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Sub-Coulomb dissociation of ^{8}B

Johannes von Schwarzenberg, J. J. Kolata, D. Peterson, P. Santi, and M. Belbot
Physics Department, University of Notre Dame, Notre Dame, Indiana 46556

J. D. Hinnefeld
Physics Department, Indiana University-South Bend, South Bend, Indiana 46634

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The sub-Coulomb breakup of ^{8}B on a ^{58}Ni target is studied at an incident energy of 26 MeV. These data provide a measure of the $E2$ component of the breakup cross section as a function of the astrophysical factor S_{17} for radiative capture of protons on ^{7}Be. Implications for the solar neutrino problem are discussed. [S0556-2813(96)51006-X]

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In a recent paper [1], Motobayashi *et al.* have presented results on the Coulomb dissociation of ^{8}B on ^{208}Pb. This process, which can be viewed as the absorption of a virtual photon from the Coulomb field of the target, is of special interest for ^{8}B since it can provide an independent probe of ^{7}Be radiative proton capture at low energies. Determination of the cross section for this reaction is essential for the understanding of solar neutrino emission [2]. The data presented in Ref. [1] have generated a considerable amount of interest for two reasons. First of all, the value of S_{17} they imply is appreciably smaller than the value used [3] in deriving the standard solar model (SSM). In fact, their quoted result is smaller than even the lowest value reported from recent direct measurements of the proton capture cross section [4]. Furthermore, there has been considerable controversy about the role played by $E2$ photons in the breakup process. Corrections for $E2$ photon absorption, which is negligible in the capture reaction but possibly important for Coulomb dissociation, have been estimated [5] on the basis of a particular theoretical model [6] to be very important, leading to a further reduction of perhaps 25% in the value of S_{17} at solar energies. Other models [7] lead to smaller corrections so that the theoretical $E2$ contribution is highly model dependent [8]. In fact, the ''best fit'' to the data of Ref. [1] implies little or no $E2$ component [8]. However, a more precise determination of this important process is clearly desirable. The present experiment was designed to measure $E2$ dissociation below the Coulomb barrier, where

