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Proton elastic scattering from ^{7}Be at low energies

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The elastic scattering of protons on ^{7}Be has been measured in the energy region from 1–3.3 MeV via the thick-target technique. The data conclusively demonstrate the existence of a 2^- state at an excitation energy of approximately 3.5 MeV in ^{8}B, and rule out a predicted 1^+ state near 1.4 MeV. The relevance of these results for the ^{7}Be (p,γ) reaction, of interest in solar neutrino physics, is discussed.

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The ^{7}Be$(p,\gamma)^8$B reaction plays a very important role in nuclear astrophysics, since it is the source of the high-energy solar neutrinos detected in the Cl neutrino experiment [1]. There have been many measurements of the excitation function for this critical reaction, both direct using a radioactive ^{7}Be target (see Ref. [2] for a comprehensive review of these experiments and Ref. [3] for the most recent result), and indirect via Coulomb dissociation [4–7] of ^{8}B. The astrophysical S factor [8] deduced from the direct experiments is dominated by the narrow 1^+ resonance at 0.63 MeV which plays no role at solar energies (20 keV). However, it is not possible to measure the cross section at 20 keV so one must rely on extrapolations from higher-energy data. After evaluating all the direct measurements, Adelberger *et al.* [2] gave a recommended value of $S_{17}=19^{+4}_{-2}$ eV b at zero energy (1σ error), and stated that further measurements are desirable to reduce the uncertainties below 5% in order to achieve a full understanding of the data from new solar neutrino experiments.

The present work was occasioned by recent experimental [9] and theoretical [10] work relating to the extrapolation of the (p,γ) data to solar energies. Gol'dberg *et al.* [9] report evidence for a broad, s-wave level of ^{8}B at an excitation energy of approximately 3 MeV from a study of proton elastic scattering on ^{7}Be. They suggest 1^- or 2^- for the spin/parity of this level but were unable to give a good account of its width due to the poor statistics in the experiment. Csótó [10] used a microscopic cluster model to predict the existence of a second 1^+ state at low excitation energy which is also broad enough to have important consequences for the $S(0)$ value. We have measured proton elastic scattering from ^{7}Be in the ^{8}B excitation-energy range from 1–3.3 MeV in order to clarify the resonance structure in this important region.

The experiment was carried out using the TwinSol radioactive ion beam (RIB) facility [11]. A 2.5 cm long gas target containing 1 atm of ^{3}He was bombarded by a high-intensity (up to 100 particle-nA), nanosecond-bunched primary ^{10}B beam at an energy of 51.0 MeV. The entrance and exit windows of the gas cell consisted of 2.0 μm Havar foils. The secondary beam was momentum selected and transported through the first of two superconducting solenoids, which focused it onto an 8.0 μm Havar foil. Differential energy loss in this foil allowed for the purification of the beam as it passed through the second solenoid. The laboratory energy of the ^{7}Be beam at the secondary target position was 25.5 MeV, with a resolution of 1.5 MeV full width at half maximum (FWHM) and an intensity of up to 1.0×10^5 particles per second. The energy spread was due to a combination of the kinematic shift in the production reaction plus energy-loss straggling in the gas-cell windows and energy-loss foil. The beam had a maximum angular divergence of $\pm4°$ and a spot size of 5 mm FWHM. Although contaminant ions were still present in the beam, they could be identified 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 detector telescope and the rf timing pulse from the beam buncher. The time resolution of better than 3 ns (FWHM) was adequate to cleanly separate ^{7}Be from all other ions. This is illustrated in Fig. 1, which was obtained with a Si ΔE-E telescope placed directly in the secondary beam, after reducing the primary beam intensity by 3 orders of magnitude. Some of the more important contaminants are indicated. The intensity of the beam during the experiment was determined by relating the number of ^{7}Be ions in this figure to the integrated charge of the primary ^{10}B beam collected in the TwinSol Faraday cup.

