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Abstract

In an effort to understand the implications of Coulomb dissociation experiments for the determination of the ^{7}Be(p,γ)^{8}B reaction rate, longitudinal momentum distributions of ^{7}Be fragments produced in the Coulomb dissociation of 44 and 81 MeV/nucleon ^{8}B beams on a Pb target were measured. These distributions are characterized by asymmetries interpreted as the result of interference between E1 and E2 transition amplitudes in the Coulomb breakup. At the lower beam energy, both the asymmetries and the measured cross sections are well reproduced by perturbation theory calculations, allowing a determination of the E2 strength. This measurement yields S_{E2}/S_{E1} =

$6.7\ ^{+2.8}_{-1.9} \times 10^{-4}$ at the 0.63 MeV 1^+ resonance.

25.60.Gc, 26.65.+t, 27.20.+n

The long-standing discrepancy between observed and predicted fluxes of neutrinos from the sun has become known as the solar neutrino problem. All solutions to this problem, including the possibility that solar neutrinos have mass and change (oscillate) into different types of neutrinos to which current detectors are less sensitive [1], rely on accurate predictions of solar neutrino fluxes. The rates of nuclear reactions that produce solar neutrinos should be known well enough that they do not limit the precision of the predicted fluxes. Of all the nuclear reaction rates that influence the flux of high energy solar neutrinos, the rate of the radiative capture reaction $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ is the least well known [2]. It is customary to characterize its energy dependent cross section by a cross section factor $S_{17}(E)$, the value of which at $E \approx 0$ determines the rate of this reaction in the sun. Direct measurements of $S_{17}(0)$ are difficult and have yielded conflicting results [3–9]. A recent analysis of data on $S_{17}(0)$ [2] yielded a recommended value of 19^{+4}_{-2} eV b, a figure too imprecise for a detailed understanding of solar neutrino experiments.

With the hope of providing a more reliable value, or at least a measurement with different systematic errors, $S_{17}(0)$ was measured indirectly at RIKEN by studying the Coulomb dissociation of ^{8}B [10]. The cross section of the reaction $^{208}\mathrm{Pb}(^8\mathrm{B},^7\mathrm{Be}+p)^{208}\mathrm{Pb}$ was obtained as a function of the relative energy of the ^{7}Be and p fragments. In such an experiment, the heavy target nucleus creates a virtual photon field in the rest frame of the incident ^{8}B projectile. Virtual photons with energies greater than or equal to 137.4 keV can dissociate the ^{8}B nucleus into $^7\mathrm{Be} + p$. The principle of detailed balance then gives the radiative capture cross section for photons of a given multipolarity. Thus a Coulomb dissociation measurement provides information about the inverse radiative capture reaction rate. In the future, Coulomb breakup experiments will be an important source of information about nuclear reactions of astrophysical interest inaccessible by other means. Gaining an understanding of the contributions of photons of different multipolarities and their interferences will be crucial in the interpretation of these experiments. To do so for the important $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction is the purpose of this letter.

A considerable controversy arose over the interpretation of the RIKEN data. Although at solar energies the radiative capture reaction proceeds almost exclusively by E1 induced transitions, E2 photons can contribute significantly in the Coulomb dissociation process. The controversy centered on the role of E2 transitions in the RIKEN experiment. It was argued that the E2 contribution was uncertain and could be large [11,12]; the E2 strength is difficult to estimate reliably on theoretical grounds [13]. Two attempts to measure the E2 strength have concluded that it is small [14,15]. However, as we will discuss later, it is not certain that these measurements are free from the effects of background or nuclear induced breakup.

