Photodisintegration of deuterium and big bang nucleosynthesis

K. Y. Hara, H. Utsunomiya, S. Goko, H. Akimune, T. Yamagata, and M. Ohta
Department of Physics, Konan University, Okamoto 8-9-1, Higashinada, Kobe 658-8501, Japan

H. Toyokawa, K. Kudo, A. Uritani, and Y. Shibata
National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

Y.-W. Lui
Cyclotron Institute, Texas A & M University, College Station, Texas 77843, USA

H. Ohgaki
Institute of Advanced Energy, Kyoto University, Gokanosho, Uji, Kyoto 611-0011, Japan

(Received 27 April 2003; revised manuscript received 24 June 2003; published 8 October 2003)

Photodisintegration cross sections were measured for deuterium with Laser-Compton scattering γ beams at seven energies near threshold. Combined with the preceding data, $R(E)=N_a\sigma v$ for the $p(n,\gamma)$D reaction is for the first time evaluated based on experimental data with 6% uncertainty in the energy region relevant to the big bang nucleosynthesis (BBN). The result confirms the theoretical evaluation on which the BBN in the precision era relies.

DOI: 10.1103/PhysRevD.68.072001 PACS number(s): 25.20.−x, 26.35.+c, 26.65.+t, 27.10.+h

I. INTRODUCTION

Deuterium is one of four elements (D, ^{3}He, ^{4}He, ^{7}Li) whose primeval abundances lend firm support to big bang cosmology. From the dawn [1–4] before the discovery of the cosmic microwave background (CMB) in 1965 [5], through the development era for the subsequent three decades [6–13], one might be witnessing the *precision era* of standard big bang nucleosynthesis (BBN) [14–16].

The recent observations of a primeval deuterium abundance [17–20] in metal-poor hydrogen clouds at high redshifts toward quasers alone might constrain the baryon density, for instance, providing a best value of $\Omega_b\ h^2=0.020\pm0.002$ [21]. This value is the highest possible value that is concordant with the primordial abundances of ^{4}He and ^{7}Li within statistical plus systematic uncertainties in observations. However, when limited only to the quoted statistical uncertainties, the overall concordance is lost in such a way that the baryon density allowed by the abundances of ^{4}He and ^{7}Li is separated by $\sim2\sigma$ from that by the D abundance [22].

The baryon density is one of cosmological parameters *embedded* in temperature anisotropies of the CMB detected by Boomerang [23], Maxima-i [24], and Dasi [25]. In the adiabatic inflationary model with the priors adopted for Hubble parameter and reionization optical depth, the baryon density inferred from the CMB may well agree with that derived from the primeval deuterium abundance [25]. It is to be noted, however, that the CMB result is sensitive to priors assumed for degenerated cosmological parameters [26–28], in particular, to primordial density fluctuations with broken scale invariance [29].

The *precision era* envisages reduction of the systematic errors by increasing samples of high-redshifts absorption systems and resolution of the degeneracies by missions of the Wilkinson Microwave Anisotropy Probe satellite [30] and Planck Surveyor.

Recently, a Monte Carlo method of directly incorporating nuclear inputs in the standard BBN calculations dramatically reduced the uncertainties in the calculated abundances by as large a factor as three [15,31]. Among nuclear inputs for 12 key reactions in the standard BBN, only the one for $p(n,\gamma)$D is very scarce. Capture data for D are available only at four energies relevant to the BBN [32,33] though a large collection of photodisintegration data is available above 5 MeV [34–40]. In the energy region of the BBN, the cross section starts deviating from the $1/v$ law for the M1 capture due to the contribution of the E1 capture. The scarcity of data in this transitional energy region forces a theoretical evaluation of the cross section. Although the theoretical cross section is available in the ENDF-B/VI data library [41], it is said that details of the theoretical evaluation are not possible to trace; consequently, an arbitrary 5% uncertainty of the cross section was employed in the Monte Carlo BBN code [15].

