Angular Distribution for the ^{7}Be$(d,n)^8$B Reaction at $E_{\mathrm{c.m.}} = 5.8$ MeV and the $S_{17}(0)$ Factor for the ^{7}Be$(p,\gamma)^8$B Reaction

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The differential cross section for the ^{7}Be$(d,n)^8$B reaction at $E_{\mathrm{c.m.}} = 5.8$ MeV has been measured using the ^{7}Be beam generated by the radioactive nuclear beam facility at China Institute of Atomic Energy. The ^{8}B ions were detected in full geometry with a two-dimensional position sensitive ΔE-E counter telescope. The reaction cross section was determined to be 58 ± 8 mb. The angular distribution data were analyzed with the distorted-wave Born approximation calculation. The astrophysical $S_{17}(0)$ factor for the ^{7}Be$(p,\gamma)^8$B reaction was derived to be 27.4 ± 4.4 eV b through the asymptotic normalization constant extracted from the experimental data. [S0031-9007(96)00541-8]

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The high energy neutrinos from the β^+ decay of ^{8}B produced via the ^{7}Be$(p,\gamma)^8$B reaction at solar energies play a crucial role in the long-standing solar neutrino problem [1]. Consequently, the ^{7}Be$(p,\gamma)^8$B reaction cross section, or more precisely, its astrophysical $S_{17}(0)$ factor has attracted increasing attention for many years. There were a number of great efforts to study the $S_{17}(0)$ factor through both direct radiative capture reaction [2] and Coulomb dissociation reaction of ^{8}B [3]. However, the obvious disagreement among the experimental results is still a challenging puzzle. Therefore further experiments are called for to reduce the uncertainties of the $S_{17}(0)$. Recently, the proton pickup reactions of ^{7}Be were emphatically proposed as indirect methods to extract the $S_{17}(0)$ factor by introducing a simple relation between the asymptotic normalization constant (ANC) and the overall normalization of the $S_{17}(0)$ factor [4]. This approach is expected to yield the $S_{17}(0)$ factor with an accuracy at least comparable to that of direct radiative capture or Coulomb dissociation reactions, and thus can provide a significant cross examination. Aiming at this indirect method, we have carried out a measurement of the ^{7}Be$(d,n)^8$B reaction cross section and the angular distribution using a radioactive ^{7}Be beam. To the best of the authors' knowledge, only two experiments were dedicated to this reaction, which were performed at different energies and presented the raw cross sections alone [5,6].

The experiment was performed by use of the radioactive beam facility GIRAFFE built at the HI-13 tandem accelerator of China Institute of Atomic Energy. The detail of GIRAFFE have been reported previously [7]. An important modification for purifying the secondary beams is that the angle for collecting the primary reaction products has changed from 0° to 3°. The ^{7}Be beam with energy of 26.0 MeV was produced via the ^{1}H$(^7\mathrm{Li},^7\mathrm{Be})n$ reaction by bombarding a H_2 gas cell at 1.2 atm pressure with 34 MeV ^{7}Li ions from the HI-13 tandem accelerator. At an appropriate setting of the parameters of the secondary beam line, the ^{7}Be beam was focused into a spot of 10 mm in diameter with an angular divergence of 1.9° FWHM. The beam typically comprises more than 90% $^7\mathrm{Be}^{4+}$ ions with the major contaminants being $^7\mathrm{Be}^{3+}$ ($<1\%$, 12 MeV) and $^7\mathrm{Li}^{3+}$ ions ($<9\%$, 13 MeV).

The ^{7}Be beam was further collimated by a $\phi 4$ mm aperture and then directed onto a secondary target placed on the focal plane. The resulting beam energy resolution was 1.2 MeV FWHM. A deuterated polyethylene $[(\mathrm{CD_2})_n]$ foil of 0.97 mg/cm^2 in thickness was used as the secondary target to study the reaction of interest, and a polyethylene $[(\mathrm{CH_2})_n]$ foil was used to determine the background. The reaction products were detected and identified using a ΔE-E counter telescope. It consisted of a 9 cm long ionization chamber filled with 75 torr P-10 gas backed by a 45×45 mm^2 Hamamatsu two-dimensional position sensitive silicon detector (PSSD) of 450 μm in thickness. The latter enabled us to determine both the energy and emission angle of the outgoing particles. The distance between the reaction target and PSSD was 10 cm. The reverse kinematics of the ^{2}H(^{7}Be, ^{8}B)n reaction restricted the maximum emerging angle of ^{8}B to about 9°; thus the full angular distribution could be covered. The overall angular resolution was 1.1° FWHM, which resulted from the ^{7}Be beam position uncertainty (0.6°), the beam angular divergence after collimation (0.8°), the beam energy resolution ($<0.3°$), and the position resolution of PSSD (0.6°) as well as the ^{8}B angular straggling in passing materials ($<0.4°$).

