Low-lying non-normal parity states in $^8$B measured by proton elastic scattering on $^7$Be

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Abstract

A new measurement of proton resonance scattering on $^7$Be was performed up to the center-of-mass energy of 6.7 MeV using the low-energy RI beam facility CRIB (CNS Radioactive Ion Beam separator) at the Center for Nuclear Study of the University of Tokyo. The excitation function of $^7$Be+p elastic scattering above 3.5 MeV was measured successfully for the first time, providing important information about the resonance structure of the $^8$B nucleus. The resonances are related to the reaction rate of $^7$Be(p,γ)$^8$B, which is the key reaction in solar $^8$B neutrino production. Evidence for the presence of two negative parity states is presented. One of them is a $2^-$ state observed as a broad $s$-wave resonance, the existence of which had been questionable. Its possible effects on the determination of the astrophysical S-factor of $^7$Be(p,γ)$^8$B at solar energy are discussed. The other state had not been observed in previous measurements, and its $J^\pi$ was determined as $1^-$. 

Key words: RI beam, Proton resonance scattering, $^7$Be(p,γ)$^8$B, Solar neutrino

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The astrophysical S-factor $S_{17}(E)$ of the $^7$Be(p,γ)$^8$B reaction is one of the most important parameters in the standard solar model, because its value at the energy of the solar center is directly related to the flux of the $^8$B neutrino, which is the dominant component of the solar neutrinos detected by some of the major neutrino observatories on earth [1,2]. $S_{17}$ should be determined with a precision greater than about 5%, in the energy region below 300 keV, in order to test the solar model by comparing the theoretical prediction for the $^8$B neutrino flux with the observations [3]. For this reason, a number of experimental groups have put in great efforts in that direction [4,5,6,7,8,9,10,11,12,13,14,15]. The precision of the existing data, however, is still limited because of the very small cross section of the

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\(^7\)Be\((p,\gamma)\)\(^8\)B reaction in such a low-energy region.

To evaluate \(S_{17}\) at low energies, one needs information about the nuclear structure of \(^8\)B, which has been poorly known until recently. Only the lowest two excited states, at 0.77 and 2.32 MeV, were observed clearly in previous experiments [16]. A broad 2\(^-\) resonance was observed around 3 MeV [17], however, negative parity is non-normal for nuclei with a mass number of 8, and the 2\(^-\) state was explained as a low-lying 2\(s\) state. In another measurement [18], the broad state was not directly observed; nevertheless, the spectrum was considered consistent with the presence of the state, if it is located at 3.5 MeV with a width of 4 MeV, or more. Such a broad resonance may affect the \(^7\)Be\((p,\gamma)\)\(^8\)B reaction rate in the energy region far below 1 MeV. Investigating why a 2\(s\) state appears at such low energy is also interesting, and there are studies that predict the presence of the 2\(^-\) state in \(^8\)B or its mirror nucleus, \(^8\)Li [19,20,21,22,23,24]. The 2\(^-\) resonance is possibly related to the proton-halo structure of the \(^8\)B nucleus [25]. Thus, we intended to study the resonance structure of \(^8\)B to evidently observe the 3.5 MeV resonance reported in previous measurements, and explore the unknown energy region above 3.5 MeV.

The measurement was performed using CRIB (CNS Radioactive Ion Beam separator) at the Center for Nuclear Study (CNS) of the University of Tokyo [26,27]. CRIB can produce RI beams with the in-flight method, using primary heavy-ion beams from the AVF cyclotron of RIKEN. The primary beam used in this measurement was \(^7\)Li\(^{3+}\) of 8.76 MeV/n at 100 pnA. The RI-beam production target was pure hydrogen gas at 760 Torr and room temperature (~300 K), enclosed in an 8-cm-long cell. A secondary \(^7\)Be beam at 53.8 MeV was produced from \(^7\)Li via \((p,n)\) reaction in inverse kinematics. The typical intensity of the \(^7\)Be\(^{4+}\) beam was \(3 \times 10^5\) particles per second at the target of resonance scattering. A Wien filter was used to purification of the secondary beam. The beam purity (the number ratio of \(^7\)Be\(^{4+}\) to the total), before and after passing through the Wien filter, was 56% and 100%, respectively.

