PHOTODISINTEGRATION OF DEUTERIUM

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Abstract:
Photodisintegration cross sections were measured for deuterium with Laser Compton scattering γ beams at E_γ = 2.3 - 4.6 MeV. The present data made it possible to experimentally evaluate $R(E) = N_a \sigma v$ for the p(n,γ)D reaction with 6% uncertainty in the energy region relevant to big bang nucleosynthesis (BBN). The result confirms the past theoretical evaluation and the recent calculation based on the effective field theory. The reaction rate for the p(n,γ)D reaction is presented for the BBN in the precision era.

1. Introduction

Big bang nucleosynthesis (BBN), which is one of the cornerstones of big bang cosmology, has been developed based on the primeval abundances of four elements (D, ^{3}He, ^{4}He, ^{7}Li) [1-8]. BBN may be entering a precision era in view of the latest observations of deuterium abundances for quasar systems [9-12] and temperature anisotropies of the cosmic microwave background by WMAP [13]. In the precision era, the primeval abundance of deuterium is expected to play a role of a *cosmic baryometer* [14-17], because of its good sensitivity to baryon density.

Recently, a Monte Carlo method of directly incorporating nuclear inputs in the standard BBN calculations dramatically reduced uncertainties in the predicted abundances by as large as a factor of three [15, 18]. Among nuclear inputs for twelve key reactions in the standard BBN, however, only the one for p(n,γ)D is very scarce. Capture data for deuterium are available only at four energies relevant to the BBN [19, 20] though a large collection of photodisintegration data is available above 5 MeV [21-27]. In the energy region of the BBN, the cross section starts deviating from the $1/v$ law for the M1 capture and including the contribution from the E1 capture. The scarcity of data in this transitional energy region made a theoretical evaluation of the cross section mandatory. Although the theoretical cross section is available in the ENDF/B-VI data library [28], it is said that details of the evaluation are not possible to trace [15]. Very recently, revived attempts were made of evaluating the cross section within the framework of the effective field theory [29, 30].

Experimental cross sections for deuterium with sufficient accuracy are desired in the precision era. In this work, photodisintegration cross sections for deuterium were measured at 7 energies near threshold. We discuss the dependence of the p(n,γ)D reaction cross section on the energy relevant to the BBN in comparison with theoretical evaluations. We present the reaction rate of the p(n,γ)D reaction for BBN.

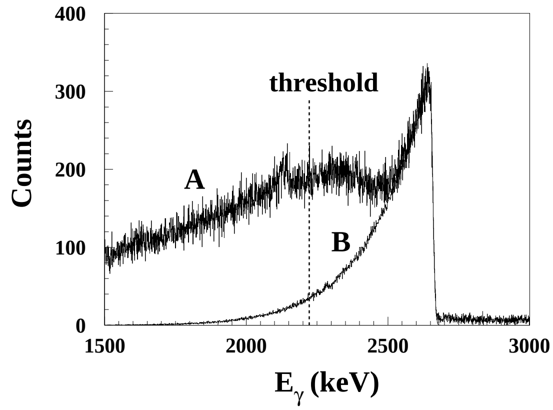

Figure 1: Response of a 120% Ge detector to the LCS γ rays (A) and an energy distribution of the LCS γ beam determined by a Monte Carlo analysis of the Ge response with the code EGS4 (B). A fractional γ flux above the threshold is responsible for the photodisintegration of deuterium.

2. Experimental method

The laser Compton scattering (LCS) γ beam has been developed at the National Institute of Advanced Industrial Science and Technology (AIST) [31, 32]. The LCS γ rays were produced in head-on collisions of Nd:YLF Q-switch laser photons with relativistic electrons in the accumulator ring TERAS. Quasi-monochromatic γ beams, which were collimated into a 2 mm spot in diameter with a 20 cm Pb block, were used to irradiate heavy water.

Energy spectra of the LCS γ rays were measured with a 120% Ge detector and analyzed with a Monte Carlo code EGS4 [33] to determine the tail profile of the LCS beam. An energy spectra of the LCS γ rays that best reproduced the Ge response (A) is shown (B) in Fig. 1. The fraction of LCS γ rays above 2.22 MeV was responsible for photodisintegration.

