MeV/c). We conclude that the absolute momentum is determined by these measurements with an uncertainty of approximately 4 MeV/c.

To obtain an independent estimate of the sensitivity of the apparatus to small changes in momentum as a function of angle, the elastic scattering of ^{11}Be was compared for Be and Au targets. The energy resolution was not sufficient to rule out inelastic scattering to low-lying bound states of the target, but at the very forward angles measured in this experiment, elastic scattering is expected to dominate the data. The results are shown in Fig. 2. The data without γ rays were used, providing an additional method for rejecting the contribution of inelastic scattering within the energy uncertainty of the measurement. The average momentum at each angle was determined by fitting the peak to a Gaussian and/or by calculating the numerical centroid of the data. No background was subtracted. When the numerical centroids were used, a lower momentum cutoff was applied to exclude a continuum of inelastic events; this was only a problem at the largest scattering angles. The solid curves are the predictions of two-body kinematics. The data show the expected larger kinematic shift with angle for the Be target compared to Au. No direct estimate of the momentum uncertainty is available for measurements where the magnetic field is kept fixed and the physical angle of the spectrograph is varied. The error bars shown in Fig. 2 were then estimated from the dispersion of the data from the kinematic curves. The same estimated errors were then used for the measurements of the fragment momenta (see below).

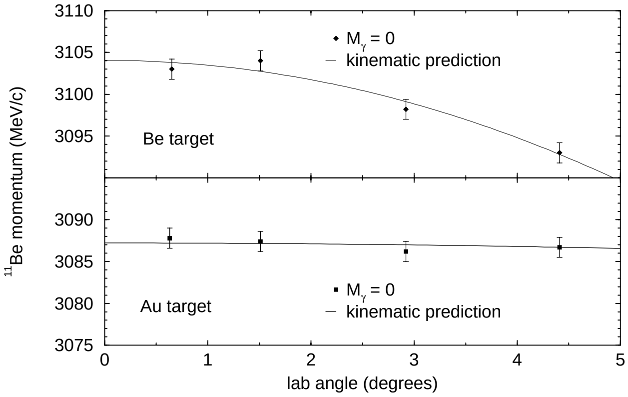

FIG. 2. Average momenta as a function of scattering angle for quasielastic scattering of ^{11}Be on targets of Be (top) and Au (bottom). The solid curves are the predictions of two-body kinematics for elastic scattering.

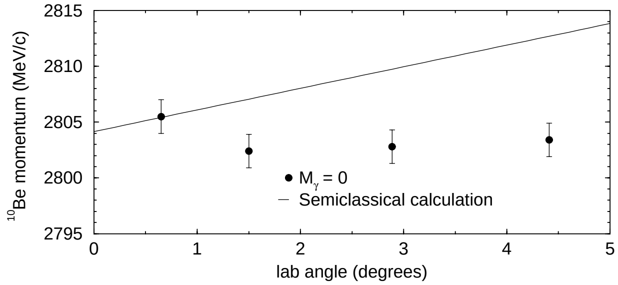

FIG. 3. Average momenta of ^{10}Be fragments from breakup on a gold target as a function of scattering angle. The solid curve corresponds to the shift observed in Ref. [10] recalculated for the lower bombarding energy of the present study.

Figure 3 shows the momenta measured for the ^{10}Be fragments for the Au target, obtained by fitting a Gaussian to the observed fragment momentum spectra. The solid curve is a prediction as in Fig. 2 of Ref. [10] but adapted to the present lower bombarding energy. These data do not support the results found in Ref. [10], and are, in fact,

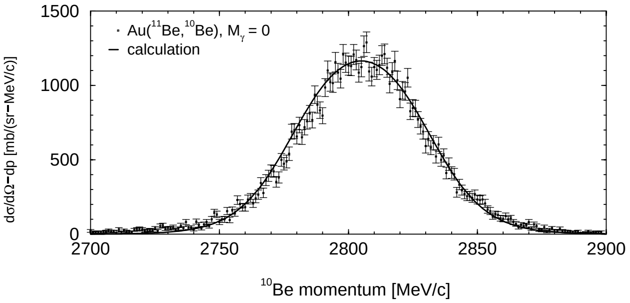

FIG. 4. Comparison of the ^{10}Be momentum distribution observed in the range from 0° to 0.88° on a Au target. The solid curve is the prediction of the simple Coulomb excitation of Ref. [4] [Eq. (5), p. 135], folded with the measured incoherent broadening from the finite width of the beam and straggling in the target.

consistent with a constant longitudinal momentum as a function of scattering angle over the range measured. As was found in Ref. [10] and noted above, the uncertainty in the absolute value of the fragment momentum is considerably larger than the uncertainty in its variation as a function of angle. Comparison of the ^{11}Be (projectile) and ^{10}Be (core) momenta (Figs. 2 and 3) from breakup on the Au target gives a difference between the momentum of the ^{10}Be fragments and $(10/11)$ of the momentum of the ^{11}Be beam of 0 ± 4 MeV$/c$. This is consistent with no change in velocity within the estimated uncertainty.

Finally, we can compare the observed longitudinal momentum distribution on the Au target with the predictions of a calculation based on Coulomb excitation. The calculated differential cross section in the center of mass was taken from the zero-range approximation in Anne *et al.* [Eq. (5)] [4] and has been normalized to the data. The combined effect of the energy spread of the incident beam and energy straggling of the beam and fragment in the target was estimated by examining the elastic scattering peak at angles near zero degrees. The total incoherent spread deduced from the FWHM of this peak was parametrized as a triangular distribution with the same FWHM and folded with the theoretical spectrum predicted in [4] suitably averaged over the finite acceptance of the spectrograph. We make the comparison at zero degrees: here the classical impact parameter is the largest and, consequently, the distorting effects on the particle trajectories of the Coulomb field of the target are the smallest. The observed and calculated distributions are compared in Fig. 4; the agreement is very good. We emphasize that the agreement deteriorates badly at larger angles, where the predicted distributions are systematically much wider than the observed ones. The distortion includes the effects of the Coulomb field on the particle motion before and after the breakup. Further investigation of these and other effects is presently under way.

In conclusion, precision measurements of the ^{10}Be fragment momenta as a function of scattering angle following the breakup of ^{11}Be at a beam energy of 41 MeV$/$nucleon show no evidence for a previously reported reacceleration effect. Our data for this simple two-body system are therefore consistent with the breakup taking place on a time scale long compared to the collision time.

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