Photodisintegration Cross Section of the Reaction ^{4}He(γ, p)^{3}H between 22 and 30 MeV

R. Raut,[1,2,*] W. Tornow,[1,2] M. W. Ahmed,[1,2,3] A. S. Crowell,[1,2] J. H. Kelley,[4,2] G. Rusev,[1,2] S. C. Stave,[1,2] and A. P. Tonchev[1,2]

[1]*Duke University, Durham, North Carolina 27708-0308, USA*
[2]*Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308, USA*
[3]*North Carolina Central University, Durham, North Carolina 27707, USA*
[4]*North Carolina State University, Raleigh, North Carolina 27695, USA*

(Received 10 August 2011; published 25 January 2012)

The two-body photodisintegration cross section of ^{4}He into a proton and triton was measured with monoenergetic photon beams in 0.5 MeV energy steps between 22 and 30 MeV. High-pressure ^{4}He-Xe gas scintillators of various ^{4}He/Xe ratios served as targets and detectors. Pure Xe gas scintillators were used for background studies. A NaI detector together with a plastic scintillator paddle was employed for determining the incident photon flux. Our comprehensive data set follows the trend of the theoretical calculations of the Trento group very well, although our data are consistently lower in magnitude by about 5%. However, they differ significantly from the majority of the previous data, especially from the recent data of Shima *et al*. The latter data had put into question the validity of theoretical approaches used to calculate core-collapse supernova explosions and big-bang nucleosynthesis abundances of certain light nuclei.

DOI: 10.1103/PhysRevLett.108.042502 PACS numbers: 21.45.−v, 21.30.Fe, 24.30.Cz, 25.10.+s

For many reasons the ^{4}He nucleus is often considered as the link between the classical few-body systems, i.e., deuteron, triton, and ^{3}He, which do not have excited states, and more complex nuclei. Because of the increased complexity of rigorous four-nucleon (4N) calculations as compared to three-nucleon (3N) calculations, the theoretical treatment of the photodisintegration of ^{4}He is not as advanced as that of ^{3}He or ^{3}H. Only recently it became possible to calculate the total photoabsorption cross section of ^{4}He [1] with a realistic nucleon-nucleon (NN) potential (Av18) [2] and a three-nucleon force (3NF) (Urbana IX [3]) using the Lorentz integral transform (LIT) method of the Trento group [4]. These calculations reproduce the strong giant dipole-resonance peak, but they provide only a 6% reduction in the cross section in this energy regime once the 3NF is turned on. This is a surprising result, because the same kind of calculation yields an 8% reduction of the 3N photodisintegration cross section [5], where 3NF effects are expected to be much smaller. Also recently, the total photoabsorption cross section of ^{4}He was calculated [6] using NN and 3N interactions based on chiral effective field theory (ChEFT) [7], again employing the LIT method, but this time in conjunction with the *ab initio* no-core shell-model approach [8]. The ChEFT method allows for a consistent treatment of NN and 3N interactions and their associated currents. These calculations basically support the findings of Ref. [1]. However, any comparison of theoretical results with experimental total photoabsorption cross-section data is inconclusive [4,6] due to the large discrepancy between individual data sets.

Unfortunately, it is more difficult to calculate exclusive reactions, i.e., the individual photodisintegration cross sections, than the total photoabsorption cross section. Theoretical calculations for the ^{4}He(γ, p)^{3}H photodisintegration cross section are available from the Trento group [9] in the energy region of interest. Their results were obtained with the semirealistic central NN potential of the Malfliet-Tjon I-III type [10], including the Coulomb interaction, and taking into account the full-final state interaction via the LIT method.