Measurements of the distribution of longitudinal momenta of ^{7}Be fragments resulting from the breakup of ^{8}B on heavy targets provide an independent measurement of E2 strength. First order perturbation theory calculations of the Coulomb dissociation of ^{8}B predict that the distribution of the longitudinal momenta of the emitted ^{7}Be fragments will be asymmetric due to interference between E1 and E2 transition amplitudes [16]. The magnitude of this asymmetry depends on the beam energy, because the ratio of the number of virtual E1 photons to E2 photons increases with beam energy. Hence, an effective way to gauge the strength of E2 transitions in the Coulomb dissociation of ^{8}B is to measure the asymmetry of the longitudinal momentum distributions of the emitted fragments at different beam energies. A recent study of the longitudinal momentum distribution of ^{7}Be fragments from the Coulomb dissociation of 41 MeV/nucleon ^{8}B on a gold target [17] found an asymmetry of roughly the predicted size, but poor statistics prevented a definitive conclusion.

We used the new S800 spectrometer at the National Superconducting Cyclotron Laboratory (NSCL) to carry out a much improved experiment. The large solid angle ($7^\circ \times 10^\circ$), high resolution, and large momentum acceptance (6%) of the S800 made possible a high precision, high statistics measurement. The beam energies were chosen to be 44 and 81 MeV/nucleon. The lower energy is close to the energies of the earlier experiments of Refs. [10,17].

In this experiment, ^{12}C ions from the K1200 cyclotron at the NSCL bombarded a 1.9 g cm^{-2} Be target and produced ^{8}B nuclei by fragmentation [18]. The A1200 fragment separator [19] purified the secondary ^{8}B beams. A thin plastic scintillator was placed near the exit of the A1200 for time of flight, rate, and transmission measurements. A 300 μm silicon p-i-n diode detector at the target position of the S800 was used to periodically monitor the transmission and composition of the secondary beams.

^{8}B nuclei were dissociated in a 28 mg cm^{-2} Pb target. The spectrometer was set at 0° to detect ^{7}Be fragments, and was operated in a dispersion matched mode, so that the momentum spread of the incident beam did not limit the momentum resolution of the spectrometer. The focal plane of the S800 was instrumented with two position sensitive cathode readout drift chambers (CRDCs) [20], a 16 segment ionization chamber, and 3 thick plastic stopping scintillators. Energy loss signals were provided by the ionization chamber, and the first scintillator was the source of total energy signals. Reaction products were unambiguously identified by comparing the energies and energy losses of the detected particles with those of a calibration beam of ^{7}Be having the same rigidity as the ^{8}B beam. The ion optics code COSY INFINITY [21] was used to calculate momenta and scattering angles for each event from the two dimensional position signals provided by each CRDC and the magnetic field settings.

First order perturbation theory calculations of the Coulomb dissociation of ^{8}B on Pb at the energies of this experiment based on the model of Ref. [16] have been performed. The model predicts that $S_{17}(0)$ = 17 eV b, and that $S_{E2}/S_{E1} = 9.5\times10^{-4}$ at the 0.63 MeV 1^+ resonance. This E2 strength is smaller than that of the model of Kim *et al.* [22] by about a factor of 2. The total momentum distribution was calculated for several ^{7}Be scattering angle cuts. Projecting these events on the beam direction yields the calculated longitudinal momentum distribution.

The measured longitudinal momentum distributions of ^{7}Be fragments produced in the Coulomb dissociation of ^{8}B on Pb at 44 MeV/nucleon are shown in Fig. 1 (a) for three different angle cuts. The systematic uncertainties in the measured cross sections are $\pm$ 10% and include contributions from the target thickness, acceptance and CRDC efficiency corrections, and beam intensity, added in quadrature. The predicted longitudinal momentum distributions, convoluted with the experimental resolution of 5 MeV/c, are superposed on the measured distributions. The description of the data with the original model was quite good, but not precise. It would be surprising if a better prediction were obtained a priori. Both the value of $S_{17}(0)$ and the E2 strength are implicit in the structure model used, but are not robust predictions of such models. Different models yield different predictions, as was noted earlier. Since the predicted cross sections depend on $S_{17}(0)$ and the E2 strength, the normalization and E2 strength are effectively free parameters. In addition, there is the 10% systematic uncertainty in the normalization of our cross section measurements. We therefore adjusted the E2 strength and the overall normalization of the model to minimize χ^2 for the central 6 points of the 3.5° distribution. This yields a normalization factor of 1.22 and an E2 strength 0.7 times as large as the original value. The value of $S_{17}(0)$ corresponding to this normalization factor is 21 eV b, well within the limits of the recommendation of Ref. [2]. The value of the ratio S_{E2}/S_{E1} at the 0.63 MeV 1^+ resonance corresponding to this E2 strength is 6.7×10^{-4}, which is consistent with the upper limit of 7×10^{-4} given in Ref. [13]. It is worth noting that the E2 strength was extracted from the present experiment under the assumption of first order perturbation theory. If higher order post-acceleration effects are large, then the E2 strength extracted here is a lower limit. This is because for a given E2 strength, the predicted asymmetry is smaller when higher order effects are included than when they are neglected [16].