Experimental cross sections for deuterium with sufficient accuracy are desired because of the role of the primeval deuterium as a precision *cosmic barometer* that may help to clarify Galactic and stellar chemical evolution (^{3}He, ^{7}Li) and the cosmological limit to the number of light neutrino species (^{4}He) [14]. In addition to the BBN, the importance of the cross section also lies in the solar neutrino observation at the Sudbury Neutrino Observatory (SNO) via the neutral current reaction. The neutral current (NC) reaction, $\nu_x+\mathrm{D}\rightarrow\nu_x+p+n$, will determine the total neutrino flux because the reaction is equally sensitive to active neutrinos of all three flavors [42,43]. Neutrons, which are the signal of the NC interaction, are to be captured by the chlorine nuclei in highly purified NaCl added to the heavy water, liberating 8.6 MeV γ rays. However, neutrons are also produced in photodisintegration of D by γ rays above 2.2 MeV from the decay chain of U and Th in the detector components. Since the SNO is much more sensitive to radioactive backgrounds than Super Kamiokande [44], photodisintegration data near

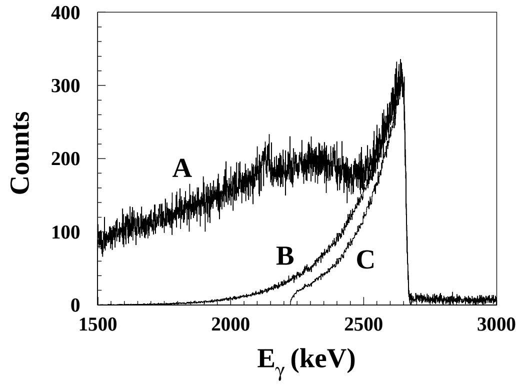

FIG. 1. Response of a 120% Ge detector to the LCS γ rays (A) and an energy distribution of the LCS γ beam determined by a Monte Carlo analysis of the Ge response with the code EGS4 (B). An energy distribution weighted with the best-fit cross sections is also shown (C). See text for details.

threshold are useful to estimate the background contribution [45].

In this paper, we provide photodisintegration cross sections for deuterium at seven energies near threshold. The present data can readily be incorporated in the Monte Carlo BBN code of Nollett and Burles [15]. We discuss the dependence of the $p(n,\gamma)$D reaction cross section on the energy relevant to the BBN in comparison with theoretical evaluations.

II. EXPERIMENTAL METHOD

Before emergence of Laser-Compton scattering (LCS) γ rays at synchrotron radiation facilities, the best photon source used in nuclear physics experiments was the positron annihilation in flight [46,47]. This source is characterized by a quasimonochromatic annihilation component accompanied by positron bremsstrahlung. In contrast, the LCS photon source based on nearly head-on collisions of laser photons on relativistic electrons is purely quasimonochromatic, being free from bremsstrahlung.

The experimental procedure is similar to that found in Ref. [48]. LCS γ beams developed at the National Institute of Advanced Industrial Science and Technology (AIST) [49] were used to irradiate heavy water. A Nd:YLF Q-switch laser with $\lambda = 1053$ nm was used. The LCS γ beam, which was collimated into 2 mm in diameter with a 20-cm Pb block, keeps 100% linear polarization of the laser photons unless it is depolarized by an optical element called depolarizer. Heavy water filled a 4.0 cm long cylindrical container made of aluminum with 50-μm Mylar foils being entrance and exit windows. The purity of the heavy water was determined to be $97 \pm < 1\%$ with a NMR spectrometer.

Energy spectra of the LCS γ rays were measured with a 120% Ge detector and analyzed with a Monte Carlo code EGS4 [50] to determine the tail profile of the LCS beam. An energy spectrum 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. Both the γ fraction and the neutron counting statistics tend to be small as the peak energy of the beam approaches the neutron threshold, constituting major sources of statistical uncertainty.

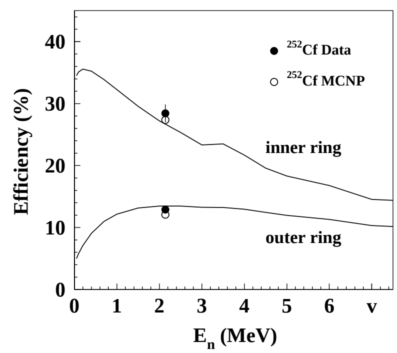

FIG. 2. Neutron detection efficiencies for the inner and outer rings of eight ^{3}He counters embedded in the polyethylene moderator, respectively. The solid circles are results measured for a calibrated ^{252}Cf source, while the open circles are results of the MCNP simulations for ^{252}Cf. The solid lines stand for efficiencies for neutrons with monochromatic energies obtained by the MCNP calculations.