As can be seen in Fig. 1, the status of the total photodisintegration cross-section data for the two-body reaction ^{4}He(γ, p)^{3}H is very unsatisfactory, and it basically mirrors the status of the available total photoabsorption cross section data. In the energy region shown (between E_γ = 20 and 35 MeV) the experimental data are scattered considerably, and they hardly provide any guidance to judge the quality of theoretical approaches. The data shown in Fig. 1 by solid symbols were obtained with photon beams (mostly bremsstrahlung beams), while the data presented by open symbols were deduced from the time-reversed radiative-capture reaction using the principle of detailed balance. The calculation of the Trento group (solid curve in Fig. 1) seems to support the upper band of the available experimental results, while the recent data of Shima *et al.* [11] (large solid dots in Fig. 1), obtained with a quasi monoenergetic photon beam and a time-projection chamber, are about a factor of 2 lower than the prediction of the Trento group at about 26 MeV. Clearly, some of the data are incorrect. Obviously, systematic uncertainties are underestimated considerably in some cases. The goal of this work is to provide theory with a recommended set of cross-section data for the ^{4}He(γ, p)^{3}H reaction.

The data of Shima *et al.* suggest that the peak of the giant dipole resonance is located at energies above 30 MeV.

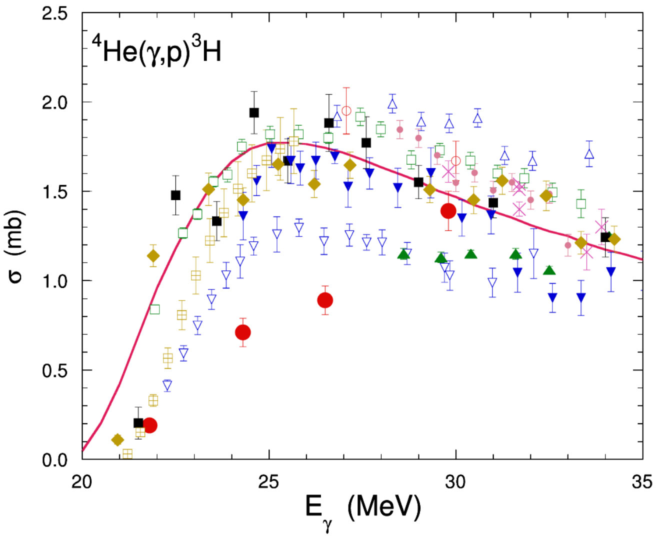

FIG. 1 (color online). Existing data for the photodisintegration cross section of the reaction ^{4}He$(\gamma, p)^3$H in comparison to the calculation of the Trento group [9]. The data shown by solid symbols were obtained with bremsstrahlung beams, except for the data of Shima *et al.* [11] (large solid dots) and Bernabei *et al.* [28] (upside solid triangles), which were obtained with monoenergetic photon beams. The data indicated by open symbols are from the radiative-capture reaction ^{3}H$(p, \gamma)^4$He using the principle of detailed balance. The data given by crosses [29] were obtained with an incident electron beam. Symbols and references for the other data are solid squares [18], solid diamonds [20], downside solid triangles [21], small solid dots [30], open squares with inside cross [22], open squares [23], upside open triangles [31], open dots [32], downside open triangles [33].

Because of the analogy between the operators involved in electromagnetic and neutrino induced nuclear reactions, this latter finding led to the conjecture that theory is not able to correctly calculate neutrino-nucleus cross sections [12], which are important for understanding the dynamics and properties of core-collapse supernova explosions. In particular, precise knowledge of the ^{4}He$(\nu, \nu' p)$, ^{4}He$(\nu, \nu' n)$, ^{4}He$(\nu_e, e^- p)$, and ^{4}He$(\bar{\nu}_e, e^+ n)$ cross sections is needed. The result of Shima *et al.* also led to theoretical studies of its impact on big-bang nucleosynthesis [12], resulting in a sizable change of the nonthermal production yields of ^{2}H, ^{3}He, and ^{4}He.

In view of these far-reaching consequences a measurement of the ^{4}He$(\gamma, p)^3$H total (i.e., angle-integrated) photodisintegration cross section was undertaken at the High-Intensity Gamma-ray Source (HIγS) [13], using an experimental approach similar to the one very recently applied for measurements of the total photodisintegration cross section of the reaction ^{3}He$(\gamma, p)^2$H [14].