The total number of γ rays was determined from responses of a large volume (8 in. in diameter and 12 in. in thickness) NaI(Tl) detector to multi photons per pulse of the 1 kHz LCS beam and to single photons of the dc beam. The uncertainty in the total flux arose from nonlinearity in the response of our beam monitoring system to the pulsed multi photons. In view of the statistical analysis of pile-up spectra [34], we assigned 3% uncertainty to the γ flux.

The neutron detector consists of sixteen ^{3}He proportional counters (EURISYS MEASURES 96NH45) embedded in a polyethylene moderator. Eight counters were placed in a concentric ring at 7 cm from the beam axis; the other eight at 10 cm. The neutron detection efficiency was measured with a neutron source of ^{252}Cf whose uncertainty in the absolute neutron emission rate is 5%. The results for the ^{252}Cf source were well reproduced by Monte Calro simulations with the MCNP code [35]. The efficiencies for monoenergetic neutrons were calculated with the same code and were used in the data analysis.

3. Photodisintegration cross sections for deuterium

The present photodisintegration cross sections are shown in Fig. 2. The data analysis method and the numerical values of the cross sections are given in our recent paper [36, 37]. All the photonuclear data compiled in the IAEA document [38] are also shown in Fig. 2(a). In Fig. 2(b), the data of Bishop *et al.* [39], though not included in the IAEA compilation, are shown. The

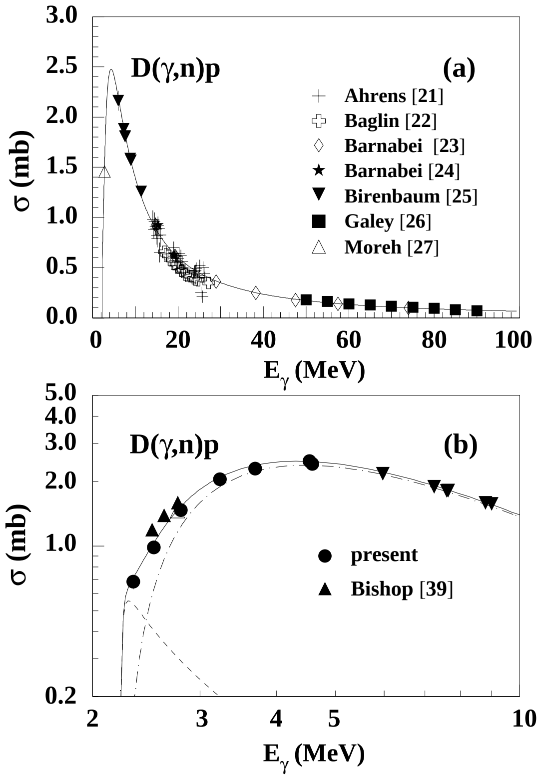

Figure 2: Photodisintegration cross sections for deuterium. The JENDL evaluations are shown by the dashed line for the M1 cross section, by the dot-dashed line for the E1 cross section, and by the solid line for the sum, respectively.

datum of Moreh *et al.* [27] is consistent with our data, whereas the data of Bishop *et al.* [39] are not. The solid line is the JENDL evaluation [40] which is the sum of the E1 (the dot-dashed line) and the M1 (the dashed line) cross sections. The JENDL evaluation is based on the M1 cross section of Segre [41] and the E1 cross section of the simplified Marshall-Guth model [42] below 10 MeV and that of Partovi above 10 MeV [43].

The systematic uncertainty of the cross section has three source: the neutron emission rate of the ^{252}Cf source (5%), the total flux of the LCS γ rays (3%), and the angular distribution of neutrons (2%). The overall systematic uncertainty is 6.2% after adding three sources in quadrature.

4. Evaluation of the reaction rate for the p(n,γ)D reaction

The present data were converted to capture cross sections with the detailed balance theorem. Figure 3 shows $R(E) = N_a \sigma v$ for the p(n,γ)D reaction as a function of the center of mass energy E, where N_a is the Avogadro's number, σ is the capture cross section, and v is the c.m. velocity. High-energy capture data [44-49] are also shown in the figure. A least squares fit was performed to the present data combined with the preceding data in the energy region up to 2 MeV. The preceding data included the latest thermal neutron capture datum [50], the capture data [19, 20], and the photodisintegration datum [27]. The data of Ref. [39] were not included in the fit. The same polynomial expansion formula as that [Eq. (19), m=5] in Ref. [7] was used. The thick solid