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 multiphotons 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 multiphotons. In view of the statistical analysis of pileup spectra [51], we assign 3% uncertainty to the γ flux.

The neutron detector consists of 16 ^{3}He proportional counters (EURISYS MESURES 96NH45) embedded in a polyethylene moderator; two sets of eight counters are mounted in double concentric rings at 7 cm and 10 cm, respectively, from the beam axis. The neutron detection efficiency was measured with a neutron source of ^{252}Cf. The absolute neutron emission rate of the ^{252}Cf source was determined with 5% uncertainty relative to a calibrated source of 4 Ci Am/Be with a standard graphite pile. The detection efficiency is shown in Fig. 2. The results for the ^{252}Cf source (solid circles) were well reproduced by Monte Carlo simulations with the MCNP code [52] (open circles). The efficiencies for monoenergetic neutrons were calculated with the same code (solid lines). These were used in the data analysis (Sec. III.) Average neutron energies were kinematically calculated for the photodisintegration of deuterium with the LCS γ beam. The calculated energies were consistent with those derived from the so-called ring ratio of the detector.

Figure 3 shows time-to-amplitude (TAC) spectra for detecting neutrons with the inner and outer rings of eight ^{3}He counters embedded in the polyethylene moderator, respectively. The spectra were taken with signals from the ^{3}He counters as a start and the 1-kHz laser signals as a stop to an ORTEC-566 TAC module. The high-efficiency detector allowed us to separate reaction neutrons from background neutrons that time independently arrived at the ^{3}He counters with excellent single-to-noise ratios except near the neutron threshold.

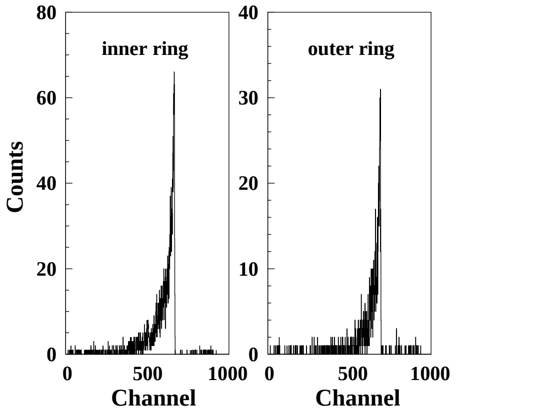

FIG. 3. Time-to-amplitude spectra for neutrons detected with the inner and outer rings of ^{3}He counters embedded in the polyethylene moderator, respectively. The TAC module (ORTEC 566) was started by signals from the ^{3}He counters and stopped by the 1-kHz laser signals after $\sim$750 μs delay. The time full scale is 1 ms.

III. DATA ANALYSIS

The number of neutrons emitted in the D(γ,n)p reaction is expressed by

$$N_n = n_T\left(\frac{1-e^{-\mu t}}{\mu t}\right)\int I_0(E'_\gamma)\sigma(E'_\gamma)dE'_\gamma, \tag{1}$$

where n_T is the number of target nuclei per cm^2, μ is the absorption coefficient for γ rays in the target material (D_2O), t is the target thickness, $I_0(E_\gamma)$ is the energy distribution of LCS γ rays, and $\sigma(E_\gamma)$ is the photodisintegration cross section for deuterium. Note that the term $(1-e^{-\mu t})/(\mu t)$ is characteristic of a thick-target measurement, where the condition $\mu t \ll 1$ is not necessarily met. The energy dependence of μ can be ignored due to the small energy spread of the LCS beam. Equation (1) can be approximated for the quasimonochromatic γ-ray beam by

$$N_n(\hat{E}_n) = n_T N_\gamma\left(\frac{1-e^{-\mu t}}{\mu t}\right)\sigma(\hat{E}_\gamma), \tag{2}$$

where N_γ is the number of LCS γ rays above the neutron separation energy S_n,

$$N_\gamma = \int_{S_n} I_0(E'_\gamma)dE'_\gamma, \tag{3}$$

and $\sigma(\hat{E}_\gamma)$ is weighted-average cross section with a weight $I_0(E_\gamma)$. By definition,

$$\sigma(\hat{E}_\gamma) = \frac{\int I_0(E'_\gamma)\sigma(E'_\gamma)dE'_\gamma}{N_\gamma}. \tag{4}$$