We used high-pressure ^{4}He-Xe gas scintillators with total pressure of 51 atm as target and detector. In such detectors the measured pulse height is a linear function of the deposited energy, independent of the nature of the strongly ionizing particles [15]. High-pressure noble-gas scintillators have been studied extensively in the 1950s and 1960s (see Ref. [16] for an overview). Except for wall effects, their efficiency for detecting charged particles is known to be 1.0. This feature is due to the special characteristics of excitation and ionization of noble gases and their subsequent deexcitation. The Q value of the ^{4}He$(\gamma, p)^3$H reaction is -19.81 MeV. For monoenergetic incident γ rays of 26 MeV, the total energy deposited by the proton plus triton is 6.2 MeV, while the proton alone has a maximum energy of 5.2 MeV. In pure ^{4}He gas pressurized to 51 atm, the range of those protons is about 4.6 cm, resulting in unwanted wall effects in our 5.1 cm diameter cylindrical stainless steel vessels of 0.1 cm wall thickness [14,15]. Therefore, depending on the incident γ-ray energy, we added xenon at concentrations ranging from 7% to 47% (keeping the total pressure at 51 atm), thus providing the necessary stopping power for the maximum proton range to be less than 1.5 cm. In order to check on photon-induced reactions on xenon and the MgO coating on the inner surface of the scintillator vessel [15], runs were taken with identical scintillator vessels filled with xenon only.

The photons were produced via Compton backscattering of free-electron laser (FEL) photons from relativistic electrons in one of the two straight sections of the Duke University electron storage ring [13]. The electron energies were varied between 650 and 750 MeV and the FEL wavelength was changed between 350 and 400 nm to cover the γ-ray energy range between 22.0 and 29.5 MeV. Typically, the electron current in the storage ring was kept constant at 40 mA. Two 1 cm diameter and 10 cm long collimators made of lead defined the diameter and energy spread of the incident monoenergetic γ-ray beam. The total energy spread (FWHM) was about 0.5 MeV at the lowest energy and about 0.8 MeV at the highest energy studied in the present work. The actual γ-ray energies were determined using a calibrated NaI detector. The absolute photon flux was obtained using the combination of a 10 in. diameter $\times$ 12 in. long NaI detector and the HIγS scintillator paddle system [17]. In order to eliminate pile-up events in the ^{4}He-Xe gas scintillator, and to operate the HIγS scintillator paddle system used for relative flux determination in its linear counting-rate range, an 8 cm long attenuator made of copper was inserted into the γ-ray beam (inside of the concrete shielding wall some 50 m upstream of the location of the ^{4}He-Xe gas scintillator), reducing the γ-ray flux on target to $\sim 4 \times 10^6$ γ/s.

Figure 2 shows typical spectra obtained with incident γ-ray energies of 22.0 MeV for a 47.6 atm ^{4}He-3.4 atm Xe gas scintillator [2(a)] and of 28 MeV for a 27.2 atm ^{4}He-23.8 atm Xe [2(c)] gas scintillator. The yield at small pulse heights is dominated by electrons. The pulses of interest due to the protons and tritons from the two-body breakup of ^{4}He generate the enhancement seen at higher pulse heights. The background due to photon-induced