Fig. 1 (b) shows the central region of the 44 MeV/nucleon momentum distribution for the 3.5° angle cut. Also shown are three calculations with different E2 strengths, expressed as fractions of the original E2 strength of the model, normalized to the center of the distribution. The dependence of the calculated asymmetry on the E2 strength is apparent.

In order to compare the asymmetries measured in the experiment with those predicted by the model, the slopes of the central regions of the longitudinal momentum distributions were extracted. However, the slopes of the theoretical distributions are proportional to the normalization factor by which the calculation has been multiplied. It is possible to eliminate this dependence on the normalization factor by taking the logarithm of the distributions before extracting a slope. Therefore, straight lines were fitted to the logarithms of the measured and theoretical distributions between 2020 and 2035 MeV/c for the lower energy, and between 2771 and 2791 MeV/c for the higher energy. The results of this comparison are shown in Fig. 2. The calculations at both energies were performed with the same optimal E2 strength described above. At both energies, the experimental slopes decrease more rapidly with angle than the Coulomb dissociation calculation predicts. This is interpreted as the result of nuclear induced breakup at angles approaching the grazing angle, which is 4.4° at the higher beam energy. Nuclear breakup results in a symmetric longitudinal momentum distribution [17]. The calculations presented here do not account for nuclear processes. The systematically smaller slopes at the higher beam energy reflect the lesser relative importance of E2 transitions there.

Fig. 3 depicts a measured longitudinal momentum distribution of ^{7}Be fragments produced in the dissociation of ^{8}B on Pb at 81 MeV/nucleon. Also shown is the prediction of the model with the same optimal E2 strength, again convoluted with the experimental resolution. The agreement between experiment and calculation at this energy is not as good as at 44 MeV/nucleon. The main difference between the prediction of the model and the experimental measurement is the slightly greater width of the measured distribution. It is likely that nuclear stripping (not accounted for by the model) is responsible for broadening the measured distributions. The nuclear stripping cross sections are approximately equal at the two beam energies of this experiment [23], while the Coulomb excitation cross section at a given impact parameter is roughly proportional to the inverse square of the beam velocity. Hence nuclear stripping is relatively more important at 81 MeV/nucleon, and it will probably not be possible to understand the measurement at this energy without including nuclear processes in the calculation. For this reason we utilized only the 44 MeV/nucleon data in extracting the E2 strength.

Good agreement between the observed and predicted shapes of the distributions implies that the shapes of the E1 and E2 responses predicted by the model of Ref. [16] are realistic, requiring only slight adjustments in absolute magnitude. The evident asymmetry of the distributions, characteristic of interference between ℓ=1 and ℓ=2 amplitudes, is therefore interpreted as the result of interference between E1 and E2 transition amplitudes. The asymmetry is observed at scattering angles corresponding to minimum impact parameters greater than 25 fm, indicating that it arises from Coulomb and not nuclear processes.

The momentum distributions measured in this experiment are consistent with the low statistics measurement on the gold target reported in Ref. [17]. However, they apparently contradict the results of two experiments that found the E2 component of the Coulomb dissociation of ^{8}B to be smaller than the theoretical predictions. The experiment of Ref. [15] was designed to determine the E2 contribution to the Coulomb dissociation of ^{8}B by measuring the angular distributions of the emitted fragments. While acknowledging the possibility of large systematic errors [15], the E2 strength obtained was much smaller than all published theoretical predictions. The interpretation of this experiment is complicated by the necessity of extracting the breakup yield from a large background due to reactions in a helium bag located between the target and detector systems. This background, which varies with angle, is considerably larger than the yield from the target. Although the experiment appears to have been done well, the subtraction of this background, particularly from the large angle regime where E2 transitions are important and the yield is small, could be problematic. Nuclear effects at large angles (6-10°) [12] also complicate the extraction of E2 strength.

