PROCEEDINGS OF SCIENCE

Proton resonance scattering of ^{7}Be

H. Yamaguchi*
Center for Nuclear Study, Graduate School of Science, University of Tokyo
2-1 Hirosawa, Wako, Saitama 351-0198, Japan
E-mail: yamag@cns.s.u-tokyo.ac.jp

Y. Wakabayashi, G. Amadio, S. Kubono, H. Fujikawa
Center for Nuclear Study, Graduate School of Science, University of Tokyo
2-1 Hirosawa, Wako, Saitama 351-0198, Japan

A. Saito
Department of Physics, Graduate School of Science, University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

J.J. He
School of Physics, The University of Edinburgh
Mayfield Road, Edinburgh EH9 3JZ

T. Teranishi
Department of Physics, Kyushu University
6-10-1 Hakozaki, Fukuoka 812-8581, Japan

Y.K. Kwon
Department of Physics, Chung-Ang University
Seoul 156-756, South Korea

S. Nishimura
The Institute of Physical and Chemical Research(RIKEN)
2-1 Hirosawa, Wako, Saitama 351-0198, Japan

Y. Togano
Department of Physics, Rikkyo University
3-34-1 Nishi-Ikebukuro, Toshima-ku, Tokyo 171-8501, Japan

N. Iwasa, K. Inafuku
Department of Physics, Tohoku University
Aoba, Sendai, Miyagi 980-8578, Japan

M. Niikura
Center for Nuclear Study, Graduate School of Science, University of Tokyo
2-1 Hirosawa, Wako, Saitama 351-0198, Japan

L.H. Khiem
Institute of Physics and Electronics, Vietnam Academy of Science and Technology
18 Hoang Quoc Viet St., Nghia do, Hanoi, Vietnam

PoS(NIC-IX)049

PROCEEDINGS OF SCIENCE

We have studied the proton resonance scattering of ^{7}Be by using a pure ^{7}Be beam produced at CRIB (CNS Radioactive Ion Beam separator; CNS stands for Center of Nuclear Study, University of Tokyo). The excitation function of ^{8}B was measured up to the excitation energy of 6.8 MeV, using the thick-target method. The excited states of ^{8}B higher than 3.5 MeV were not known by the past experiments. This proton elastic scattering is also of importance in relation with the ^{7}Be(p,γ)^{8}B reaction, which is a key reaction in the standard solar model.

International Symposium on Nuclear Astrophysics — Nuclei in the Cosmos — IX
June 25-30 2006
CERN, Geneva, Switzerland

*Speaker.

1. Introduction

The astrophysical S-factor $S_{17}(E)$ is one of the most important parameters in the standard solar model, and is defined as

$$S_{17}(E) = E\sigma_{17}(E)\exp(2\pi\eta), \tag{1.1}$$

where $\sigma_{17}(E)$ is the cross section of the ^{7}Be(p,γ)^{8}B reaction, and η is the Sommerfeld parameter. This S_{17} value at the solar energy is directly related to the flux of the ^{8}B neutrino observed on the earth. ^{8}B neutrinos are only less than 0.01 % of the total neutrinos emitted from the sun, but they are the majority of the detected neutrinos in many neutrino detectors such as Super-Kamiokande and Sudbury Neutrino Observatory (SNO). Due to this fact, $S_{17}(E)$ is regarded as an important factor for the solar neutrino problem in the standard solar model. Although great efforts were spent by many experimental groups [1], the experimental precision remains still around 10 %, because of the small reaction cross section. It is claimed that the determination of the S_{17} below 300 keV with a precision better than 5% may make a major contribution to our knowledge for the solar model [2].

The existence of excited levels of ^{8}B may affect the determination of S_{17}. However, we do not have sufficient knowledge of the nuclear structure of ^{8}B. Only the lowest two excited states at 0.77 MeV and 2.32 MeV were clearly observed in past experiments. Another excited state around 3 MeV was observed as an unexpectedly wide resonance, and this was explained as a low-lying 2s state [3]. The reason why a 2s state appeared at such a low energy is also an interesting subject [4, 5, 6]. This kind of wide states may affect the measurement of ^{7}Be(p,γ)^{8}B cross section even at very low energies (much less than 1 MeV). In the same measurement, an indication of 1^+ state at 2.8 MeV was also reported. In another recent measurement [7], on the other hand, they could not observe the 1^+ state at 2.8 MeV nor yet another 1^+ state at 1.5 MeV, the latter of which was theoretically proposed in [8]. The wide state was not directly observed, however, they concluded that their spectrum is consistent with the existence of the state, if it is located at 3.5 MeV with a width of 4 MeV or more. Thus we intended to measure the resonances of ^{8}B, to evidently observe the 3.5 MeV resonance reported in the past measurements, and also to explore the totally unknown region $E >$3.5 MeV, where we may find new resonances. The “thick target method”, by which we can measure proton elastic resonance scatterings, was suitable for our purpose.