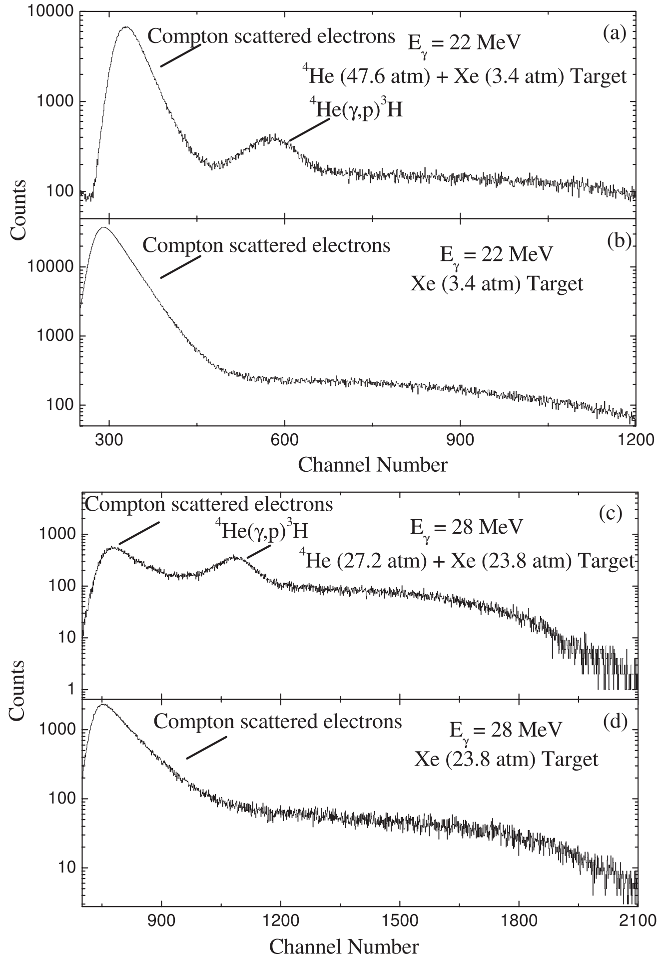

FIG. 2. Spectra for incident γ energies $E_\gamma = 22.0$ MeV (a),(b) and 28.0 MeV (c),(d). Notice the logarithmic vertical scales.

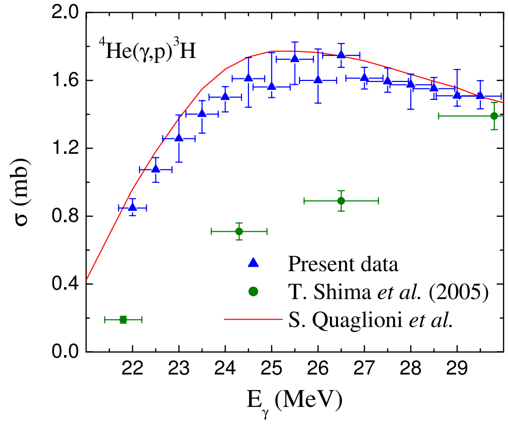

FIG. 3 (color online). Present results (triangles with error bars) for the total cross section of the reaction ^{4}He$(\gamma, p)^3$H in comparison with the data of Shima *et al.* [11] (dots with error bars) and the theoretical calculation of the Trento group [9]. The horizontal error bars are a measure of the energy spread of the incident monoenergetic photon beams. Our data at energies above 27.0 MeV were corrected for events originating from the three-body and four-body photodisintegration reactions ^{4}He$(\gamma, pn)^2$H and ^{4}He$(\gamma, 2p2n)$, respectively, which are estimated to contribute to the measured yield between 27.5 and 29.5 MeV at the 0.5%–2.5% level, respectively.

reactions on Xe and the vessel wall extends to even higher pulse heights. The associated pure xenon spectra are shown in Figs. 2(b) and 2(d), indicating a smooth background in the region of interest. Our data were corrected for losses of events due to wall effects using Monte Carlo techniques. Because of the $\sin^2\theta$ angular distribution of the differential cross section, the associated corrections were fairly small, reaching 1.4% at 29.5 MeV. Differential cross-section data were taken from Ref. [18].

Figure 3 shows our data for the total photodisintegration cross section of the reaction ^{4}He$(\gamma, p)^3$H in comparison to the recent data of Shima *et al.* (dots) and the theoretical prediction of the Trento group (solid curve). The horizontal error bars associated with our data are a measure of the energy spread of the incident photon beam and do not reflect the uncertainty of the mean photon energy, which is more than 1 order of magnitude lower. As can be seen from Table I, the statistical uncertainty of our data is 1% or less. The uncertainty in the incident γ-ray flux determination is $+2\%$ and -4%. This asymmetric uncertainty is due to the fact that our calculated NaI detector efficiency of 0.98 cannot be larger than 1.0. We estimate that our background subtraction procedure contributes an additional uncertainty of about 3%–10%. The uncertainty associated with determining the helium content in our gas scintillators is 1%. All those uncertainties were added in quadrature, resulting in a total uncertainty of 5%–13%.