The ^{7}Be beam was stopped in a 12.0 mg/cm^2 thick CH_2 target. The recoil protons from back-angle elastic scattering in this target lose only a small amount of energy in traversing the foil, and emerge from it with sufficient energy to be detected. Note that the lowest-energy protons, from the scattering of ^{7}Be ions near the end of their range, encounter the least amount of material before leaving the target. In this

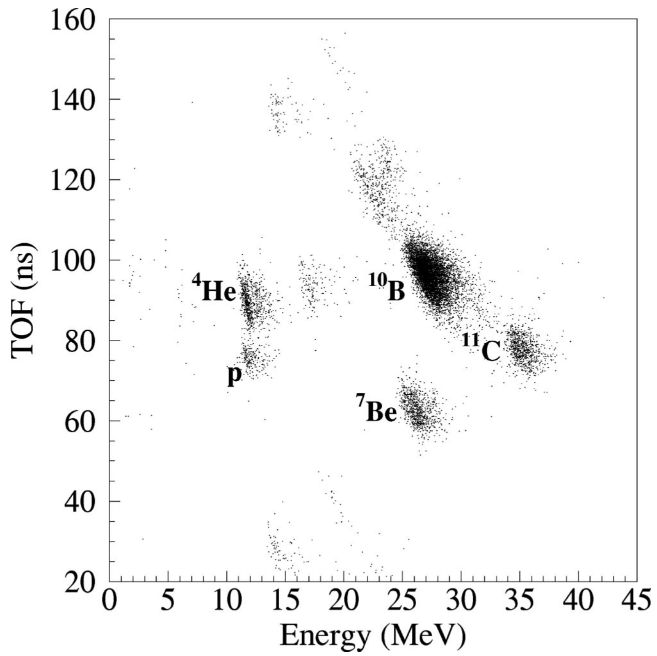

FIG. 1. Time of flight vs energy for the secondary beam, showing the major contaminant groups. Note that ^{7}Be is easily separated by time of flight.

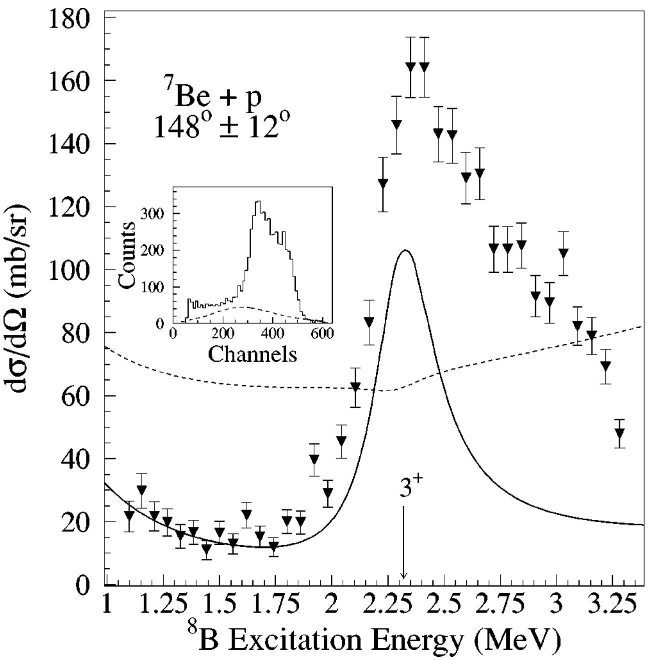

FIG. 2. Excitation function for ^{7}Be$+p$ elastic scattering at a c.m. angle of $148\pm12°$ measured in the present experiment. The data are compared with an *R*-matrix calculation including the well-known 3^+ state at 2.32 MeV. The dashed curve shows an *R*-matrix result when the phase shifts are set to hard-sphere plus Coulomb for all partial waves. See text for a discussion of this calculation.

way, an excitation function for elastic scattering down to very low energies can be measured with high efficiency and good resolution. The recoil protons were detected with two telescopes consisting of 17.8 and 19.2 μm Si ΔE detectors, backed by 1000 μm Si E detectors. The active area of the ΔE detectors was 450 mm^2, and that of the E detectors was 600 mm^2. Each telescope had a circular collimator that subtended a solid angle of 11 msr. They were placed on either side of the beam at $\Theta_{\rm lab}=\pm15°$. It would have been preferable to place a telescope at 0° to the beam, but the light-ion contamination (Fig. 1) produced a count rate in this position that was unacceptable since these ions penetrated the target and directly entered the telescope. It was verified that the recoil proton TOF signal was only slightly shifted in time relative to ^{7}Be and was stable during the course of the experiment, so that the separation from elastic scattering of contaminant ions was excellent. Low-energy protons can also result from fusion of ^{7}Be with C in the target. We measured a spectrum for this process using a thick C target, and subtracted it from that obtained with the CH_2 target. The inset in Fig. 2 shows a raw proton spectrum measured on a CH_2 target plus background (dashed curve) coming from reactions of ^{7}Be on carbon. Finally, inelastic scattering of ^{7}Be on ^{1}H can occur at energies high enough to populate the first excited state of ^{7}Be. However, as discussed below, the cross section for this process is negligible and it will be ignored here.

