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Photodisintegration cross section of the reaction ^{4}He(γ,n)^{3}He at the giant dipole resonance peak

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The photodisintegration cross section of ^{4}He into a neutron and helion was measured at incident photon energies of 27.0, 27.5, and 28.0 MeV. A high-pressure ^{4}He-Xe gas scintillator served as target and detector while a pure Xe gas scintillator was used for background measurements. A NaI detector in combination with the standard HIγS scintillator paddle system was employed for absolute photon-flux determination. Our data are in good agreement with the theoretical prediction of the Trento group and the recent data of Nilsson *et al.* [Phys. Rev. C **75**, 014007 (2007)] but deviate considerably from the high-precision data of Shima *et al.* [Phys. Rev. C **72**, 044004 (2005)].

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The experimental situation for the angle-integrated cross section of the reaction ^{4}He(γ,n)^{3}He, shown in Fig. 1, is very unsatisfactory. The data obtained during the last four decades scatter considerably and to a large extent contradict each other. The large dots in Fig. 1 are the data of Shima *et al.* [1], while the upward triangles represent the data of Nilsson *et al.* [2]. These two most recent data sets differ in the region of the giant-dipole resonance peak. The curve is the theoretical prediction of Quaglioni *et al.* [3] from the Trento group.

From an experimental point of view, the "active target" scheme of Shima *et al.* is the ideal experimental approach, because it allows for the simultaneous measurement of both the ^{4}He(γ,p)^{3}H and ^{4}He(γ,n)^{3}He cross sections, and in addition, it avoids the complications associated with neutron detection [2]. We used the active target approach in Ref. [12] for the measurement of the ^{4}He(γ,p)^{3}H angle-integrated cross section by employing a high-pressure ^{4}He-Xe gas scintillator. Our data are in good agreement with theoretical predictions of the Trento group [3] but are in dramatic disagreement with the ^{4}He(γ,p)^{3}H data of Shima *et al.* [1].

Due to the impact of the high-precision data of Shima *et al.* on the understanding of the giant dipole resonance in few-nucleon systems, we decided to stretch our approach, described briefly in Ref. [12] and in more detail in Ref. [13], to its limits in order to measure the cross section of the ^{4}He(γ,n)^{3}He reaction at the peak of the giant dipole resonance.

The Q-value for the reaction ^{4}He(γ,n)^{3}He is −20.58 MeV. Incident photons with $E_\gamma = 27$ MeV provide helions of energies between 1.0 and 2.3 MeV, depending on the emission angle of the undetected neutron. The pulse height produced by strongly ionizing charged particles in gas scintillators is proportional to the energy deposited and independent of the particle type. For example, 2 MeV protons, deuterons, tritons, helions, and ^{4}He ions all produce the same pulse height and have 100% detection efficiency, provided they are completely stopped in the gas volume [14]. Therefore, in principle, the pulse-height interval associated with helions is clearly separated from the summed pulse height of the protons and tritons from the competing reaction ^{4}He(γ,p)^{3}H, which deposits a total energy of 7.2 MeV for 27 MeV incident photons. However, in standard ^{4}He-Xe gas scintillators, the pulse heights produced by electrons through Compton scattering of the incident γ rays overlap with those generated by some fraction of the low-energy helions, unless the Xe/^{4}He ratio is kept very low to reduce the stopping power for charged particles. In addition, at high incident photon flux, the electron-produced pulses tend to pile up on top of each other, creating pulse heights beyond those expected from the maximum electron range available within the scintillator volume. Therefore, a quite complicated optimization process is required if one wants to measure the ^{4}He(γ,n)^{3}He cross section with ^{4}He-Xe gas scintillators. The required small Xe/^{4}He ratio makes it impractical to measure the ^{4}He(γ,p)^{3}H and ^{4}He(γ,n)^{3}He cross sections simultaneously. Xe/^{4}He ratios well below 5% not only result in poor energy resolution of the gas scintillator, but in addition, the protons from the ^{4}He(γ,p)^{3}H reaction will range out, i.e., strike the inner wall of the gas scintillator housing without depositing their full energy. As a matter of fact, at too small Xe admixtures, the reaction products of the reactions ^{4}He(γ,p)^{3}H and ^{4}He(γ,n)^{3}He become indistinguishable due to the lack of sufficient pulse height produced by the energetic protons.