As can be seen in Fig. 3, our data below 27 MeV are in glaring disagreement with the recent three data points of Shima *et al*. However, our highest energy data support the datum of Shima *et al.* near 30 MeV. It should be mentioned that very recently Shima *et al.* [19] extended their measurements to photon energies up to 37 MeV, confirming their datum just below 30 MeV, and indicating a maximum cross section in the 32–33 MeV energy range. Comparing Figs. 1 and 3 one notices that the current data are in very good agreement with the early photon data of Arkatov *et al.* [20] and Balestra *et al.* [21], while the radiative-capture data provide either too large or too small cross-section values, except for the data of Perry and Bame [22] above 22 MeV and Meyerhof *et al.* [23] below 27 MeV. Our data closely follow the trend of the theoretical calculations of the Trento group, although the former are consistently lower in magnitude by about 5%, except at energies above 28 MeV, where data and calculations seem to agree. Given that the semirealistic potential used by the Trento group overbinds ^{4}He considerably, the agreement between the present data and the available calculations is satisfactory. Calculations using realistic NN potentials and 3NFs are currently being pursued by Gazit and his group and their collaborators from Trento [24]. At incident photon energies above 26.1 MeV, the three-body photodisintegration

TABLE I. ^{4}He(γ, p)^{3}H reaction cross-section values.

E_γ (MeV)	σ (mb)	$\pm\Delta\sigma_{stat}$ (mb)	$\pm\Delta\sigma_{total}$ (mb)
22.0	0.848	0.005	$+0.055 - 0.045$
22.5	1.074	0.008	$+0.071 - 0.074$
23.0	1.257	0.013	$+0.139 - 0.139$
23.5	1.401	0.011	$+0.080 - 0.112$
24.0	1.501	0.012	$+0.077 - 0.087$
24.5	1.610	0.012	$+0.124 - 0.168$
25.0	1.561	0.011	$+0.202 - 0.085$
25.5	1.724	0.011	$+0.102 - 0.148$
26.0	1.600	0.008	$+0.185 - 0.134$
26.5	1.747	0.009	$+0.089 - 0.089$
27.0	1.613	0.009	$+0.080 - 0.080$
27.5	1.594	0.007	$+0.085 - 0.084$
28.0	1.574	0.010	$+0.063 - 0.144$
28.5	1.551	0.010	$+0.087 - 0.083$
29.0	1.509	0.010	$+0.155 - 0.083$
29.5	1.507	0.011	$+0.091 - 0.075$

channel of ^{4}He is kinematically accessible. Theoretical calculations [9] and experimental data [25–27] indicate that this cross section is only a few percent of the two-body photodisintegration cross section. Using the three-body photodisintegration cross-section data of Refs. [25–27], and taking into account the energy spread of the incident photon beam and the energy resolution of our gas scintillator, it is estimated that our raw datum at 29.5 MeV is contaminated at the 2% level by events originating from the three-body photodisintegration of ^{4}He. Because of the tiny cross section of the four-body photodisintegration just above threshold (28.3 MeV), our data are even less affected by events from this reaction. Corrections for the effect of the three- and four-body photodisintegration cross sections [25–27] have been applied to the data shown in Fig. 3 above $E_\gamma = 27.0$ MeV.

As stated earlier, the calculations of the Trento group are based on a semirealistic NN potential and, in addition, do not include 3NF effects. Comparing the results of Refs. [1] and [6], the total photoabsorption cross section does not appear to be very sensitive to details of the NN potential employed in the calculations once 3NF effects are included. Therefore, one could conclude that only 3NF effects are missing in the calculation shown in Fig. 3. Applying the reduction in cross section of about 6% as found in Refs. [1,6] for the total photoabsorption cross section, the Trento group's calculation for the two-body photodisintegration cross section of the reaction ^{4}H(γ, p)^{3}H is in perfect agreement with the present data.

In conclusion, for the comparison of experimental data and theoretical calculations of the cross section for the ^{4}He(γ, p)^{3}H reaction, we recommend to not use the majority of the radiative-capture data. Our precise and comprehensive data set for the total photodisintegration cross section of the reaction ^{4}He(γ, p)^{3}H in the energy range from just above threshold to just below 30 MeV is in fair agreement with the present calculations of the Trento group. Applying the about 6% reduction calculated for the total photoabsorption cross section once 3NF effects are included in rigorous 4N calculations using high-precision NN potential models, our data are in perfect agreement with the calculation of the Trento group. Therefore, contrary to the results of Shima *et al.*, theory is not only correctly predicting the location of the giant dipole resonance, but in addition, the magnitude of the photodisintegration cross section of the reaction ^{4}He(γ, p)^{3}H is very well reproduced, providing confidence in the related neutrino-nucleus cross-section calculations.