The cross sections for back-angle proton scattering from ^{7}Be measured in this experiment are shown in Fig. 2, compared with a one-channel *R*-matrix calculation that includes only a single resonance, the well-known 3^+ state in ^{8}B [12]. A one-channel approximation was used since the elastic-channel penetrability factors for the 3^+ state far exceed that of all other channels. The parameters of this state were fixed according to Ref. [12]. The phase shift for the resonance was defined as in [13]:

$$\delta_l=\tan^{-1}[R_lP_l/(1-R_lS_l)]-\phi_l+\omega_l, \tag{1}$$

where $R_l\approx\gamma_{\lambda l}^2/(E_\lambda-E)$, ϕ_l is a hard-sphere scattering phase shift, and ω_l is the Coulomb phase shift. The correct excitation energy and width for the 3^+ state were obtained with $E_\lambda=2.04$ MeV and $\gamma_{\lambda l}=0.59$ MeV$^{1/2}$. (A zero-derivative boundary condition is used.) It was found that the inclusion of the hard-sphere phase shift in the $l=0$ partial wave, with no resonance in this channel, was completely inadequate to reproduce the observed excitation function. Agreement with the data could not be obtained even for excitation energies as low as 1–2 MeV. (The dashed curve in Fig. 2 shows the result of an *R*-matrix calculation with hard-sphere phase shifts included for all partial waves.) For this reason, the phase shifts for all *nonresonant* partial waves were set equal to the Coulomb phase shift ω_l to produce the solid curve in Fig. 2. In all calculations, the channel radius was taken to be 4.3 fm. This value of the channel radius was successfully used by Knox *et al.* [14] in an *R*-matrix analysis of the ^{7}Li$+n$ system. Use of a different channel radius will alter other *R*-matrix parameters, such as $\gamma_{\lambda l}$ and E_λ, but will not change the shape of the curve since the excitation energy and width of the 3^+ resonance are known and must be reproduced by the calculation. Thus, the solid curve in Fig. 2 was obtained with no free parameters. The absolute normalization of the data was determined in the experiment and has

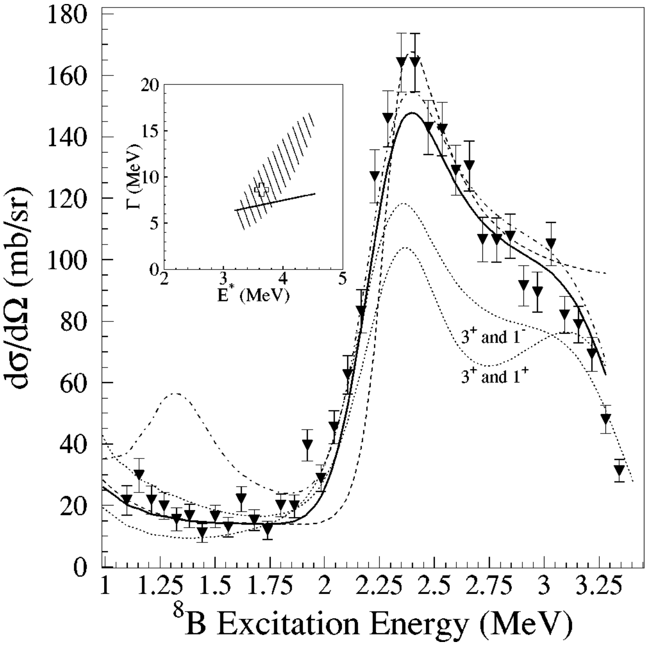

FIG. 3. Elastic data compared with the full *R*-matrix calculation, including the 2^- level at 3.5 MeV. The dashed curve shows the calculation prior to convolution with the experimental response function. The dash-dotted curve shows the comparison with a calculation including a predicted 1^+ state at 1.4 MeV. Dotted curves show the behavior of the excitation function in case of different spin-parity assignments for the new resonance (1^-,1^+). The insert gives a confidence band for the excitation energy and width of the 2^- resonance. The cross indicates the best fit point; the solid line is the Wigner limit for the 2^- state calculated for a channel radius of 4.3 fm.

not been adjusted to improve the fit. It can be seen that, as in the previous work [9], there is clear evidence for a very large amount of additional resonance strength that is not accounted for by the known 3^+ level. Our data are consistent with those of Ref. [9], but the much-improved statistics allow for more definitive conclusions regarding the parameters of the ''missing'' state.