We used a high-pressure ^{4}He-Xe gas scintillator filled with a mixture of 48.3 atm ^{4}He and 2.7 atm of Xe as target and detector. Details about He-Xe gas scintillators are given in Ref. [14]. For background estimation we used an identical

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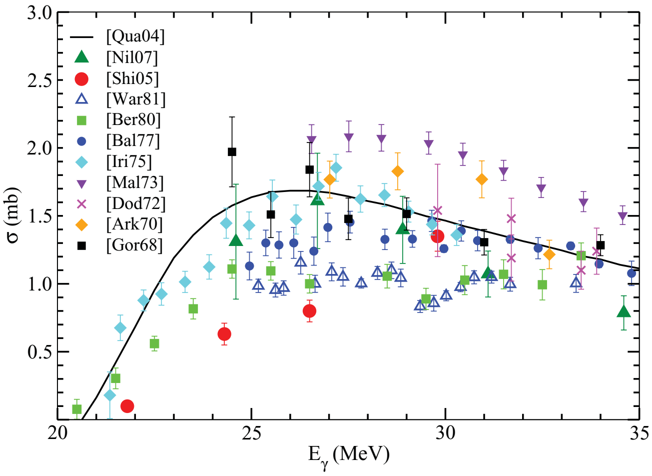

FIG. 1. (Color online) Existing angle-integrated cross-section data for the ^{4}He(γ,n)^{3}He reaction [1,2,4–11] in comparison to the calculation of Quaglioni *et al.* [3] from the Trento group.

scintillator housing filled with 2.7 atm of Xe. A schematic of the scintillator housing with its photomultiplier tube (PMT) is shown in Fig. 2. Experimental details are similar to those given in Ref. [12].

Briefly, the high-energy photons were produced via Compton backscattering of free-electron laser (FEL) photons from relativistic electrons in a straight section of the Duke University electron storage ring [15]. The electron energy was varied between 616 and 627 MeV, and the electron current was kept constant at 40 mA. The FEL wavelength was 244 nm. The resulting photon beams of 27.0, 27.5, and 28.0 MeV were collimated to 1-cm diameter and its energy spread (FWHM) was 780 keV. The actual γ-ray energies were determined to an accuracy of about 50 keV using a calibrated NaI detector. The absolute photon flux was obtained using a NaI detector in combination with the HIγS scintillator paddle system [16]. Using a copper attenuator with length of 2.45 cm inserted into the photon beam about 50 m upstream of the gas scintillator, the photon flux on target was reduced to below $1.5 \times 10^6\ \gamma/\mathrm{s}$. This reduction in flux limited the electron pile-up events to manageable levels. A pulse-height spectrum obtained with 28.0 MeV incident photons is shown in Fig. 3(a). The events caused by electrons are located at the low pulse heights below channel 500. The broad and symmetric enhancement centered at channel 800 is due to the helions of interest. The symmetric shape is the result of the $\sin^2\theta$ angular distribution of the associated, but undetected, neutrons. At larger pulse height one notices the broad distribution caused by tritons and ranged-out protons, which are also responsible for the "saturated" events at the very end of the pulse-height distribution. Due to their short range of less than 1 mm, the helions of interest are practically not affected by any edge effects in our gas scintillator housing of 50-mm inner diameter. Figure 3(b) represents a spectrum obtained with a pure 2.7 atm Xe gas scintillator, indicating the structureless background underneath the region of interest shown in Fig. 3(a). The background seen in Fig. 3(b) is due to charged particles resulting from photon-induced reactions on Xe and the reflector material MgO plus wavelength shifter deposited on the inside of the scintillator housing [14].

