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Coulomb excitation of the one-neutron halo nucleus ^{11}Be

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An exotic beam of ^{11}Be at 57–60 MeV/nucleon has been used for a study of the excitation cross section of the 320 keV first excited state in collisions with targets of Pb, Au, C, and Be. The deexcitation γ rays were observed in an array of position-sensitive NaI(Tl) detectors in coincidence with the scattered fragment. The reduced transition strengths $B(E1)$ extracted for the heavy targets suggest a predominantly electric excitation mechanism. Although the $B(E1)$ value is marginally in agreement with that obtained from the lifetime of the state, the deviation is of the size expected from higher-order Coulomb and nuclear effects. Excitations on the lighter targets have sizable nuclear contributions. [S0556-2813(97)50307-4]

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The nucleus ^{11}Be has only two bound states, the $1/2^+$ ground state and the $1/2^-$ excited state [1,2], both neutron halo states with root-mean-square radii of approximately 7 fm. Millener *et al.* [1], who were the first to realize the special character of this system, measured the lifetime of the excited state with a Doppler-shift technique and found it to be 166(15) fs corresponding to a $B(E1)$ value of 0.116(12) e^2 fm^2. This makes it the fastest known $E1$ transition between bound states in nuclei and suggests ^{11}Be as an attractive test case for Coulomb excitation with a radioactive beam. There is also the possibility that more subtle effects will appear when reduced transition matrix elements from lifetime measurements are compared with the ones deduced from cross sections for inelastic scattering. The Coulomb transition amplitude approaches unity at small impact parameters so that first-order perturbation theory may no longer be valid, and the extended halo wave functions may lead to nuclear excitation even beyond distances normally considered ‘‘safe’’ in Coulomb excitation experiments. However, the first such experiment [3] in which a ^{11}Be beam bombarded a lead target produced an excitation cross section of 191(26) mb at 43 MeV/nucleon, only 40% of the expected value for pure Coulomb excitation at this energy. This reduction is well beyond what could be expected from higher-order effects that are predicted to be on the order of 10–20 % [3–6]. We report here a new experiment in which both heavy and light targets (lead, gold, carbon, and beryllium) were studied in order to obtain additional information on the various contributions to the cross section that scale differently with Z and A. Our measured cross sections for the heavy targets agree with a very recent experiment with a lead target carried out at the same energy by Nakamura *et al.* [7].

An 80 MeV/nucleon ^{18}O beam from the K1200 cyclotron at the National Superconducting Cyclotron Laboratory irradiated a 884 mg/cm^2 target of ^{9}Be located at the mid-acceptance target position of the A1200 fragment separator [8]. The energy spread of the resulting ^{11}Be fragments was limited to ±1% with an aperture and separation of the beam fragments was obtained by placing an achromatic wedge (^{27}Al, 425 mg/cm^2) at the second dispersive image of the