The introduction of a 2^- $(2s)$ state having width greater than 4 MeV and energy about 3.5 MeV produces very good agreement with the data, as shown by the solid curve in Fig. 3. This result was obtained by convolution of the *R*-matrix calculation with an energy-dependent resolution function which includes the effect of energy straggling of ^{7}Be and ^{1}H in the target, the kinematic shift over the aperture of the detector telescope, and the spot size, energy resolution, and angular divergence of the incident beam. This resolution function was computed with Monte Carlo techniques from the known parameters of the experiment. (Note that the dropoff in the measured cross section at energies above 3 MeV is a direct result of the finite energy resolution of the ^{7}Be beam.) The dashed curve shows the unconvoluted *R*-matrix excitation function. The structure at 2–3 MeV is now the result of interference between the 3^+ and 2^- resonances. It is important to note that in this case there has been *no* adjustment of the background phase shifts, which were set equal to the hard sphere plus Coulomb value, nor of the absolute cross section. The only two free parameters are the energy and width of the 2^- state.

Attempts to assign spin-parity 1^- to the new resonance failed due to the fact that a 1^- state has channel spin $s=1$ and does not interfere with the 3^+ state. The elastic-scattering cross section of the presumed 1^- state itself is insufficient to reproduce the observed cross section in the $E_x=2$–3 MeV energy region. We also failed to obtain a good fit with spin-parity 1^+ for the resonance in question since the cross section was too low, even though a 1^+ state could have channel spin $s=2$ and therefore interfere with the 3^+ state. The typical interference pattern for these two states results in a minimum in the cross section, which in our case should be near 2.75 MeV and is not observed in the experimental data. Typical shapes of excitation functions in case of 1^- and 1^+ spin-parity assignments are shown in Fig. 3 as dotted curves. We have assumed here that the 1^+ and 1^- states are pure single-particle resonances with only one decay mode—via the elastic channel. The assumption that other modes of decay are present would lead to even lower cross sections and worsen the agreement with experiment. As discussed above, the phase shifts for all nonresonant partial waves were taken to be hard-sphere plus Coulomb, except for the $l=0,\ s=2$ channel for which the hard-sphere phase was arbitrarily set equal to zero to produce the dotted curves shown in Fig. 3. Without this very unrealistic assumption, even the approximate agreement shown would not apply and the curves would be nowhere near the experimental data. Still another possibility is spin-parity 2^+ for the resonance. Two arguments are against this: a 2^+ state with noticeable elastic partial width would be a strong resonance which should be observed in the elastic scattering of neutrons from ^{7}Li. The closest 2^+ state in ^{8}Li is found only at 4.76 MeV [14], so it is highly unlikely that this resonance occurs as low as 3 MeV in ^{8}B. Also, the interference of 3^+ and 2^+ states leads to a minimum in the cross section between resonances, contrary to experiment.

We have not included an R_0 term [13,15] in our analysis. This purely phenomenological term is often used to model the influence of unknown high-lying resonances. However, the density of states in $A=8$ nuclei is very low at the excitation energies of interest. For example, the next 2^- and 3^+ resonances are observed at excitation energies near 7 MeV in ^{8}Li [14]. Accounting for these resonances had only a negligibly small influence on the elastic cross section at our energies. Thus, neglecting high-lying resonances seems to be a very good approximation in this particular case, and it has the virtue that additional, arbitrary parameters are not introduced into the fitting procedure. Note also that the resonance spectrum is dominated by the 2^- and 3^+ states, which could decay to the first excited state of ^{7}Be via angular momentum $l=2$ and 3, respectively. However, since the penetrability factors for such large l values are very small, inelastic decay can be ignored.