The ^{7}Be(p,γ)^{8}B reaction and ^{8}B structure are important topics in the nucleosynthesis as well. In the standard nucleosynthesis theory, the triple-α process is considered as the dominant process to pass over the stability gap at A=8. However, in special environments such as metal-deficient high temperature stars, the proton- or α-capture process of ^{7}Be might play a significant role, and thus how they compete each other is an interesting problem. We are able to study these processes by measuring the ^{7}Be(p,p)^{7}Be elastic scatterings.

2. Method

The measurement was performed at CRIB [9, 10]. CRIB can produce RI beams with the in-flight method, using primary heavy-ion beams from the AVF cyclotron of RIKEN (K=70). The primary beam used in this measurement was ^{7}Li^{3+} of 8.76 MeV/u, with the beam current of about 100 pnA. The RI-beam production target was pure hydrogen gas, which was enclosed in an 8

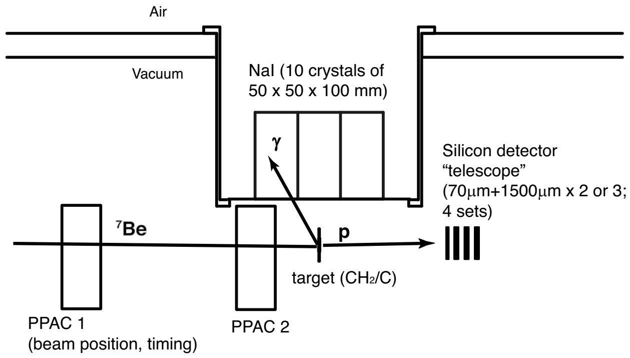

Figure 1: Arrangement of the detectors and targets in the experimental chamber.

cm-long cell, at 760 Torr and room temperature ($\sim$ 300 K). The ^{7}Be beam energy used in this measurement was 53.8 MeV, which enabled us to measure events with the center-of-mass energy up to 6.7 MeV. The beam purity (the number ratio of ^{7}Be^{4+} to total) was 56% before going through the Wien filter, and 100% after the Wien filter. The intensity of the produced ^{7}Be^{4+} beam was 3×10^5 particles per second at the resonance scattering target.

We used a standard experimental method for the proton elastic resonance scattering, well-established at CRIB [11]. A main feature of this method is the thick target [12, 13, 14], which makes it possible to measure the cross section of various excitation energies at the same time.

The targets and detectors for the scattering experiment were in a vacuum chamber located at the downstream of the Wien filter. Figure 1 shows a schematic view of the experimental setup in the chamber. Two PPACs (Parallel-Plate Avalanche Counters [15]) measured the timing and position of the incoming ^{7}Be beam. The timing information was used for making event triggers, and also for the particle identification with the time-of-flight (TOF) method. The position of the beam and the incident angle at the target were determined by extrapolating the positions measured by the PPACs. The targets were foils of 39 mg/cm^2-thick polyethylene (CH_2), and 54 mg/cm^2-thick carbon, both of which were thick enough to stop all of the ^{7}Be beam. Carbon foils were used for evaluating backgrounds coming from carbon atoms in the polyethylene target. Multi-layered silicon detector sets, referred to as ΔE-E telescopes, were used for measuring the energy and angular distribution of the recoil protons. They were placed $\sim$23 cm distant from the target, and they covered scattering angle of up to 45 degrees in the laboratory frame. Each ΔE-E telescope consisted of a ΔE counter and two or three E counters, all of which had an area of 50 mm x 50 mm. Each of the ΔE counters was about 70 μm thick and divided into 16 strips for both sides. The E counters, which were 1.5 mm thick, were placed behind the ΔE counters. The recoil proton energy was 23 MeV at maximum, and the silicon detectors were sufficiently thick to stop all the recoil protons in them. With these ΔE-E telescopes, we identified recoil protons from other particles. NaI detectors were used for measuring 429 keV gamma rays from inelastic scatterings, $p(^7\mathrm{Be}, ^7\mathrm{Be}^*)p$. Each NaI crystal has a geometry of 50 mm x 50 mm x 100 mm. In this measurement we used ten crystals covering $\sim$20% of the total solid angle.