We used an experimental method similar to past measurements of proton elastic resonance scattering at CRIB [28,29]. A main feature of this method is a thick target [30,31], which enables simultaneous measurements of cross section of various excitation energies. The targets and detectors for the scattering experiment were in a vacuum chamber located at the end of the beam line. Figure 1 shows a schematic view of the experimental setup in the chamber. Two parallel-plate avalanche counters (PPACs) [32] measured timing and position of the incoming \(^7\)Be beam with a position resolution of 1 mm or better. The timing signal was used for producing event triggers, and for particle identification using the time-of-flight (TOF) method. The position and incident angle of the beam at the target were determined by extrapolating the positions measured by PPACs. The targets were films of 39-mg/cm\(^2\)-thick polyethylene, and 54-mg/cm\(^2\)-thick carbon, both sufficiently thick to stop the \(^7\)Be beam. Carbon targets were used for evaluating background events originating from carbon nuclei contained in the polyethylene target. We accumulated data for 51 h with the polyethylene, and 17 h with the carbon target. Multi-layered silicon detector sets, referred to as \(\Delta E-E\) telescopes, measured the energy and angular distributions of the recoiling protons. Four telescopes were placed at a distance of 23 cm from the target to cover the scattering angle in the laboratory frame \(\theta_{\text{lab}}\) from 0 to 45 degrees. Each telescope consisted of a thin \(\Delta E\) counter and two or three thick \(E\) counters, each with an area of 50 \(\times\) 50 mm. The \(\Delta E\) counters were 60 to 75-\(\mu\)m thick, and divided into 16 strips for each side. The 1.5-mm-thick \(E\) counters were placed behind the \(\Delta E\) counters. NaI detectors were used for measuring 429-keV gamma rays from inelastic scatterings to the first excited state of \(^7\)Be. We used ten NaI crystals, each with a geometry of 50 \(\times\) 50 \(\times\) 100 mm, covering 20% of the total solid angle altogether.

Proton events were selected using measured energy \((\Delta E-E)\) and timing information. The center-of-mass energy \(E_{\text{cm}}\) of each event was determined from the measured proton energy and angle by calculations of kinematics and the energy loss in the target. Cross sections of the proton scattering events for both the polyethylene and carbon targets were calculated from the number of proton events and ir-
radiated beam particles, the solid angle of the detector, and the target thicknesses. The excitation function for the proton target was deduced by subtracting the carbon contribution from the polyethylene spectrum.

$E_{\text{em}}$, resolution of the excitation function was 40–70 keV in full width at half maximum (FWHM) at the most forward angle. The uncertainty was mostly from energy straggling of the particles in the thick target, along with the energy resolution of the silicon detectors. At larger angles, the angular resolution of the recoiling proton produced large energy uncertainty and the resulting energy resolution was 70–300 keV at $\theta_{\text{lab}} = 25$ degrees.

When the compound $^8$B nucleus has an excitation energy exceeding the threshold at 1.72 MeV, decay to the 3-body channel ($^4\text{He} + ^3\text{He} + p$) may occur. Background proton events from this 3-body-channel decay distributed over wide energy and angular ranges must be subtracted from the obtained excitation functions. The energy and angular distributions of the background protons were estimated by a Monte Carlo simulation, assuming isotropic particle emissions in the center-of-mass frame. The absolute value of the contribution was normalized by measured numbers of multiple hit (proton with $^4\text{He}$ and/or $^3\text{He}$) events. The estimated 3-body background contribution was 30 mb/sr at maximum and structureless in the excitation functions, and thus it is not very influential on the line shape.

We measured de-excitation $\gamma$ rays in the inelastic events with the NaI detectors. These detectors had an energy resolution of 10% (FWHM) for 662-keV gamma rays. The 429-keV photopeak detection efficiency $\epsilon$ was measured as 7.1%, using $\gamma$-ray sources placed at the target position. The $\gamma$-ray energy spectrum of proton-$\gamma$ coincident events showed an intense peak at 429 keV and the contribution to the excitation function by the inelastic scattering events was successfully deduced. The inelastic contribution, about 10% of the elastic scattering, was subtracted from the total excitation function.