The experiment scheme also facilitated beam normalization with a high precision because the beam itself was simultaneously recorded by the counter telescope. However, it brought about a knotty problem of pulse pileup. In order to solve this problem, the beam intensity on the target was kept at a very low level of 200–400 cps. Moreover, a particular consideration was given to pileup rejection. In addition, a mixing trigger was used in which the logical output for the low ΔE(<2.1 MeV) events corresponding to the ^{7}Be beam was scaled down by a factor of 100 to lighten the unnecessary burden of data taking system and off-line analysis. The beam time taken for the $(CD_2)_n$ target was approximately 150 hours, during which about 300 ^{8}B events were accumulated. The background measurement with the $(CH_2)_n$ target took about 50 hours.

A contour plot of ΔE vs E_t from a few runs with the $(CD_2)_n$ target is shown in Fig. 1(a), where ΔE and E_t denote the energy loss and the total energy of particles, respectively. The two-dimensional cut in Fig. 1(a) refers to the ^{8}B candidates from the $^2H(^7Be, ^8B)n$ reaction. The cut was determined on the basis of reaction kinematics calculation that has taken the energy resolution of the ^{7}Be beam and the target thickness into account. The events outside the cut in the figure were well identified to be the beam components, the remainder peak-to-peak pileup pulses from the beam, as well as the products from other reaction channels, respectively. Figure 2(a) displays the contour plot of E_t vs θ_{lab} for the events within the cut from the sum of all runs, where the θ_{lab} is the laboratory emission angle converted from the position data of PSSD. A parabola shaped window finally selects ^{8}B events. The window was defined with a Monte Carlo calculation simulating the realistic experimental condition. Correspondingly, those for background runs with $(CH_2)_n$ target are shown in Figs. 1(b) and 2(b). It can be seen from Fig. 2(b) that the background appears mainly around 0° and obviously results from the remaining beam pulses piling up on each other. Because the considerable contaminants from the reactions on carbon infiltrate into the region which corresponds to $\theta_{c.m.} > 160°$, the data in that region were discarded. After the normalization to the numbers of incident ^{7}Be particles, the net ^{8}B events with background subtracted were obtained. The total cross section for the $^7Be(d,n)^8B$ reaction at $E_{c.m.} = 5.8$ MeV was then determined to be 58 ± 8 mb. The error mainly stemmed from statistics (9%), background subtraction (7%), as well as target thickness (6%). The data were converted to a center-of-mass (CM) frame, where the nonuniform angular intervals were assigned in accordance with the laboratory angular uncertainty discussed above. The resulting CM angular distribution is presented in Fig. 3. Since ^{8}B has no excited states with detectable half-lives in the present experiment, the data include the ground state transition only.

The zero-range distorted-wave Born approximation (DWBA) code [8] is adopted in the analysis of the data. It is known that the mechanism of a deuteron stripping reaction or a transfer reaction at small angles is reliably established. The ambiguities in the DWBA calculations due to the choice of parameters of optical potentials are minimal. The peripheral amplitudes of the reaction make a dominant or, at least, a large contribution to the differential cross sections in the peak region. Therefore our consideration is restricted to the measured differential cross section in the peak region at the small angles. The

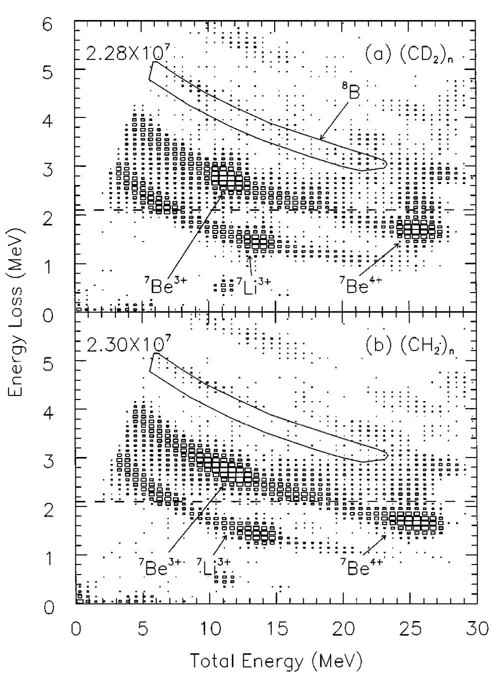

FIG. 1. Contour plots of ΔE vs E_t for (a) $(CD_2)_n$ and (b) $(CH_2)_n$ targets. The numbers of the incident ^{7}Be particles are shown at the upper left corner. The size of the points is proportional to the logarithm of the counts per channel; the smallest is for 1 count per channel. The events below the dashed line are the beam components which were scaled down by a factor of 100.