Compared to the past measurements with similar methods [3, 7], this measurement has three major advantages. The first one is the energy range. We used a high-energy ^{7}Be beam, and we could measure up to 6.8 MeV in the excitation energy of ^{8}B. The second is the covered scattering

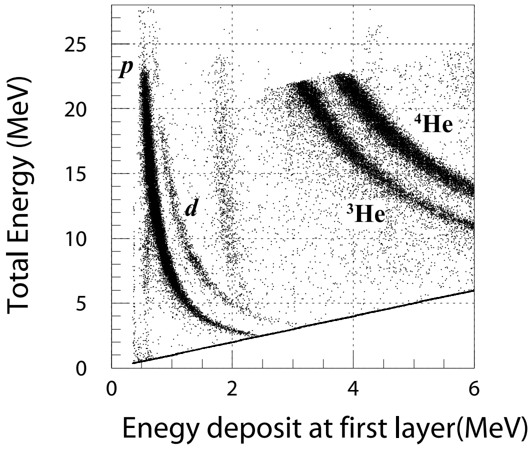

Figure 2: Energy of the particles measured with a silicon detector set. The thickness of the first layer is 70 μm.

angle. We measured data with almost full coverage between 0 and 45 degrees in laboratory frame, and thus we obtained complete information about the angular distribution. The final advantage is that we used the NaI detectors to evaluate the inelastic scattering events. The contribution of the inelastic scattering events should be taken into account for the precise evaluation of the excitation function.

3. Result

Figure 2 shows the energy deposit in the first layer and the total energy of the particles measured with one of the silicon ΔE-E telescopes. By comparing these with energy-loss calculations, we performed a clear identification of proton events, as indicated in the figure. Proton was the most frequently detected particle, but we also detected considerable amount of ^{3}He and ^{4}He, which may originated from ^{7}Be.

The proton energy at the reaction point E_p can be calculated from the measured proton energy, by evaluating the energy loss in the target. Then, the proton energy E_p can be converted into the center-of-mass energy $E_{\rm cm}$, with the following formula,

$$E_{\rm cm} = E_p \frac{m_1 + m_7}{4 m_7 \cos^2\theta}, \tag{3.1}$$

where m_1 and m_7 are the masses of proton and ^{7}Be, θ is the scattering angle. The excitation energy is the sum of center-of-mass energy of the elastic resonance scattering and the proton threshold energy (0.1375 MeV in this case),

$$E_{\rm ex} = E_{\rm cm} + E_{\rm th}. \tag{3.2}$$

Excitation functions were obtained by calculating the cross section from the numbers of the proton events, Figure 3 shows an excitation function at zero degree. The analysis is still going on, and this specturm should be regarded as a preliminary one. The cross section agree well with the past measurements [3, 7] in the energy region around the known 2.2 MeV resonance. The 3.5 MeV resonance, which was reported as a wide resonance, is not seen in this spectrum. Some part of the

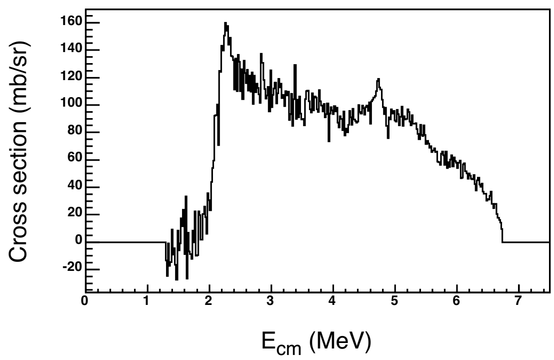

Figure 3: Preliminary analysis result on the proton excitation function of ^{7}Bemeasured at 0 degrees. The excitation energy of ^{8}B, $E_{\rm ex}$ equals to $E_{\rm cm}$+0.1375 MeV.

continuum in the spectrum is considered as contributions from inelastic scatterings and three-body decays of ^{8}B. In a near future, we will make a more detailed analysis including these effects.

4. Acknowledgments

We are grateful to RIKEN accelerator staff for their help. This work was supported by the Grant-in-Aid for Young Scientists (B) (Grant No. 17740135) of JSPS.

References

[1] C. Angulo, *et al.*, Nucl. Phys. A **656** (1999) 3.

[2] E. Adelberger, *et al.*, Rev. of Mod. Phys. **70** (1998) 1265.

[3] V. Gol'dberg *et al.*, *JETP Lett.* **67**, (1998) 1013.

[4] A. van Hees and P. Glaudemans, Z. Phys. A **314** (1983) 323.

[5] A. van Hees and P. Glaudemans, Z. Phys. A **315** (1984) 223.

[6] F. Barker, and A. Mukhamedzhanov, Nucl. Phys. A **673** (2000) 526.

[7] G. Rogachev *et al.*, Phys. Rev. C **64** (2001) 061601(R).

[8] A. Csótó *et al.*, Phys. Rev. C **61** (2000) 024311.

[9] S. Kubono *et al.*, Eur. Phys. J. A **13** (2002) 217.

[10] Y. Yanagisawa *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **539** (2005) 74.

[11] T. Teranishi *et al.*, Phys. Lett. B **556** (2003) 27.

[12] K.P. Artemov, *et al.*, Sov. J. Nucl. Phys. **52** (1990) 408.

[13] A. Huerta Hernandez, *et al.*, Nucl. Instrum. Methods B **143** (1998) 569.

[14] S. Kubono, Nucl. Phys. A **693** (2001) 221.

[15] H. Kumagai *et al.*, Nucl. Instrum. Methods A 470 (2001) 562.