The weighted-average cross section is experimentally determined from Eq. (2),

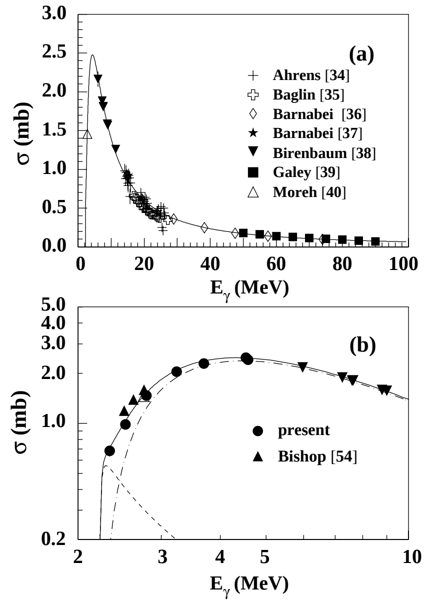

FIG. 4. Photodisintegration cross sections for deuterium. The JENDL evaluations are shown by the dashed line for the M1 cross section, by the dot-dahsed line for the E1 cross section and by the solid line for the sum.

$$\sigma(\hat{E}_\gamma) = \frac{N_n(\hat{E}_n)}{n_T N_\gamma\left(\frac{1-e^{-\mu t}}{\mu t}\right)}. \tag{5}$$

Since the weighted energies of γ rays and neutrons ($\hat{E}_\gamma, 2\hat{E}_n = \hat{E}_\gamma - S_n$) remain unknown until $\sigma(E_\gamma)$ is determined, we replaced $\hat{E}_\gamma$ with the average energy $\overline{E}_\gamma$ of the quasimonochromatic γ rays. $N_n(\overline{E}_n)$ was determined from the number of neutrons detected by the ^{3}He counters with the efficiency $\varepsilon(\overline{E}_n)$. Uncertainties in the γ energy were estimated in the following iteration procedure. First, a best fit to the dataset ($\overline{E}_\gamma$, $\sigma(\overline{E}_\gamma)$) $\sigma^{fit}(E_\gamma)$ was obtained. Then, a weighted-average energy $\hat{E}_\gamma^{fit}$ is calculated for $I_0(E_\gamma)$ with a weight $\sigma^{fit}(E_\gamma)$. It is most plausible that the true value of $\hat{E}_\gamma$ lies in the interval of $\overline{E}_\gamma \pm \Delta E_\gamma (=\hat{E}_\gamma^{fit} - \overline{E}_\gamma)$. In Fig. 1, a weighted energy distribution of LCS γ rays (C) is shown in comparison with the original distribution (B). The resultant uncertainty (ΔE_γ) is of the order of 20 keV near the neutron threshold and several tens of keV at higher LCS beam energies. ΔE_γ at higher energies are determined by uncertainties of the low-energy tail of the distribution $I_0(E_\gamma)$ rather than by the weight $\sigma^{fit}(E_\gamma)$.

IV. RESULTS AND DISCUSSION

Figure 4 shows photodisintegration cross sections for deuterium as a function of the average γ-ray energy. Numerical values are given in Table I. All the photonuclear data compiled in the IAEA document [53] are also shown in Fig. 4(a). In Fig. 4(b), the data of Bishop *et al.* [54], though not included in the IAEA compilation, are shown. The datum of Moreh *et al.* [40] is consistent with our data, whereas the data of Bishop *et al.* [54] are not. The solid line is the

TABLE I. Photodisintegration cross sections for deuterium determined in the present measurement. The cross section is given as $\sigma \pm \Delta\sigma$ (stat.) $\pm\Delta\sigma$ (syst.) in units of millibarn, where $\Delta\sigma$ (stat.) and $\Delta\sigma$ (syst.) give the statistical and systematic uncertainties, respectively. E_γ and ΔE_γ are, respectively, the average energy of the LCS γ beam and associated uncertainty.

E_γ (MeV)	ΔE_γ (keV)	σ (mb)	$\Delta\sigma$ (stat.) (mb)	$\Delta\sigma$ (syst.) (mb)
2.33	18	0.683	0.053	0.042
2.52	18	0.983	0.039	0.061
2.79	22	1.47	0.03	0.09
3.23	50	2.04	0.04	0.13
3.69	42	2.29	0.04	0.14
4.53	88	2.48	0.04	0.15
4.58	60	2.41	0.02	0.15

JENDL evaluation [55,56] 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 [57] and the E1 cross section of the simplified Marshall-Guth model [58] below 10 MeV and that of Partovi above 10 MeV [59].