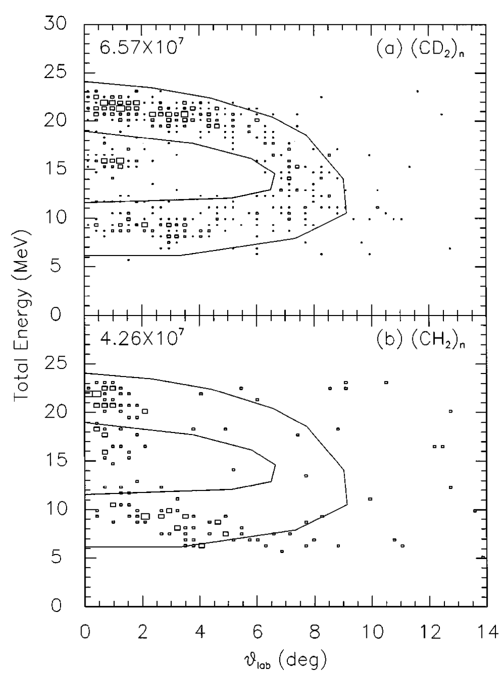

FIG. 2. Contour plots of E_t vs θ_{lab} for (a) $(CD_2)_n$ and (b) $(CH_2)_n$ targets. The numbers of the incident ^{7}Be particles are shown at the upper left corner. Here, the size of the points is proportional to the counts per channel.

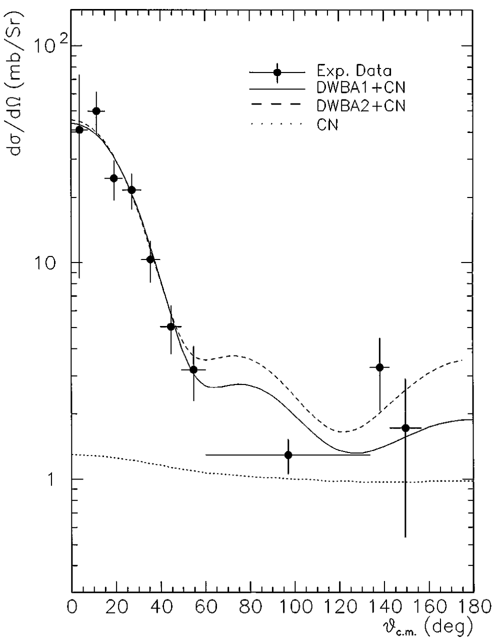

FIG. 3. Differential cross section for the $^7\mathrm{Be}(d,n)^8\mathrm{B}$ reaction at $E_{\mathrm{c.m.}} = 5.8$ MeV together with the theoretical calculations. DWBA1 and DWBA2 denote the normalized DWBA calculations with OM parameter set 1 and set 2, respectively, CN refers to the compound nucleus contribution. The parameters of proton bound state are $r_0 = 1.25$ fm and $a = 0.65$ fm, and the spectroscopic factors corresponding to DWBA1 and DWBA2 are 1.21 and 1.34, respectively.

conventional method to extract the empirical spectroscopic factor from an experiment uses the relation,

$$\sigma_{\exp}(\theta_0) - \sigma_{\mathrm{CN}}(\theta_0) = S_{lj}\sigma_{\mathrm{DWBA}}(\theta_0), \tag{1}$$

where $\sigma_{\exp}(\theta_0)$ and $\sigma_{\mathrm{DWBA}}(\theta_0)$ are the values of the experimental and calculated differential cross sections in the peak region, respectively, and $\sigma_{CN}(\theta_0)$ is the compound nucleus contribution. In above procedure, the D_0^2 is taken to be $1.58 \times 10^4\ \mathrm{MeV}^2\,\mathrm{fm}^3$ [9], where D_0 stands for the volume integral constant in zero-range approximation. It has been found in a number of papers [10,11] that spectroscopic factor S_{lj} has a large uncertainty, which strongly depends on the geometry parameters of the Woods-Saxon potential r_0 and a (the radius and diffuseness parameters) used for calculating the wave function of a single particle bound state. Such an uncertainty can be removed by introducing the ANC of the true overlap functions, C_{lj}, which is related to the spectroscopic factor by

$$C_{lj}^2 = S_{lj} b_{nlj}^2 . \tag{2}$$

The b_{nlj} is the asymptotic normalization of a single-particle radial wave function $u_{nlj}(r)$ in the shell model calculation with certain geometry parameters r_0, a of a Woods-Saxon potential,

$$u_{nlj}(r) \approx b_{nlj} W_{-\eta,l+1/2}(2\kappa r)/r, \quad r > R_N , \tag{3}$$