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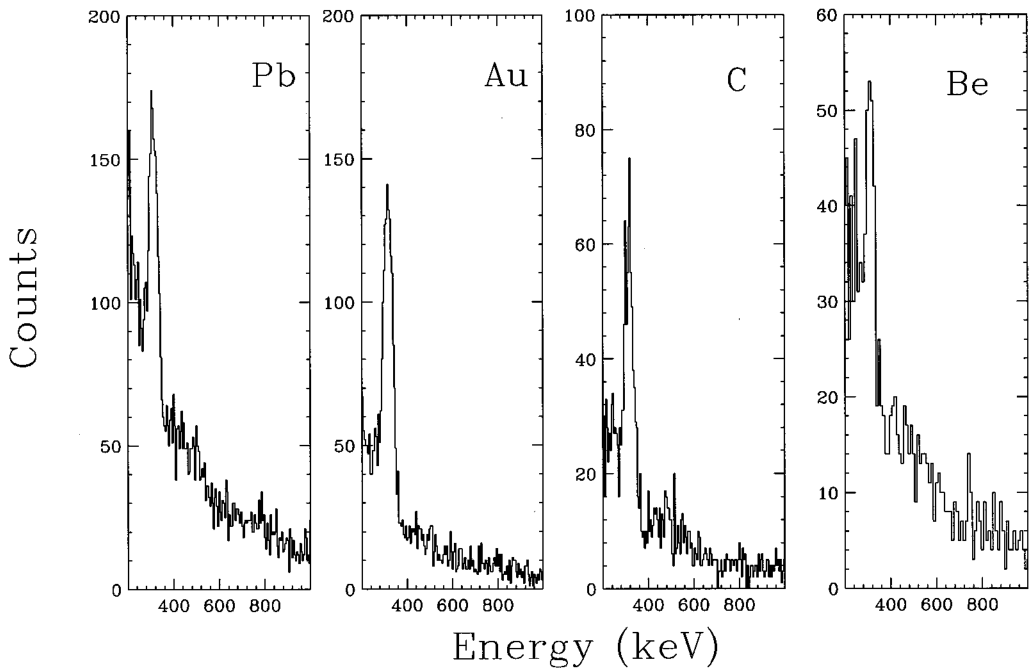

FIG. 1. Gamma energy spectra for 60 MeV/nucleon ^{11}Be beams incident on four different targets. The events have been corrected for the Doppler shift. The 320 keV gamma ray corresponding to the $\frac{1}{2}^- \rightarrow \frac{1}{2}^+$ transition in ^{11}Be is clearly seen in all cases. The bin size for the beryllium target is 10 keV, whereas that for the other spectra is 5 keV.

A1200. Three different fragment species were observed at the focal plane of the A1200, ^{9}Li, ^{11}Be, and ^{13}B with relative intensities of 1%, 20%, and 79%, respectively. The three groups were spatially well separated, and a very pure ^{11}Be secondary beam could have been produced with the moveable slits located at the exit of the A1200 fragment separator. However, the counting rate was not a limiting factor, and the fragment identification was unambiguous allowing us to study two other reactions in parallel. The average energy of the incoming ^{11}Be particles was 59.7 MeV/nucleon. The time-of-flight was measured on an event-by-event basis over the approximately 30 m long flight path from a thin fast plastic scintillator located after the exit of the A1200 to the zero-degree detector. After passing through two x-y position sensitive parallel-plate avalanche counters (PPAC) [9], the beam impinged on the secondary target. The scattered ions then passed through a third x-y position sensitive PPAC before they were stopped in the zero-degree detector, which consisted of a fast-slow plastic phoswich detector. This detector defines a half-cone opening angle of $\theta_{\mathrm{lab}} < 3.8°$. The energy and time resolution in the zero-degree detector allowed an unambiguous isotopic identification of the fragments. The secondary target was surrounded by an array of 38 position sensitive NaI(Tl) detectors arranged in three concentric rings around the target and shielded from background photons by 16.5 cm thick walls of low-background lead. In this series of measurements four different secondary targets [^{208}Pb (80 mg/cm^2), ^{197}Au (533 mg/cm^2), $^{\mathrm{nat}}$C (411 mg/cm^2), ^{9}Be (195 mg/cm^2)] were used to excite the projectiles. A more detailed description of the experimental setup and analysis procedures can be found in Refs. [10–13], which also illustrate the Doppler-shift correction technique.

TABLE I. Measured cross sections for ^{11}Be with a scattering angle of less than 3.8° in the laboratory frame, with statistical and systematic errors, the latter arising mainly from the efficiency calibration and the absorption corrections. The beam energy refers to the midplane of the target.