In the experiment of Ref. [14], ^{7}Be fragments from the breakup of 26 MeV ^{8}B on a nickel target were detected in detector telescopes located at 45° with respect to the beam axis. E2 transitions were expected to account for most of the breakup cross section. The upper limit of the dissociation cross section reported in Ref. [14] is smaller than predictions based on any published model of Coulomb dissociation [24]. Recent theoretical work suggests that nuclear processes may contribute in the dissociation of ^{8}B even at large impact parameters and energies somewhat below the Coulomb barrier [25]. In particular, the authors of Ref. [25] find that at the energy of the experiment of Ref. [14], Coulomb and nuclear amplitudes interfere destructively around 40°. The size of the nuclear amplitude at this angle is comparable to that of the Coulomb amplitude, so that the resulting total cross section is about a factor of 4 smaller than the Coulomb dissociation cross section. Since the measurement of Ref. [14] was made at and near this angle, the measured cross section may not be a good measure of the E2 strength.

In summary, longitudinal momentum distributions of ^{7}Be fragments formed in the Coulomb dissociation of 44 and 81 MeV/nucleon ^{8}B on Pb have been measured with high precision and statistics. At 44 MeV/nucleon, the shapes of the measured distributions and the magnitudes of the measured cross sections agree with the predictions of first order perturbation theory calculations based on a simple potential model description of the structure of ^{8}B. The model predicts that interference between E1 and E2 transition amplitudes will produce observable asymmetries in the longitudinal momentum distributions of the fragments formed in the Coulomb dissociation of ^{8}B at the beam energies investigated in this experiment. These asymmetries were in fact observed. The 81 MeV/nucleon distributions were not as well fit, perhaps because of a significant nuclear component, so the 44 MeV/nucleon distributions alone were used to extract the E2 strength. However, the theoretical slopes based on this E2 strength agree well with the 81 MeV/nucleon data at small angles, where nuclear effects are small. The measured distributions are consistent with a value of 6.7 $^{+2.8}_{-1.9} \times 10^{-4}$ for the ratio S_{E2}/S_{E1} at the 0.63 MeV 1^+ resonance. The calibration of the magnitude of the E1 response of the model made in order to reproduce the measured cross sections implies a value for $S_{17}(0)$ that agrees with the recommendation of Ref. [2]. However, the longitudinal momentum distribution of ^{7}Be fragments is not the most sensitive probe of this quantity. We hope that a careful measurement of the ^{8}B decay energy spectrum at low excitation energies, planned later this year, will allow a more precise determination of $S_{17}(0)$.