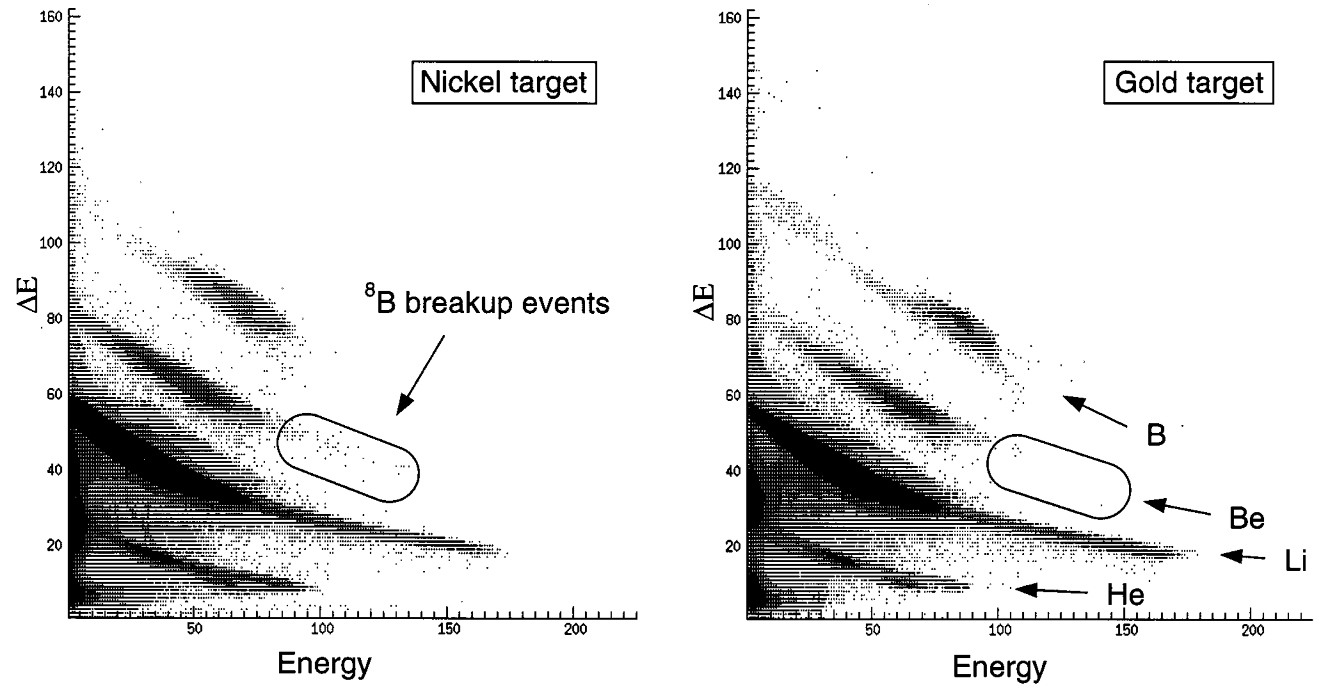

FIG. 1. Plot of ΔE vs E (arb. units) for one of the detector telescopes placed at 45° to the secondary target, illustrating the Z separation obtained in this experiment. An oval is drawn around the region of interest containing the Coulomb breakup events of ^{8}B. Although comparable amounts of elastically scattered ^{8}B were detected with both targets, the number of breakup events obtained with the gold target is significantly lower, as expected from the calculation.

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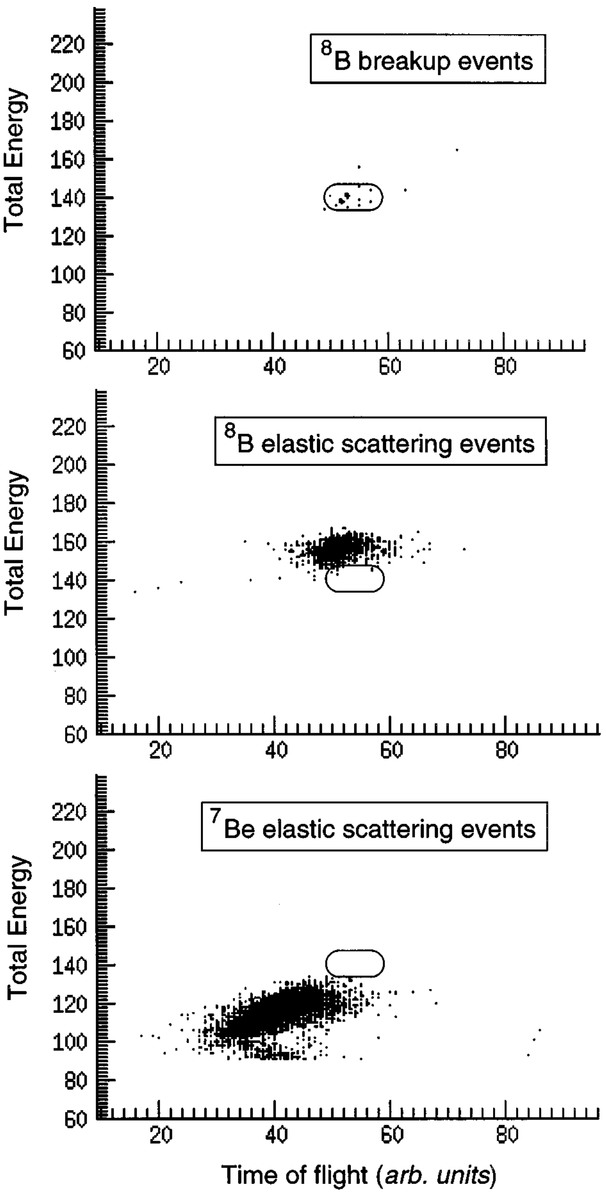

FIG. 2. Mapping of ^{8}B breakup events in the time of flight vs total energy plane (arb. units) after applying a gate on the nuclear charge Z. The breakup events are well separated in energy from the elastically scattered ^{8}B and ^{7}Be. An oval is placed around the region of interest, illustrating that the breakup events have the same timing as the incident ^{8}B beam.

it plays a much more important role than at the considerably higher projectile energies utilized in Ref. [1].