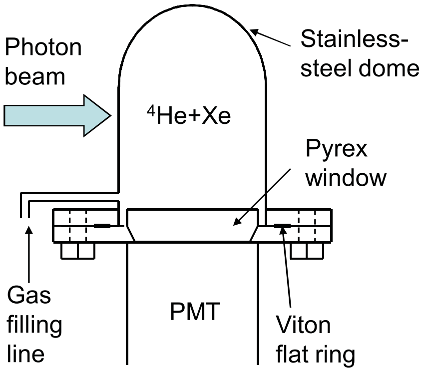

FIG. 2. (Color online) Schematic of gas scintillator housing with photomultiplier tube.

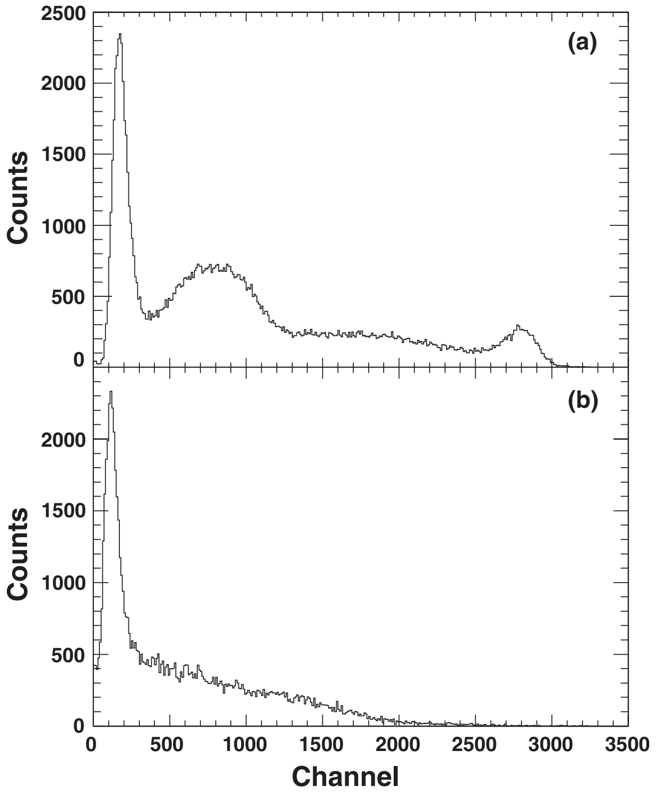

FIG. 3. Pulse-height spectrum of (a) 48.3 atm/2.7 atm ^{4}He/Xe and (b) 2.7 atm Xe gas scintillator obtained with 28.0 MeV mono-energetic photons. See text for details.

Our results for the ^{4}He(γ,n)^{3}He cross section are given in Fig. 4 by solid inverted triangles. They are in good agreement with the previously shown theoretical prediction of Quaglioni *et al.* [3] and the data of Nilsson *et al.* [2] (solid upward triangles), but in striking disagreement with the data of Shima *et al.* [1] (dots). According to Figs. 1 and 4, our data in the energy region of interest are also in agreement with the very old data of Gorbunov [11], Arkatov *et al.* [10], and Irish *et al.* [7] using bremsstrahlung beams. The data of Berman *et al.* [5] based on mono-energetic photons from the positron annihilation in-flight technique and the data of Ward *et al.* [4]