where R_N is the nuclear interaction radius between the proton and ^{7}Be, $W_{-\eta,l+1/2}(2\kappa r)$ refers to the Whittaker function, and η stands for the Sommerfeld parameter. In our calculations the optical potential parameters for the deuteron and neutron are carefully chosen to fit experimental scattering data of the nearby nuclei at the closest energies and extrapolated to the energies of the present study by a reasonable energy dependence, which are listed as set 1 in Table I. The depth of the Woods-Saxon potential for the proton bound state is chosen to fit the separation energy of the proton from ^{7}Be $B_p = 0.137$ MeV for given geometry parameters. The overall agreement between the measured and calculated differential cross section is fairly good, as shown in Fig. 3. It is found that the peak value of the differential cross section is insensitive to the distorted-wave optical potential parameters. It takes about a 10% change of ANC value to replace the optical potentials set 1 by set 2 [12], as shown in Table I, though they are quite different. The ANC $C_{1,3/2}^2$ for $^8\mathrm{B} \to {}^7\mathrm{Be} + p$ was extracted to be 0.711 ± 0.092 fm from the present experiment data using Eqs. (1)–(3), where $S_{1,3/2}$ was obtained by the weighted average of the experimental data in the peak area. The error includes only experimental uncertainty. In the calculations, we have used different values of the geometry parameters r_0 and a, which run over the whole r_0-a plane. When the geometry parameters change, the variation of the ANC values would be only about 1%, although the asymptotic normalization of the $u_{1,1,3/2}$, as well as the spectroscopic factor, would change dramatically. Xu *et al.* have proved [8] that the $S_{17}(0)$ factor for the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction can be uniquely determined by the ANC in terms of the Barker calculation [10] which includes both s and d waves in the entrance channel. They have shown that the $b_{nlj}^2/S_{17}(0)$ is almost a constant (≈ 0.026) for different proton bound wave functions in ^{8}B [8], where the spectroscopic factors are chosen as the same as those given by Barker [10], satisfying $S_{l=1,j} \approx 1.0$. Following their

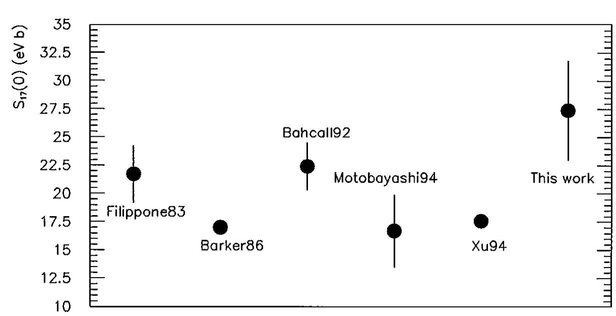

FIG. 4. The comparison between the $S_{17}(0)$ values for the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction extracted from the experiments and calculations.

TABLE I. The optical potential parameters used in DWBA calculation and the corresponding ANC and $S_{17}(0)$ values. For ^{7}Be + d of set 1, the additional parameters are $W = -14.84$, $r_W = 1.64$, $a_W = 0.29$; V and W are in MeV, r and a are in fm.

Set	Channel	V	r	a	$4W_D$	r_D	a_D	$4V_{so}$	r_{so}	a_{so}	$C^2_{13/2}$(fm)	$S_{17}(0)$ (eV b)
1	^{7}Be + d	−138.74	1.02	0.86	65.36	1.31	0.76	−28.0	1.64	0.81		
	^{8}B + n	−48.19	1.13	0.72	45.32	1.43	0.66	−24.8	1.13	0.77	0.711 ± 0.092	27.4 ± 3.6
2	^{7}Be + d	−118.00	1.00	0.94	27.48	1.98	0.59	−34.0	1.00	0.94		
	^{8}B + n	−42.36	1.35	0.55	37.76	1.35	0.75	−20.0	1.35	0.55	0.796 ± 0.103	30.6 ± 4.0

procedure, the $S_{17}(0)$ factor for $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ was derived to be 27.4 ± 4.4 eV b with the present ANC value. The uncertainty includes the experimental error (13%) and the estimated error (∼10%) from the theoretical calculation, which arises from the uncertainty of the optical potential, CN calculation, and the D_0^2.

In summary, the angular distribution of $^7\mathrm{Be}(d,n)^8\mathrm{B}$ reaction has been measured in the present experiment for the first time, from which the $S_{17}(0)$ factor for the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction was derived. Our $S_{17}(0)$ value (27.4 ± 4.4 eV b) is shown in Fig. 4 together with the currently adopted value (22.4 ± 2.1 eV b) [1], the experimental results [2,3], and the calculations [4,13]. As a result of an independent experimental approach, the present $S_{17}(0)$ value supports the missing solar neutrino found in the Kamiokande and Homestake experiments. Further experiments along this direction, e.g., the study of the $^7\mathrm{Be}(^{10}\mathrm{B}, {}^9\mathrm{Be})^8\mathrm{B}$ reaction, are under consideration.

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