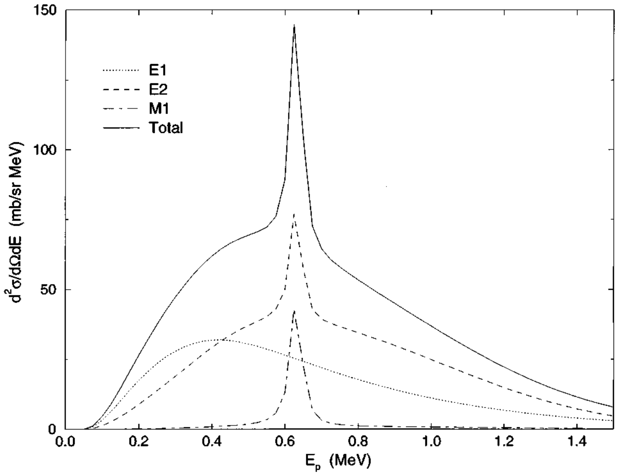

FIG. 3. Double differential cross sections for $E1$, $M1$, and $E2$ breakup of ^{8}B on a ^{58}Ni target, at an incident energy of 25.8 MeV and for a deflection angle of 40° relative to the incident beam. The quantity E_p is the c.m. proton energy. These curves have been calculated in the model of Ref. [6].

A ^{8}B beam of intensity up to 1.5×10^{5} s^{-1} was produced using the Notre Dame-Michigan radioactive nuclear beam (RNB) facility [9]. The primary target was a gas cell containing approximately one atm of ^{3}He; this cell had entrance and exit windows made of 1.5 μm Ni foil. The primary beam was 0.2 particle μA of ^{6}Li at an energy of 36 MeV. The reaction products were collected by a superconducting solenoid [9], which also serves as a momentum analysis system, and focused onto a secondary target of isotopically separated ^{58}Ni that had a thickness of 950 μg/cm^{2}. The energy of the secondary beam at the center of this target was 25.8 MeV, with a spread of 1.0 MeV full width at half maximum (FWHM). The spot size was approximately 5 mm FWHM, and the angular divergence of the beam was $\pm2.5°$. Reaction products were detected in two telescopes consisting of 25 μm Si ΔE counters followed by Si stopping detectors, placed on either side of the beam at an angle of 45°. Each telescope had a circular collimator that subtended a maximum angle of $\pm6°$.

At sub-Coulomb energies, such as used in this work, it is very difficult to carry out a coincidence measurement as was done in the RIKEN experiment [1]. In particular, accurate determination of the coincidence efficiency is problematic. Therefore, we developed an ‘‘integral’’ technique, described in more detail below, which only involves the detection of the ^{7}Be reaction products. These products are well separated in energy from the contaminant ^{7}Be beam that also comes through the solenoid system as illustrated in Fig. 1. However, in order to ensure that there was no ambiguity in the identification of the reaction products, we performed two subsidiary experiments. First of all, we bunched the primary beam with a time spread of approximately 3 ns (FWHM) and measured the time of flight of the secondary beam through the solenoid system. This provides an additional identification of the beam particles, which are expected to have different flight times from the primary to the secondary targets. Figure 2 shows that the timing for the elastically scattered ^{7}Be is very different from the ^{7}Be events that originated from the breakup of ^{8}B. The clean energy separation between the breakup events and the elastically scattered beam allowed us to sacrifice time of flight in favor of higher beam intensities. We also determined a detailed energy profile for the direct ^{7}Be beam by scattering it from a Au target (cf. Fig. 1). In this case, the breakup products are reduced by an order of magnitude relative to the direct beam, and it becomes possible to correct for the small contamination of the signal obtained with the Ni target by careful subtraction of the yields, after correcting for the kinematics and energy-loss differences in the target. Possible contributions to the reaction yield from pulse pileup of the ^{6}Li contaminant in the beam were eliminated by the use of pileup suppression techniques; the ‘‘pulse-pileup’’ events were identified and tagged