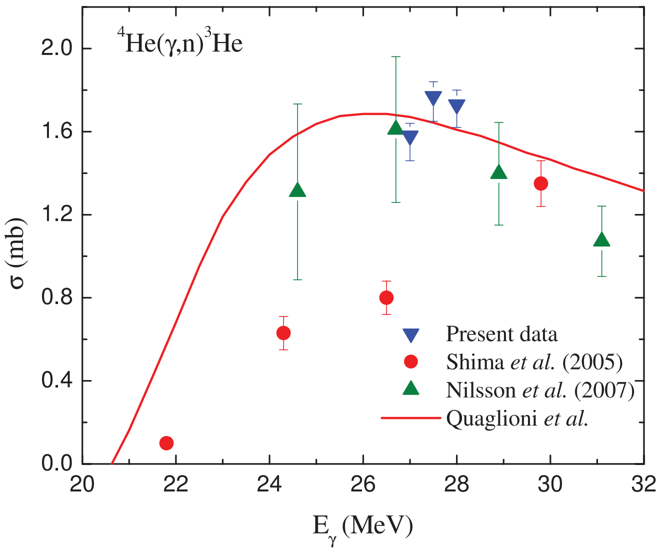

FIG. 4. (Color online) Comparison of the most recent data and available calculation for the angle-integrated cross section of the reaction ^{4}He$(\gamma,n)^3$He.

deduced from the time-reversed radiative capture reaction ^{3}He$(n,\gamma)^4$He are lower in magnitude. The cross-section values obtained from the bremsstrahlung data of Malcom *et al.* [8] are larger than those resulting from all other measurements and also significantly exceed the theoretical predictions. The work of Balestra *et al.* [6], who pioneered the Compton backscattering technique for producing mono-energetic photons, which was used also in Ref. [1] and in the present work, gives cross-section values somewhat lower than those of Irish *et al.* [7]. As can be seen from Table I, the statistical uncertainty of our data is below 1%. The uncertainty in the photon-flux determination is between +2% and −4%. Based on various fits to the spectra, the uncertainty in our background determination is estimated to be within the +6% and −3% range. The uncertainty associated with the helium content in the gas scintillator is 1%. Adding these uncertainties in quadrature results in total uncertainties of our cross-section data between +4% and −7%.

TABLE I. ^{4}He$(\gamma,n)^3$He reaction cross-section values and uncertainties

E_γ (MeV)	σ (mb)	$\pm\Delta\sigma_{\text{stat}}$ (mb)	$\pm\Delta\sigma_{\text{total}}$ (mb)
27.0	1.58	0.01	+0.06–0.12
27.5	1.77	0.01	+0.07–0.12
28.0	1.73	0.01	+0.07–0.11

The calculation [3] shown in Figs. 1 and 4 for the exclusive reaction ^{4}He$(\gamma,n)^3$He was obtained with the semirealistic central nucleon-nucleon (NN) potential of the MT I–III type [17]. The full final-state interaction was treated via the Lorentz integral transform method [18]. Calculations for the inclusive photoabsorption cross section of ^{4}He are available from Gazit *et al.* [19] using high-precision NN potential models. Those calculations indicate that the angle-integrated photoabsorption cross section is fairly insensitive to details of the NN interaction. However, adding three-nucleon forces to the calculations results in a decrease of the cross section by about 6%. Therefore, one could expect that the calculation shown in Figs. 1 and 4 overestimates the ^{4}He$(\gamma,n)^3$He cross section by about the same amount.

We conclude that the measurement of Shima *et al.* below 30 MeV provides cross-section values that are inconsistent with our data and the recent data of Nilsson *et al.* In addition, they are at variance with the most sophisticated theoretical results currently available. It should be mentioned that also the ^{4}He$(\gamma,p)^3$H cross-section data of Shima *et al.* [1] in the same energy range disagree with all other measurements and theory as well [12]. It is worthwhile to point out that most of the very early data appear to be in fairly good agreement with theory, except for those of Malcom *et al.* [8] (see Fig. 1). It seems that systematic uncertainties have been underestimated in most of the more recent experiments. Finally, we note that calculations with high-precision NN potential models including three-nucleon force effects are currently being pursued [20].

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