The presence of the $2^-$ state around 3.5 MeV was questionable because of the limited statistics and energy range in previous experiments [17,18], although the $2^-$ state was also expected to exist from the analysis on the experimental data of mirror nucleus [33,19,20,23,24] and shell model calculations [34,21,22]. We successfully performed measurements with more counting statistics and a wider energy range, and a slowly varying excitation function after the peak around 2.3 MeV was observed, as shown in Fig. 2. This excitation function strongly suggests that the peak at 2.3 MeV was enhanced by a broad state that locates at higher energy. Following this assumption, which is virtually the same as the one taken in [18], we performed an R-matrix analysis, using SAMMY [35] code. The channel radius was fixed at 4.3 fm, the same value as in [18] and [19]. We confirmed that the result was not very sensitive to a deviation of channel radius within 0.5 fm. Two known resonances at excitation energies $E_{\text{ex}} = 0.77$ and 2.32 MeV were introduced in the fit using parameters in [16], although the former was not effective in our energy range. The R-matrix calculations provide a reliable determination of the resonance parameters (energy $E$, width $\Gamma$, spin $J$, and parity $\pi$) even for such broad states. In the best fit for $J^\pi = 2^-$, shown in Fig. 2, $E_{\text{ex}} = 3.2$ MeV and $\Gamma = 3.8$ MeV. Although the $2^-$ resonance is broad and did not appear as a distinct peak, the excitation function was sensitive to variations of $E$ and $\Gamma$. When we reduced $\Gamma$ by about half ($\Gamma = 1.8$ MeV), the resulting excitation function, indicated as “$2^-\text{ narrow}$” in the figure, was in complete disagreement with the original function, proving that $\Gamma$ of the $2^-$ resonance truly affects the calculated excitation function. The resonance is considered to be an s-wave resonance, as it has negative parity and broad width. We could not obtain satisfactory fits by introducing broad $1^-$ or any possible positive parity state, while a broad $2^+$ state was introduced to reproduce the excitation function in a previous study [36].

Assuming the presence of the $2^-$ state, we expanded the R-matrix fit to the higher energy region, as illustrated in Fig. 3. The contribution of the inelastic scattering to the first excited state in $^7$Be
Fig. 3. Excitation functions of $p + ^7\text{Be}$ elastic scattering for three angular ranges, fitted with R-matrix calculations. Contributions from inelastic scattering are also shown. The best fit for each angular range with five resonances, including two unknown resonances ($1^-$ at 5.0 MeV and $3^+$ at around 7 MeV) are shown with solid curves. The dashed curves for the larger two angular ranges are the calculated functions using the same $2^-$ resonance parameters as that between 0 and 8 degrees. The dotted curve for 0–8 degrees is a 6-resonance fit with an additional $1^+$ state at 5.8 MeV.

The parameters for the $2^-$ state were determined with improved precision, showing no large discrepancies with previous measurements. Our excitation functions, including the angular dependence and measurement of inelastic scattering, strongly support the existence of the broad $2^-$ state in $^8\text{B}$ nucleus around 3.2 MeV. Excited states of $^8\text{B}$ higher than 3.5 MeV were not explored in past measurements, and we discovered new resonance at 5.0 MeV and assigned its $J^\pi$ as $1^-$. A $1^-$ resonance in the $A=8$ nuclei was predicted to emerge in the vicinity of a $2^-$ state by theoretical studies [34,20,21,22]. In [24], a structure due to $1^-$ level appeared at $E_{\text{ex}} = 4.1\text{ MeV}$ ($E_{\text{proton}} = 4.5\text{ MeV}$) in the calculated S-factor spectrum. The observed resonance might be the first evidence for these predictions in $^8\text{B}$, and could lead to extensive studies on the structure of

| $J^\pi$ | $l$ | $E_{\text{ex}}$ (MeV) | $\Gamma$ (MeV) | Reference |
|--------|-----|---------------------|--------------|-----------|
| $1^+$  | 1   | 0.7695 ± 0.0025      | 0.0356 ± 0.0006 | [16]      |
| $3^+$  | 1   | 2.32 ± 0.02          | 0.35 ± 0.03   | [16]      |
| $2^-$  | 0   | 3.2^{+0.3}_{-0.2}    | 3.4^{+0.8}_{-0.5} | present  |
| $2^-$  | 0   | 3.5 ± 0.5            | 8 ± 4        | [17]      |
| ($2^-$, $1^-$) | 0   | 3                   | 1–4          | [17]      |
| $1^-$  | 0 or 2 | 5.0 ± 0.4           | 0.15 ± 0.10  | present   |

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the $^8$B nucleus. We found an indication of resonance at around 7 MeV, but more evidence is required to determine its parameters.