Target	Thickness [mg/cm^2]	Beam energy [MeV/nucleon]	$\sigma(\theta_{\mathrm{lab}} < 3.8°)$ [mb]	$B(E1)$ [e^2fm^2]
^{208}Pb	80	59.4	$304 \pm 10 \pm 33$	0.094(11)
^{197}Au	533	57.6	$244 \pm 7 \pm 24$	0.079(8)
$^{\mathrm{nat}}$C	411	56.7	$4.0 \pm 0.2 \pm 0.5$	
^{9}Be	195	58.4	$1.7 \pm 0.2 \pm 0.4$	

The Doppler-corrected γ-ray energy spectra, recorded under the condition that a ^{11}Be fragment was detected in the zero degree detector, are shown in Fig. 1. The photopeaks centered around a γ-ray energy of 320 keV in the projectile frame ($\beta \approx 0.34$)—corresponding to the $\frac{1}{2}^- \rightarrow \frac{1}{2}^+$ transition in the ^{11}Be projectile—are clearly visible for all targets. The low energy of the γ ray leads to a substantial absorption in the thick gold target, which was calculated using the absorption coefficients of Ref. [14] taking the energy dependence of the absorption coefficient caused by the Doppler shift into account. The angular distribution is isotropic in the projectile rest frame for a $\frac{1}{2}^- \rightarrow \frac{1}{2}^+$ transition. The calculated transmission probabilities are for the gold target 57%, for the ^{208}Pb target 87%, for the carbon target 84%, and for the beryllium target 92% .

The $\frac{1}{2}^+ \rightarrow \frac{1}{2}^-$ excitation cross sections given in Table I were obtained from the efficiency-corrected gamma-ray yields normalized to the number of beam particles detected in the zero-degree detector. These, in principle, reflect the acceptance of the experiment, but are most likely close to the total cross sections for this channel. Noting that a description in terms of a classical impact parameter is valid at the ener-

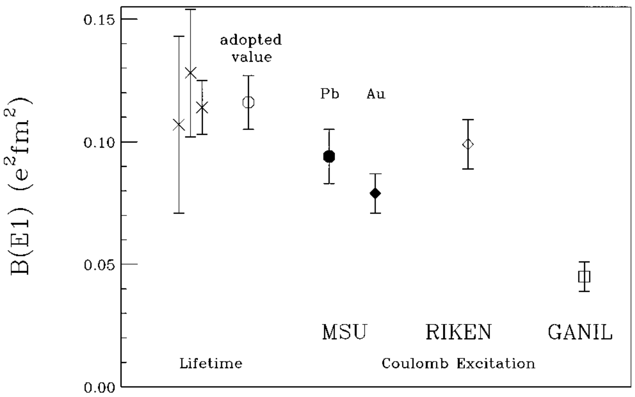

FIG. 2. Comparison of $B(E1)$ values obtained from three measurements of the lifetime of the 320 keV excited state [1,2] and from the three Coulomb excitation experiments carried out at 57–60 (this experiment), 64 MeV/nucleon [7], and 43 MeV/nucleon [3], respectively, from left to right. The solid symbols represent the present data and the error bars include both statistical and systematic errors.

gies discussed here, we find for the two heavy targets (gold and lead) that the Rutherford trajectories correspond to distances of closest approach of approximately 11.5 fm. This distance is about 2 fm larger than the sum of the target—core nuclear interaction radii and hence corresponds to a situation where nuclear contributions are normally considered to be small. (This, of course, is the rationale behind the chosen dimension of the zero-degree detector.) However, since the halo wave function of ^{11}Be extends beyond the nuclear surface with a characteristic decay length of 7 fm, appreciable nuclear contributions are possible. This is *a fortiori* true for the light targets, beryllium and carbon, for which there is no direct selection of the impact parameter and for which scattering through larger angles cannot be excluded directly. We assume in the following that this effect is small because collisions between the light targets and the ^{10}Be core, both fragile systems, will lead to fragmentation at distances smaller than the sum of the two interaction radii.