The systematic uncertainty of the cross section has three sources: 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. The effect of the neutron angular distribution, $d\sigma/d\Omega$, on the neutron detection efficiency was investigated with the MCNP code, where angular distributions were calculated with the formula of Ref. [58] for the E1 process and an isotropic angular distribution for the M1 process [57] was added. The resultant uncertainty was 2% in the present 4π-type measurement. The overall systematic uncertainty is 6.2% after adding three sources in quadrature.

All the data except for the datum at 4.58 MeV were taken with 100% linearly polarized LCS γ beams. The center-of-mass differential cross section for the $D(\vec{\gamma},n)p$ reaction can be written as [59,60]

$$\frac{d\sigma}{d\Omega} = S_0(\theta)[1+\Sigma(\theta)\cos 2\varphi], \tag{6}$$

where $S_0(\theta)$ is the cross section for a nonpolarized γ beam, θ is the angle between the neutron and photon momenta, $\Sigma(\theta)$ is the asymmetry of the differential cross section, and φ is the angle between the polarization and reaction planes. The difference between the c.m. and laboratory systems can be ignored in the present low-energy measurement because $\hbar\omega$ (the γ energy) $\ll M_d c^2$ (the rest mass energy of deuterium). Summing neutron events over the 16 ^{3}He counters in the concentric-ring configuration makes the φ-dependent term in Eq. (6) vanish. Thus, the present measurement with a polarized beam is in principle equivalent to that with a nonpolarized beam. Note, of course, that the polyethylene moderator smeared out the φ dependence of the neutron emission to large extent before the summing. As seen in Table I, the data taken with the 4.53-MeV-polarized beam and the 4.58-MeV-depolarized beam well agree with each other within the experimental uncertainties.

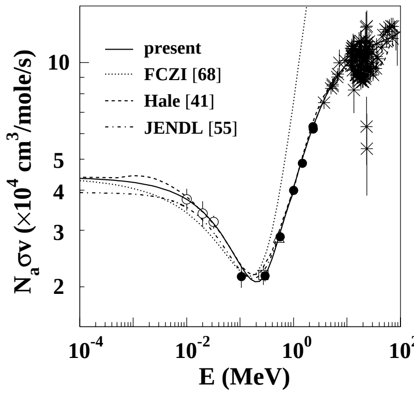

FIG. 5. $R(E)=N_a\sigma v$ for the $p(n,\gamma)$D reaction as a function of the c.m. energy. Keys for the data are solid circles (present); open circles [32]; open square [33]; and open triangle [40]. Only statistical uncertainties are shown for the present data. The high-energy data are from Refs. [61–66]. The dotted line, the dashed line, and the dot-dashed line stand for the theoretical evaluations of FCZI [68], Hale *et al.* [41], and the JENDL [55], respectively. The solid line shows the best fit to the data connected to the JENDL evaluation at 1 MeV.

Figure 5 shows $R(E)=N_a\sigma v$ 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. The present data were converted to capture cross sections with the detailed balance theorem. High-energy capture data [61–66] are also shown in the figure. A least squares fit to all available data including the latest thermal neutron capture datum [67], the capture data [32,33], and the photodisintegration datum [40] was performed in the energy region up to 2 MeV. The data of Ref. [54] were not included in the fit. The same polynomial expansion formula as that [Eq. (19), m=5] in Ref. [12] was used. The solid line shows the best fit to the data which is connected to the JENDL evaluation at 1MeV. The χ^2 value of the best fit was 0.61. For comparison, the theoretical evaluations of Fowler, Caughlan, and Zimmerman (FCZI) [68], Hale *et al.* [41], and the JENDL are shown by the dotted line, the dashed line, and the dot-dashed line, respectively.

The error involved in the experimental evaluation of $R(E)$ was estimated as follows. A normalization factor a was introduced to the best-fit curve and the χ^2 was calculated as a function of a with the 12 data points in the energy region of 0.01–2.4 MeV. The error for the normalization factor was deduced from the condition that the χ^2 value per degree of freedom changes by unity. The resultant error was 6%, which is dominated by the systematic uncertainty of the present measurement.