In the precise determination of the $^7$Be$(p, \gamma)^8$B S-factor by Junghans and coworkers [14], the resonant contribution was evaluated by the Breit-Wigner function,

$$\sigma(E_{\text{cm}}) = \frac{C}{E_{\text{cm}}(E_{\text{cm}} - E_0)^2 + \Gamma_p(E_{\text{cm}})^2/4}. \quad (1)$$

The resonant contribution of the broad $2^-$ resonance calculated using our parameters and Eq. 1 is illustrated in Fig. 4. Because the gamma width $\Gamma_{\gamma}$ was not determined by our measurement, standard width $\Gamma_{\gamma,0} = 11$ eV, corresponding to the Weisskopf unit, was defined, and the contributions were calculated for $\Gamma_{\gamma} = \Gamma_{\gamma,0}$ and $2\Gamma_{\gamma,0}$ cases as shown in Fig. 4. The curve for $\Gamma_{\gamma} = 2\Gamma_{\gamma,0}$ shows a considerable contribution, which may partly explain the structure of the the experimental data in the high energy ($E_{\text{cm}} \sim 2$ MeV) region. $\Gamma_{\gamma} = 2\Gamma_{\gamma,0}$ is an extreme case, and apparently such a contribution was not observed in the high energy region. Nevertheless, the contribution at the solar energy was negligible compared to the experimental precision. Even if $\Gamma_p$ was doubled, as shown by the dashed curve in the figure, the resulting contribution at the solar energy was negligible. Therefore, the resonant reaction by the $2^-$ state is expected to be ineffective for the determination of $S_{17}$.

In [14], the nonresonant contribution was evaluated by calculations using a microscopic cluster model [37] and other methods [38]. The model used in [37] implicitly involves the $2^-$ state as the $s$-wave contribution, but the contribution would not be very sensitive to the resonance parameters. A realistic evaluation might be possible by calculations that explicitly involve a $2^-$ state, such as the work by Barker and Mukhamedzhanov [24,39]. They introduced a $2^-$ level in $^8$B at $E_{\text{ex}} = 3.0$ MeV and $\Gamma = 3.7 - 5.2$ MeV to explain the $^8$Li+$n$ elastic scattering data. We obtained resonance parameters in agreement with these, and thus their discussion should not be altered significantly.

In summary, we have studied the proton resonance scattering on $^7$Be, using a pure $^7$Be beam produced at CRIB. The excitation function of $^8$B was measured up to the excitation energy of 6.7 MeV, using the thick-target method and resonance parameters of two negative (non-normal) parity states were determined. The $2^-$ resonance at 3.2 MeV was reported in two previous measurements, and we determined its energy and width with improved precision. The effect of the $2^-$ resonance on the determination of $S_{17}$ was estimated to be small compared to the experimental precision. Another resonance at 5 MeV was observed for the first time, and it is considered to be the $1^-$ state predicted in theoretical studies.

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References
[1] S. Fukuda et al., Phys. Rev. Lett. 86 (2001) 5656.
[2] Q. R. Ahmad et al., Phys. Rev. Lett. 89 (2002) 011301.
[3] E. G. Adelberger et al., Rev. of Mod. Phys. 70 (1998) 1265–1291.
[4] F. J. Vaughn, R. A. Chalmers, D. Kohler, J. L. F. Chase, Phys. Rev. C 2 (1970) 1657.
[5] B. W. Filippone, A. J. Elwyn, C. N. Davids, D. D. Koetke, Phys. Rev. C 28 (1983) 2222.
[6] F. Hammache, G. Bogaert, P. Aguer, C. Angulo, S. Barhoumi, L. Brillard, J. F. Chemin, G. Claverie, A. Coc, M. Hussonnois, M. Jacotin, J. Kiener, A. Lefebvre, J. N. Scheurer, J. P. Thibaud, E. Virassamyäken, Phys. Rev. Lett. 80 (1998) 928.
[7] F. Hammache, G. Bogaert, P. Aguer, C. Angulo, S. Barhoumi, L. Brillard, J. F. Chemin, G. Claverie, A. Coc, M. Hussonnois, M. Jacotin, J. Kiener, A. Lefebvre, C. L. Naour, O. Ouichaoui, J. N. Scheurer, V. Tatischeff, J. P. Thibaud, E. Virassamyäken, Phys. Rev. Lett. 86 (2001) 3985.