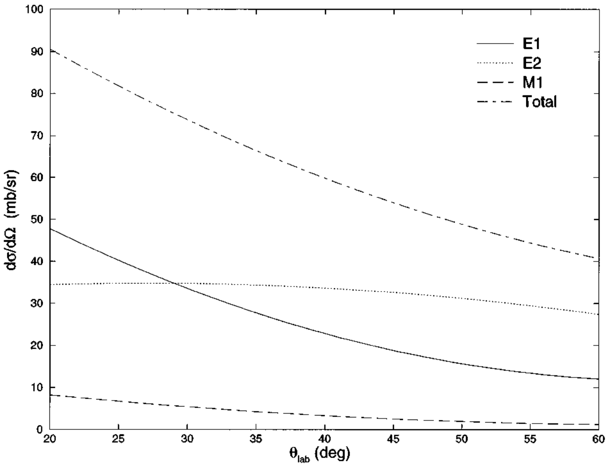

FIG. 4. Angular distributions obtained by integration over the c.m. proton energy, as a function of the deflection angle relative to the incident beam.

for elimination during the analysis of the data. Finally, we note that the experimental method is ''self-calibrating'' in that the reaction yield is determined relative to Rutherford scattering of the ^{8}B beam.

As mentioned above, the experimental method is an integral technique that relies on the detection of only the ^{7}Be reaction products. Therefore, we could not determine the energy dependence of the breakup cross section. The analysis proceeded as follows. We used the formalism of Baur *et al.* [10] to connect the breakup yield to the radiative capture cross section, and the tables of Alder and Winther [11] to compute the virtual photon spectrum. At the energy of this experiment, these semiclassical calculations give excellent predictions for Coulomb excitation as long as one accounts for the differing velocities in the entrance and exit channels [11]. The radiative capture cross sections were taken from the potential-model calculation of Kim *et al.* [6]. The predicted double differential cross sections for $E1$, $E2$, and $M1$ Coulomb dissociation, as a function of the center-of-mass (c.m.) proton energy, are shown in Fig. 3. Note that the $E2$ yield predicted in this model is quite large. It can be seen that the method determines the breakup cross section over the proton energy range from 0 to 1.5 MeV, and that the peak sensitivity is at about 400 keV for $E1$ excitation and 500 keV for E2 excitation. The peak at 633 keV is the 1^+ resonance that dominates the radiative capture experiments (but plays no role at solar energies). The angular distributions for the various multipolarities (integrated over proton energy) are shown in Fig. 4. The $E2$ yield gives the largest contribution to the breakup cross section at 45° in this model, while the $M1$ yield is small but not negligible. The comparison with the experimental data is made by integrating these distributions (as well as the Rutherford scattering of the ^{8}B projectile) over the angular aperture of the detectors. The fact that we placed detectors on both sides of the beam allowed us to determine and correct for small angular offsets that could have an important effect, particularly on the normalization of the data. The experimental value of the breakup-to-elastic scattering ratio determined this way is $(8.1\pm0.8\pm^{2.0}_{0.5})\times10^{-3}$, where the second error bars represent the systematic uncertainty in the extraction of the yield, due to the background of ^{7}Be in the direct beam as discussed above.