V. CONCLUSIONS

Photodisintegration cross sections for deuterium were measured at seven energies near threshold with the LCS γ beams at AIST. These cross sections resolve the scarcity of data relevant to big bang nucleosynthesis and help to estimate the major background in the neutral current observation at the SNO. The present data combined with the preceding data provide an experimental foundation for the $p(n,\gamma)$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.

ACKNOWLEDGMENTS

This work was supported in part by the Japan Private School Promotion Foundation and by the Japan Society for the Promotion of Science under the program Grant-in-Aid for Science Research (C).

[1] R.A. Alpher, H. Bethe, and G. Gamow, Phys. Rev. **73**, 803 (1948).
[2] C. Hayashi, Prog. Theor. Phys. **5**, 224 (1950).
[3] E. Fermi and A. Turkevich, quoted in R.A. Alpher and R.C. Herman, Rev. Mod. Phys. **22**, 153 (1950).
[4] F. Hoyle and R.J. Tayler, Nature (London) **203**, 1108 (1964).
[5] A.A. Penzias and R.W. Wilson, Astrophys. J. **142**, 420 (1965).
[6] P.J.E. Peebles, Phys. Rev. Lett. **16**, 410 (1966); Astrophys. J. **146**, 542 (1966).
[7] R.V. Wagoner, W.A. Fowler, and F. Hoyle, Astrophys. J. **148**, 3 (1967).
[8] H. Sato, Prog. Theor. Phys. **38**, 1083 (1967).
[9] H. Reeves, J. Audouze, W.A. Fowler, and D. Schramm, Astrophys. J. **179**, 909 (1973).
[10] L.M. Krauss and P. Romanelli, Astrophys. J. **358**, 47 (1990).
[11] T.P. Walker, G. Steigman, D.N. Schramm, K.A. Olive, and H.-S. Kang, Astrophys. J. **376**, 51 (1991).
[12] M.S. Smith, L.H. Kawano, and R.A. Malaney, Astrophys. J., Suppl. Ser. **85**, 219 (1993).
[13] C.J. Copi, D.N. Schramm, and M.S. Turner, Science **267**, 192 (1995).
[14] D.N. Schramm and M.S. Turner, Rev. Mod. Phys. **70**, 303 (1998).
[15] K.M. Nollett and S. Burles, Phys. Rev. D **61**, 123505 (2000).
[16] K.A. Olive, G. Steigman, and T.P. Walker, Phys. Rep. **333-334**, 389 (2000).
[17] S. Burles and D. Tytler, Astrophys. J. **499**, 699 (1998).
[18] S. Burles and D. Tytler, Astrophys. J. **507**, 732 (1998).
[19] D. Kirkman, D. Tytler, S. Burles, D. Lubin, and J.M. O'Meara, Astrophys. J. **529**, 655 (2000).
[20] J.M. O'Meara, D. Tytler, D. Kirkman, N. Suzuki, and J.X. Provhaska, Astrophys. J. **552**, 718 (2001).
[21] S. Burles, K.M. Nollett, and M.S. Turner, Astrophys. J. Lett. **552**, L1 (2001).
[22] Particle Data Group, K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002).
[23] C.B. Netterfeld *et al.*, Astrophys. J. **571**, 604 (2002).
[24] D. Stompor *et al.*, Astrophys. J. Lett. **561**, L7 (2001).
[25] C. Pryke *et al.*, Astrophys. J. **568**, 46 (2002).
[26] M. Tegmark, M. Zaldarriaga, and A.J.S. Hamilton, Phys. Rev. D **63**, 043007 (2001).
[27] J.P. Kneller, R.J. Scherrer, G. Steigman, and T.P. Walker, Phys. Rev. D **64**, 123506 (2001).
[28] R. Trotta, A. Riazuelo, and P. Durrer, Phys. Rev. Lett. **87**, 231301 (2001).
[29] J. Barriga, E. Gaztañaga, M.G. Santos, and S. Sarker, Mon. Not. R. Astron. Soc. **324**, 977 (2001).
[30] See, http://map.gsfc.nasa.gov/