The authors acknowledge valuable contributions from J. Li, S. Mikhailov, and Y. K. Wu. This work was partially supported by the U.S. Department of Energy, Office of Nuclear Physics, under Grants No. DE-FG02-97ER41033 and No. DE-FG02-97ER41042.

*Present address: UGC-DAE Consortium for Scientific Research, Kolkata Centre, Kolkata, India.

[1] D. Gazit *et al.*, Phys. Rev. Lett. **96**, 112301 (2006).
[2] R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla, Phys. Rev. C **51**, 38 (1995).
[3] B. S. Pudliner *et al.*, Phys. Rev. C **56**, 1720 (1997).
[4] V. D. Efros, W. Leidemann, and G. Orlandini, Phys. Lett. B **338**, 130 (1994).
[5] J. Golak *et al.*, Nucl. Phys. **A707**, 365 (2002).
[6] S. Quaglioni and P. Navratil, Phys. Lett. B **652**, 370 (2007).
[7] E. Epelbaum, H.-W. Hammer, and Ulf-G. Meissner, Rev. Mod. Phys. **81**, 1773 (2009).
[8] P. Navratil, J. P. Vary, and B. R. Barrett, Phys. Rev. Lett. **84**, 5728 (2000).
[9] S. Quaglioni *et al.*, Phys. Rev. C **69**, 044002 (2004).
[10] R. A. Malfliet and J. Tjon, Nucl. Phys. **A127**, 161 (1969).
[11] T. Shima *et al.*, Phys. Rev. C **72**, 044004 (2005).
[12] M. Kusakabe *et al.*, Phys. Rev. D **79**, 123513 (2009).
[13] Y. K. Wu *et al.*, in *Proceedings of the Particle Accelerator Conference, Vancouver, 2009*, http://trshare.triumf.ca/~pac09proc/Proceedings_091005/papers/th4pbc06.pdf.
[14] W. Tornow *et al.*, Phys. Lett. B **702**, 121 (2011).
[15] W. Tornow *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **647**, 86 (2011).
[16] J. B. Birks, *The Theory and Practice of Scintillation Counting* (Pergamon, Oxford, 1964), Chap. 14.
[17] R. E. Pywell, O. Mavrichi, W. A. Wurtz, and R. Wilson, Nucl. Instrum. Methods Phys. Res., Sect. A **606**, 517 (2009).
[18] A. N. Gorbunov, Phys. Lett. B **27**, 436 (1968).
[19] T. Shima *et al.*, AIP Conf. Proc. **1235**, 315 (2010).
[20] Yu. M. Arkatov *et al.*, Sov. J. Nucl. Phys. **19**, 598 (1974).
[21] E. Balestra *et al.*, Nuovo Cimento Soc. Ital. Fis. A **38**, 145 (1977).
[22] J. E. Perry and S. J. Bame, Phys. Rev. **99**, 1368 (1955).
[23] W. E. Meyerhof, M. Suffert, and W. Feldman, Nucl. Phys. **A148**, 211 (1970).

[24] D. Gazit and W. Leidemann (private communication).
[25] A. N. Gorbunov, Sov. J. Nucl. Phys. **10**, 268 (1969).
[26] Yu. M. Arkatov *et al.*, Sov. J. Nucl. Phys. **10**, 639 (1970).
[27] F. Balestra *et al.*, Nuovo Cimento Soc. Ital. Fis. A **49**, 575 (1979).
[28] R. Bernabei *et al.*, Phys. Rev. C **38**, 1990 (1988).
[29] W. R. Dodge and J. J. Murphy, Phys. Rev. Lett. **28**, 839 (1972).
[30] L. Van Hoorebeke *et al.*, Phys. Rev. C **48**, 2510 (1993).
[31] R. C. McBroom *et al.*, Phys. Rev. C **25**, 1644 (1982).
[32] J. R. Calarco *et al.*, Phys. Rev. C **28**, 483 (1983).
[33] G. Feldman *et al.*, Phys. Rev. C **42**, R1167 (1990).