The insert in Fig. 3 shows a confidence band for the energy and width of the 2^- resonance. This state is very broad, which prevents us from obtaining a really precise determination of its parameters. The excitation energy and width extracted from the *R*-matrix analysis are correlated, as expected. The best-fit point, shown on the figure as a cross, corresponds to $E=3.5\pm0.5$ MeV, $\Gamma=8\pm4$ MeV. The lower limit on the width is well defined, but the analysis is less sensitive to the upper limit. We therefore show the Wigner limit for the single-particle width (calculated for a channel radius of 4.3 fm), plotted as the solid line in Fig. 3. It can be seen that the 2^- state most likely has a width that is close to the Wigner limit. This observation is in agreement with the data on elastic scattering of neutrons on ^{7}Li [14]. A broad 2^- state (4 MeV or greater) at an excitation energy of about 3.2 MeV is required to fit the a_2 scattering length for $^7\mathrm{Li}+n$ [16].

Barker and Mukhamedzhanov [16] have analyzed the effect of a 2^- state with parameters reported by Gol'dberg *et al.* [9] on the astrophysical S_{17} factor at low energies. They noted that previous calculations of the S factor have *implicitly* included such a state through its effect on the low-energy $^7\mathrm{Li}+n$ elastic-scattering phase shifts. However, given the excitation energy ($E_x=3.0$ MeV) and width ($\Gamma^0=1$–4 MeV) reported in Ref. [9], a channel radius of 4.0 fm is required in the R-matrix calculation of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ S factor. This leads to $S_{17}(0)=16$ eV b and an excitation function which lies below essentially all the capture data at low energies. The resonance parameters determined in the current work will require the use of a larger channel radius in the treatment given in Ref. [16]. This will shift the S_{17} calculation to larger values (see the dashed- and short-dashed curves in Fig. 2 of Ref. [16]), making the predicted excitation function above $E_{\mathrm{c.m.}}=1$ MeV consistent with the data of Kikuchi *et al.* [5]. This fact gives more confidence in the applicability of the approach taken in Ref. [16], and therefore in the prediction for $S_{17}(0)$ drawn from this approach. It would therefore be of interest to repeat the calculations reported in in Ref. [16] using our new experimental data.

In addition to the negative parity state, there was an indication of a 1^+ resonance at an excitation energy of 2.8 MeV reported in Ref. [9]. It is not necessary to include such a state to obtain very good fits to our experimental data. On the other hand, we cannot rule out this resonance, especially if it has large reduced width for decay into the inelastic channel. A 1^+ resonance in ^{8}Li has been observed at a slightly higher energy (3.46 MeV) and it has a large reduced width for inelastic decay [14]. The penetrability factors for elastic and inelastic decay of the 1^+ resonance are almost equal, so a resonance with these properties would be hard to detect in our measurements on top of the "background" from the interference of the 2^- and 3^+ states. The same is true of the analog of the 1^- resonance at energy 3.47 MeV in ^{8}Li [14].

Yet another 1^+ resonance in ^{8}B has been proposed by Csótó [10] in recent theoretical work. Using a microscopic three-cluster approach, he predicted the existence of a 1^+ state at an excitation energy of only 1.4 MeV, with large elastic and negligible inelastic reduced width, and a calculated total width of 560 keV. A state with these parameters should be readily apparent in our excitation function, if it exists. We observe no indication of it in the present experiment. To demonstrate the sensitivity of our measurements, we added a 1^+ resonance with the properties predicted by Csótó into the R-matrix calculation. The result is shown as the dotted curve in Fig. 3. The ratio of elastic to inelastic reduced width would have to be at least 50 times smaller than predicted by Csótó in order to make this calculation agree with experiment.

In conclusion, we have measured back-angle elastic scattering of protons on ^{7}Be in the region from 1–3.3 MeV via the thick-target technique. A predicted broad 1^+ state at $E_x=1.4$ MeV, which would have very important consequences for $S_{17}(0)$, was shown not to exist. There is no evidence for any other 1^+ state in the energy region investigated. A state at $E_x=3.5$ MeV has been shown to have spin/parity 2^-. Its location and width have been determined with far better accuracy than in a previous experiment [9]. This state has implicitly been included in the calculations of S_{17}, but its properties determined in the present experiment will place further constraints on the theoretical calculations and thus improve the precision of the S factor at solar energies.

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