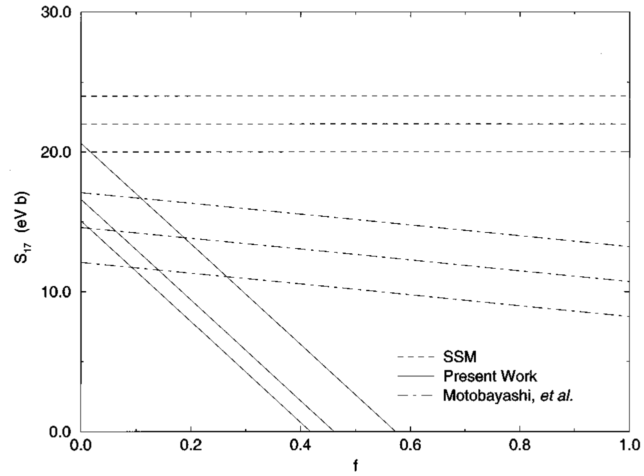

FIG. 5. Plot of the astrophysical S_{17} factor extrapolated to solar energies, as a function of the $E2$ component of the breakup yield, for the present work, the data of Ref. [1], and the standard solar model of Ref. [3]. The error bands are one-standard-deviation limits (including the systematic uncertainty). See text for a further discussion.

The experimental result will now be compared with the calculation. First of all, the predicted ratio using the model of Ref. [6] is nearly 3%. Our data therefore rule out this model as regards the $E2$ prediction, for any value of S_{17}. (The $E1$ and $M1$ predictions have already been shown to be in reasonably good agreement with the radiative capture data in Ref. [6].) Other models predict much smaller $E2$ components, in particular, Typel and Baur [7], Descouvemont and Baye [12], and Nakada and Otsuka [13]. Note, however, that the latter two only discuss the resonant yield to the 1^+ state, while both Kim *et al.* and Typel and Baur predict relatively large nonresonant yields that can have important effects on the extrapolation of the data of Ref. [1] to solar energies. While we do not separately extract the various multipole contributions, the present data can be used to determine the $E2$ contribution (expressed as a fraction f of the prediction using the model of Ref. [6]), as a function of the astrophysical S_{17} factor at solar energies. Such a plot is shown in Fig. 5. The $M1$ contribution is small (only about 10% of the $E1$ yield), and relatively well known from the capture experiments, so we include it with the $E1$ cross section in the analysis. Since we use the model of Ref. [6], the extrapolation of S_{17} to solar energies includes d-wave $E1$ capture, which can contribute up to 10–15% of the extrapolated S factor. Also shown in Fig. 5 is the result of a recent analysis of the data of Ref. [1] by Shyam *et al.* [14] that includes the $M1$ yield and the d-wave extrapolation. The systematic errors due to this model-dependent extrapolation also are discussed in Ref. [14]. It can be seen that our data are marginally consistent with the lowest reported direct measurements of the proton capture cross section [4], for f near zero. A larger $E2$ component is deduced if S_{17} is as small as that from the data of Ref. [1] given in Fig. 5. Taken together, these experiments appear to suggest a reduction of as much as 30% in the value of S_{17} compared with that used in the standard solar model of Ref. [3], in agreement with the recent theoretical analysis of Xu *et al.* [15].

Finally,we should mention that the method employed in this work is also capable of determining a precise value for S_{17}. All that is required is to replace the ^{58}Ni target with a Au target and take data at the same incident energy and angle as in the present experiment. In this case, the $E2$ (and $M1$) components are very small (even in the model of Ref. [6]), and the method is sensitive essentially only to the $E1$ component. Furthermore, the peak sensitivity is at a proton energy of about 250 keV, well below the 1^{+} resonance and in a region where the d-wave contribution to the $E1$ yield is relatively small. At present, this experiment is not practical because the expected signal is an order of magnitude less, relative to the elastic scattering, than in the work reported here, and therefore the signal-to-noise ratio is too small. However, a new RNB facility, soon to be installed at Notre Dame, will allow us to make such a measurement in the near future.

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