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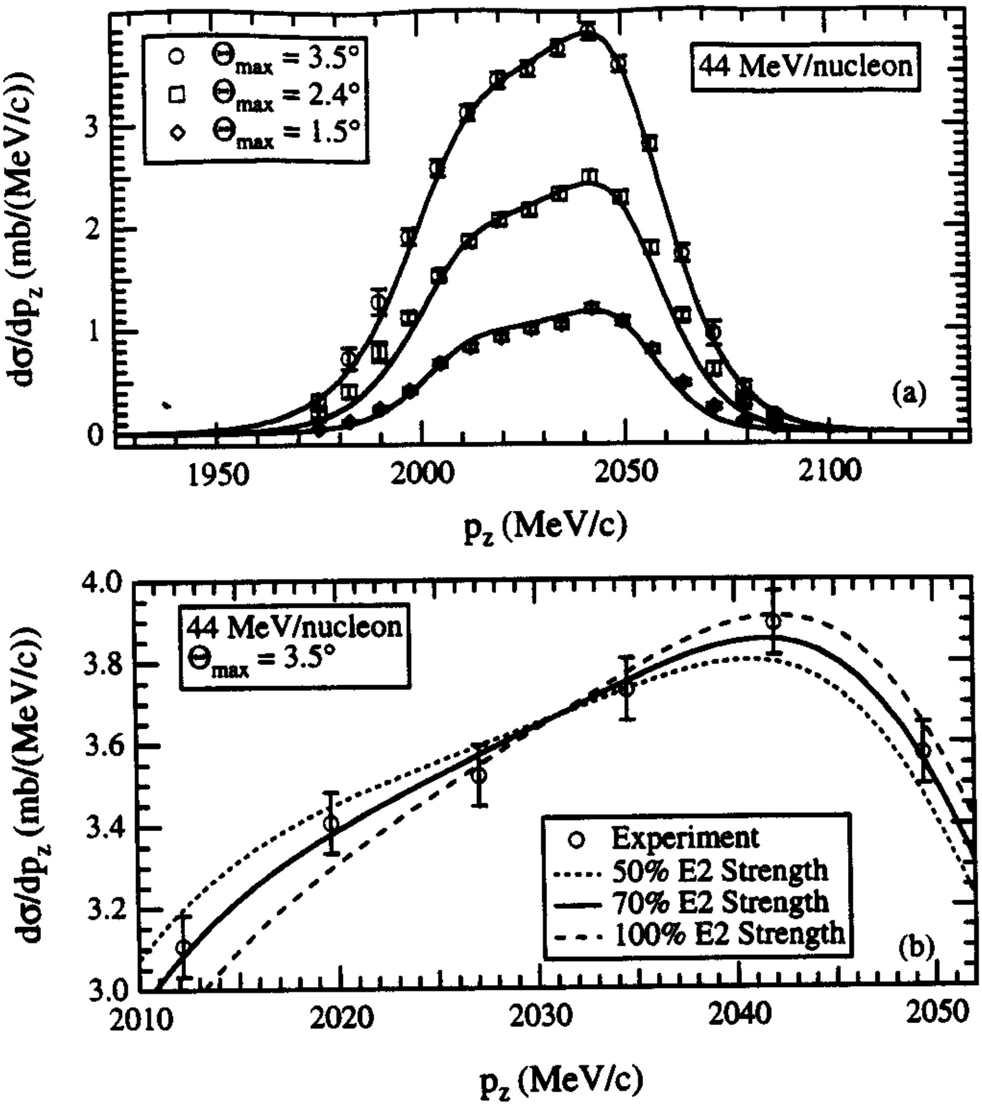
FIGURES

FIG. 1. (a) Laboratory frame longitudinal momentum distributions of ^{7}Be fragments formed in the Coulomb dissociation of 44 MeV/nucleon ^{8}B on Pb with maximum scattering angles of 1.5, 2.4, and 3.5°. The curves are the results of first order perturbation theory calculations convoluted with the experimental resolution of 5 MeV/c. The error bars indicate the relative uncertainties of the data points, which are dominated by statistical errors. (b) Central region of the 3.5° angle cut at the same beam energy. The curves are calculations performed with different E2 strengths, normalized to the center of the distribution.

FIG. 2. Comparison of slopes extracted from the central regions of the logarithms of the measured and theoretical longitudinal momentum distributions plotted versus maximum scattering angle. The agreement between the experimental results and the calculations is good at the smallest angle cuts. Deviations between the experiment and the theory are evident at large scattering angles, suggesting that nuclear breakup becomes important at these angles.