We discuss the results of Table I by proceeding from the main effects towards the smaller and more uncertain contributions. For the heavy targets (gold and lead) the dominant contribution clearly is Coulomb excitation. The relativistic theory of Winther and Alder [15], leading to the $B(E1)$ values given in Table I, is based on first-order perturbation theory in a semiclassical model which includes a lowest-order correction for the deviation from a straight-line trajectory. This correction amounts to less than 2% of the cross section for the heavy targets, so the calculation should be very reliable. In Fig. 2 the $B(E1)$ values are compared with those from previous measurements of the lifetime [2,1] and of inelastic excitation cross sections [3,7]. Our results confirm the recent RIKEN result and agree, at least marginally, with the lifetime measurements and seem to exclude the small $B(E1)$ value from the GANIL experiment. Below we shall return to the question of whether Coulomb contributions beyond perturbation theory and nuclear interactions might affect the measured cross sections.

The nuclear interaction becomes much more important for the two light targets (beryllium and carbon) as the Coulomb and nuclear contributions scale approximately as Z^2 and $A^{1/3}$, respectively. The $B(E1)$ values found from the heavy target data lead to Coulomb cross sections of 0.9 mb (beryllium) and 1.9 mb (carbon). An estimate of the nuclear cross sections was obtained with an eikonal model similar to that of Ref. [16], which used Woods-Saxon single-particle wave functions to obtain the transition amplitude from the $s_{1/2}$ to the $p_{1/2}$ state. With an additional factor of 0.7 to correct for the single-particle occupancy of the two states, we arrive at an estimate of approximately 2.5 mb for the two nuclear cross sections. (This method is not valid for the heavy targets, which have a diameter much larger than the decay length of the halo wave function.) Thus, with possible interference effects neglected, the total estimates for the excitation cross sections on carbon and beryllium come out to be 3.4 mb and 4.4 mb, respectively, in qualitative agreement with the measured values of 1.7 mb and 4.0 mb.

As an aside one can compare the relative sizes of the Coulomb and nuclear cross sections for excitations to the bound state discussed here with the excitation of ^{11}Be to continuum states of $n+{}^{10}$Be in reactions with a Be target. There (albeit at a slightly different energy of 41 MeV/nucleon) the calculated Coulomb cross section [17] is about 7 mb to the continuum p states and the corresponding nuclear cross section is relatively much larger, about 180 mb in agreement with the experiment [17].

The question is now whether the cross sections for the two heavy targets are influenced by mechanisms other than the first-order Coulomb excitation used for translating the cross sections into the reduced $E1$ transition probability given in Table I. This problem has been considered by several authors [3,4,6] in connection with the GANIL experiment with the small reported cross section at 43 MeV/nucleon [3]. One possible contribution would be higher-order electromagnetic effects that couple the excited state to the continuum. A coupled-channels calculation by Bertulani *et al.* [6] found that this leads to a 4% reduction in the cross section. Another method is to evaluate the transition probability in the sudden approximation, which allows the excitation amplitude to be evaluated to all orders. Comparison of this result with that obtained with the corresponding first-order term gives the magnitudes of the reduction of the cross section, which were found to be 6–11 % by Typel and Baur [4] and 8% by Anne *et al.* [3]. The effects should decrease with increasing beam energy. Nuclear interactions were found to be very small in a model [6] that considered collective monopole and quadrupole excitation modes, but the main effect is presumably the nuclear interaction of the halo with the target, which has a strong dipole component. An evaluation in a model [3] based on the interaction of a black disc with the halo wave function suggested another reduction by 8%. All the estimates are consistent with a 10–20 % reduction in the effective $B(E1)$ value at 43 MeV/nucleon. The higher-order Coulomb corrections are expected to decrease with increasing beam energy.

At the larger energy of this experiment the ratio of the weighted average of $B(E1)$ values from the three Coulomb excitation measurements carried out at the same energy (and leaving out the result of [3]) to the average obtained from the lifetime measurements is 0.77 ± 0.09. Although this is suggestive of a larger reduction in cross section than calculated, the experimental data available are consistent with theoretical predictions. More precise experiments that can differentiate between first-order Coulomb effects and other contributions are required to elucidate the importance of the latter. The results for the light targets help to assess the non-Coulomb contributions to the cross section.

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