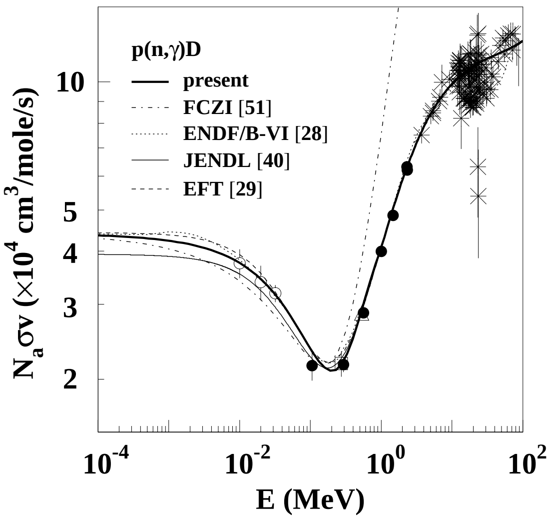

Figure 3: $R(E)$=$N_a\sigma v$ for the p(n,γ)D reaction as a function of the c.m. energy. Keys for the data are solid circles (present); open circles [19]; open square [20]; open triangle [27]. Only statistical uncertainties are shown for the present data. The high-energy data are from Refs. [44-49]. The dot-dashed line, the dotted line, the shin solid line, and the dashed line stand for the theoretical evaluations of FCZI [51], ENDF/B-VI [28], JENDL [40], and EFT [29], respectively. The solid line shows the present fit to the data connects to the JENDL evaluation at 1 MeV.

line shows the present fit to the data which is connected to the JENDL evaluation [40] at 1 MeV. The χ^2 value of the best fit was 0.61. The error involved in the fit was estimated to be 6%, which is dominated by the systematic uncertainty of the present measurement. For comparison, the theoretical evaluations of Fowler, Caughlan, and Zimmerman (FCZI) [51], ENDF/B-VI, and JENDL are shown by the dot-dashed line, the dotted line, and the thin solid line, respectively. In addition, the result of the effective field theory (EFT) calculation [29] is shown by the dashed line. The present $R(E)$ evaluation based on experimental data is consistent with the theoretical evaluations of the ENDF/B-VI and the EFT.

The reaction rate $N_a\langle\sigma v\rangle$, which is the thermal average of the present $R(E)$ function over the Maxwell-Boltzmann velocity distribution, was calculated in the temperature range $0.01<\mathrm{T}_9<100$. The numerical intergration was made from 0.1 keV to 100 MeV. The resultant reaction rate is presented by the solid line in Fig. 4 in comparison with the past theoretical evaluation of FCZI (dot-dashed line) and ENDF/B-VI (dotted line).

5. Conclusions

Photodisintegration cross sections for deuterium were measured at 7 energies near threshold with the LCS γ beams at AIST. These cross sections resolve the scarcity of data relevant to BBN. The present data combined with the preceding data provide an experimantal fundation for the p(n,γ)D reaction cross section which has been evaluated only theoretically for more than three decades since the FCZI. The present $R(E)$ evaluated with 6% uncertainty confirms those theoretical evaluations made in the past and the recent EFT calculation. The reaction rate for the p(n,γ)D reaction is presented for the BBN in the precision era.

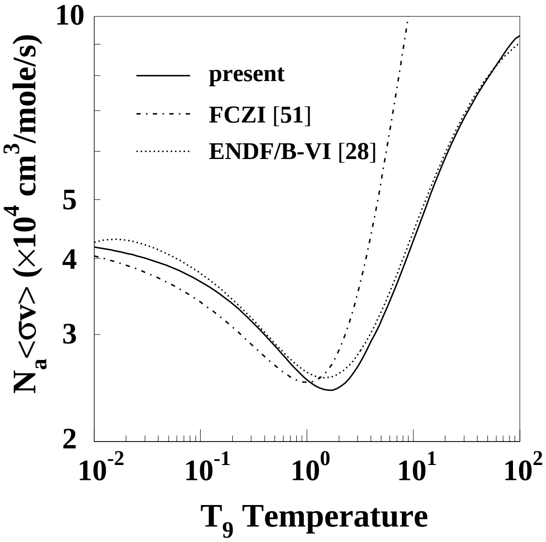

Figure 4: Reaction rate for the p(n,γ)D reaction. The solid line shows the present evaluation based on experimantal data. The theoretical evaluation of FCZI [51] and ENDF/B-VI [28] for the reaction rate were shown by the dotted line and the dashed line, respectively.

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