[31] S. Burles, K.M. Nollett, J.W. Truran, and M.S. Turner, Phys. Rev. Lett. **82**, 4176 (1999).
[32] T.S. Suzuki *et al.*, Astrophys. J. Lett. **439**, L59 (1995).
[33] Y. Nagai *et al.*, Phys. Rev. C **56**, 3173 (1997).
[34] J. Ahrens *et al.*, Phys. Lett. **56B**, 49 (1974).
[35] J.E.E. Baglin, R.W. Carr, E.J. Bentz, and C.-P. Wu, Nucl. Phys. **A201**, 593 (1973).
[36] R. Bernabei *et al.*, Phys. Rev. Lett. **57**, 1542 (1986).
[37] R. Bernabei *et al.*, Phys. Rev. C **38**, 1990 (1988).
[38] Y. Birenbaum, S. Kahane, and R. Moreh, Phys. Rev. **32**, 1825 (1985).
[39] J.A. Galey, Phys. Rev. **117**, 763 (1960).
[40] R. Moreh, T.J. Kennett, and W.V. Prestwich, Phys. Rev. C **39**, 1247 (1989).
[41] G.M. Hale, D.C. Dodder, E.R. Siciliano, and W.B. Wilson, Los Alamos National Laboratory, ENDF/B-VI evaluation, Mat No. 125, Rev. 1 1991.
[42] J.N. Bahcall, F. Calaprice, A.B. McDonald, and Y. Totsuka, Phys. Today **49** (7), 30 (1996).
[43] Q.R. Ahmad *et al.*, Phys. Rev. Lett. **87**, 071301 (2001).
[44] B. Schwarzschild, Phys. Today **54** (8), 13 (2001).
[45] Y.-D. Chan (private communication).
[46] R.L. Bramblett, J.T. Cladwell, G.F. Auchampaugh, and S.C. Fultz, Phys. Rev. **129**, 2723 (1963).
[47] R. Bergère, H. Beil, and A. Veyssière, Nucl. Phys. **A121**, 463 (1968).
[48] H. Utsunomiya *et al.*, Phys. Rev. C **67**, 015807 (2003).
[49] H. Ohgaki *et al.*, IEEE Trans. Nucl. Sci. **38**, 386 (1991).
[50] W.R. Nelson, H. Hirayama, and W.O. Roger, ''The EGS4 Code Systems'' SLAC-Report No. 265 1985.
[51] H. Toyokawa *et al.*, IEEE Trans. Nucl. Sci. **47**, 1954 (2000).
[52] J.F. Briesmeister, computer code MCNP, Version 4C (Los Alamos National Laboratory, Los Alamos, 2000).
[53] Photonuclear data for applications, ''Cross Sections and Spectra,'' IAEA Report No. 1178, 2000.
[54] G.R. Bishop *et al.*, Phys. Rev. **80**, 211 (1950).
[55] T. Murata, Technical Report No. JAERI-M 94-019 1994.
[56] N. Kishida, T. Murata, T. Asami, K. Maki, and T. Fukahori, J. Nucl. Sci. Technol. **2**, 56 (2002).
[57] E. Segre, *Nuclei and Particles* (Benjamin/Cummings, Mento Park, CA, 1977), p. 496.
[58] J.F. Marshall and E. Guth, Phys. Rev. **78**, 738 (1950).
[59] F. Partovi, Ann. Phys. (N.Y.) **27**, 79 (1964).
[60] W. Del Bianco *et al.*, Phys. Rev. Lett. **47**, 1118 (1981).
[61] M. Bosman *et al.*, Phys. Rev. B **82**, 212 (1979).
[62] T. Stiehler *et al.*, Phys. Rev. B **151**, 185 (1985).
[63] M. Cerineo, K. Ilakovac, I. Šlaus, and P. Tomaš, Phys. Rev. **124**, 1947 (1961).

[64] C. Dupont, P. Leleux, P. Lipnik, P. Macq, and A. Ninane, Nucl. Phys. **A445**, 13 (1985).
[65] P. Michel, K. Moeller, J. Moesner, and G. Schmidt, J. Phys. G **15**, 1025 (1989).
[66] P. Wauters *et al.*, Few-Body Syst. **8**, 1 (1990).
[67] S.F. Mughabghab, M. Divadeenam, and N.E. Holden, *Neutron Cross Sections, Vol. 1, Neutron Resonance Parameters and Thermal Cross Sections, Part A,* $Z=1-60$ (Academic, New York, 1981).
[68] W.A. Fowler, G.R. Caughlan, and B.A. Zimmerman, Annu. Rev. Astron. Astrophys. **5**, 525 (1967).