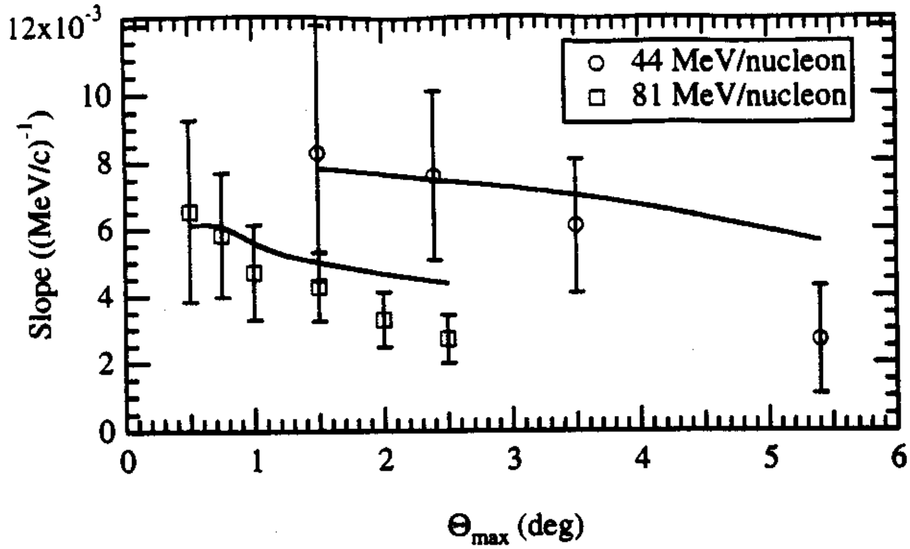
FIG. 3. Measured longitudinal momentum distribution of ^{7}Be fragments with scattering angles less than 1.5° formed in the dissociation of 81 MeV/nucleon ^{8}B, along with the prediction of the model. The slightly greater width of the experimental distribution indicates the presence of a broad component interpreted as the result of nuclear stripping not accounted for in the calculation.

Fig. 1



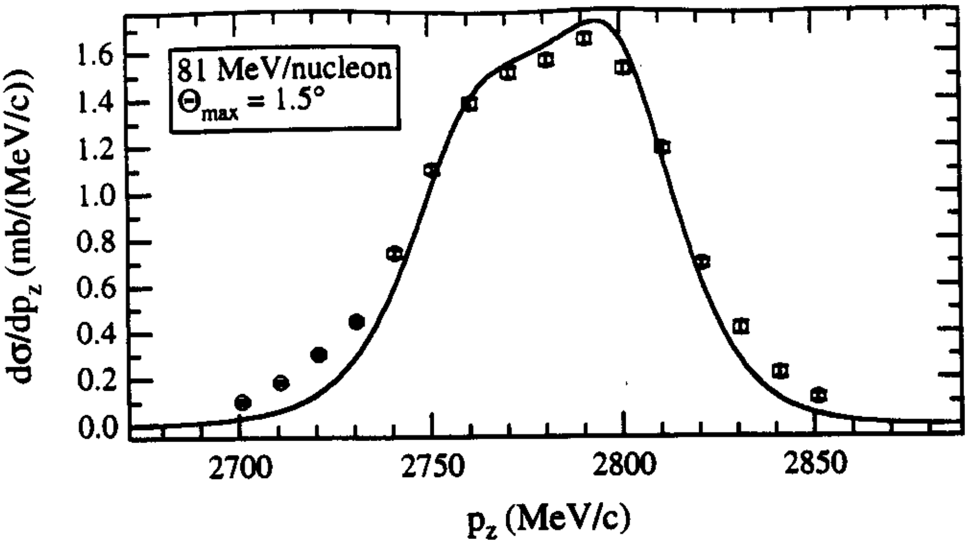
Θmax = 3.5°
Θmax = 2.4°
Θmax = 1.5°
44 MeV/nucleon
(a)
dσ/dpz (mb/(MeV/c))
pz (MeV/c)
44 MeV/nucleon
Θmax = 3.5°
Experiment
50% E2 Strength
70% E2 Strength
100% E2 Strength
(b)
dσ/dpz (mb/(MeV/c))
pz (MeV/c)

Fig. 2



12x10^{-3}
10
8
6
4
2
0
Slope ((MeV/c)$^{-1}$)
0
1
2
3
4
5
6
Θ_{max} (deg)
44 MeV/nucleon
81 MeV/nucleon

Fig. 3



81 MeV/nucleon
Θmax = 1.5°
dσ/dpz (mb/(MeV/c))
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
2700
2750
2800
2850
pz (MeV/c)