Measurement of the $^4He(\gamma,p)^3H$ total cross section and charge symmetry

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The absolute total cross section for the $^4He(\gamma,p)^3H$ reaction has been measured in the γ-ray energy region between 28.6 and 58.1 MeV with a monochromatic photon beam and a nearly 4π proton detector. The comparison of our results with the most recent data on the $^4He(\gamma,n)^3He$ total cross section provides a mean value of $R_\gamma=\sigma(\gamma,p)/\sigma(\gamma,n)=1.01\pm0.06$ between 28.6 and 42.4 MeV and tends to exclude a strong isospin mixing in the ^4He due to charge symmetry breaking of the nuclear force.

I. INTRODUCTION

The theoretical and experimental study of the $^4He(\gamma,p)^3H$ and $^4He(\gamma,n)^3He$ processes in the giant dipole resonance (GDR) energy region has attracted special attention as a useful method to verify the charge symmetry of the nuclear force. In this energy region the ratio of the photoproton to the photoneutron cross sections $R_\gamma=\sigma(\gamma,p)/\sigma(\gamma,n)$ is expected to be about 1, for an equal strength of the *p-p* and *n-n* forces. On the other hand, since the cross sections for these reactions below about 35 MeV are essentially due to electric dipole radiation, a ratio $R_\gamma>1$ should be mainly due to an isospin mixing between different $J^P=1^-$ states, having respectively $T=0$ and $T=1$. At energies higher than about 28 MeV an increase of the R_γ value of the order of 10% is provided by Coulomb effects, while larger values should be related to a charge symmetry breaking of the nuclear forces in ^4He.[1-14]

Many experiments have been performed attempting to establish the value of the two-body photodisintegration cross sections. An important step forward was realized by Berman *et al.*[15] with a highly reliable measurement of the $^4He(\gamma,n)^3He$ total cross section; that removed the uncertainties due to the large discrepancies between the already existing measurements. They used a gaseous high-pressure $\sim4\pi$ detector and monoenergetic photons. Their results, confirmed by Ward *et al.*,[16] gave $^4He(\gamma,n)^3He$ cross-section values lower than those previously known and pointed out the problem of a possible charge symmetry breaking of the nuclear forces in ^4He. In fact, some of the published experimental results[15-31] for the process $^4He(\gamma,p)^3H$ (although with very large discrepancies) compared with the $^4He(\gamma,n)^3He$ from Berman *et al.*, may suggest a value for the ratio R_γ far from unity in the γ-ray energy region around and below 35 MeV.

Calarco *et al.*[1] have made a considerable effort to analyze critically the bulk of the existing experiments. They selected what in their opinion were the most reliable experiments and suggested a set of values for the two-body $\sigma(\gamma,p)$ and $\sigma(\gamma,n)$ total cross sections. A large amount of credibility was given to the $^3H(p,\gamma)^4He$ data[25-30] partly because of their better internal consistency. Calarco did not give much credibility to the measurements on the direct $^4He(\gamma,p)^3H$ process when only the proton was detected as in the case we present here, but no measurements were available at that time with monochromatic photons and a proton detector with nearly 4π coverage.

As a consequence of Calarco's critical review, the ratio $R_\gamma=\sigma(\gamma,p)/\sigma(\gamma,n)$ shows a maximum of about 1.8 around 26 MeV (see Sec. IV). These R_γ values imply an amount of isospin mixing between the excited states of ^4He largely exceeding that expected from the Coulomb force.[1,2] Furthermore, experiments performed at $E_\gamma\geq28$ MeV, with the (γ,p) and (γ,n) reaction cross sections measured nearly simultaneously with the same apparatus, found R_γ values consistent with unity with the exception of a small energy range around $E_\gamma\sim44$ MeV.[18,32-34] The simultaneous measurement of both the cross sections could allow a good determination of R_γ even when systematic uncertainties on the two different cross sections are present. Likewise, a recent measurement[35] of π-^4He inelastic scattering in the region of the $J^P=1^-$ states (excitation energies ranging from 23 to 30 MeV) gave a π^+/π^- cross-section ratio $R_\pi=1.05\pm0.08$, corresponding to a very weak isospin mixing between the $T=0$ and $T=1$ states. We want to stress that the Calarco value of R_γ would imply a value $R_\pi\sim2.9$. In addition, theoretical calculations which take into account a reasonable charge symmetry breaking interaction do not provide such a high value for R_γ.[2,7–14]

Clearly this theoretical and experimental situation requires further clarification. A reliable critical analysis of the experiments of other authors is very difficult and sometimes too subjective, so this is not our aim. The purpose of this paper is to present our measurements of the total cross section of the $^4He(\gamma,p)^3H$ process in an energy interval between $E_\gamma=28.6$ and 58.1 MeV, using a gaseous high-pressure $\sim 4\pi$ detector and monochromatic photons as in the experiment of Berman *et al.*[15]

To demonstrate clearly the degree of accuracy of our results we will discuss in some detail how we collected and analyzed the data. Data have been taken in several runs for effective photon mean energies $E_\gamma=28.6$, 29.6, 30.4, 31.6, 32.5, 34.1, 37.5, 42.4, 44.9, and 58.1 MeV, alternating between full (~ 30 bars of ^4He) and empty (~ 1 bar of ^4He) targets.

II. EXPERIMENTAL SETUP

The radiation source was the LADON photon beam of the Frascati National Laboratories, produced by backward scattering of laser light on the high-energy electrons circulating in the Adone storage ring.[36] The beam was collimated and had an average γ-ray intensity of $\sim 10^5$ s^{-1}. The bremsstrahlung background, due to the impact of electrons on the residual gas inside the Adone vacuum tube ($\sim 10^{-9}$ Torr), was of the order of 5 percent, integrated over the whole spectrum above 2 MeV. Contributions from the bremsstrahlung component of the beam were measured by turning off the laser light.

A magnetic pair spectrometer measured the beam energy spectrum. The photon counting was provided continuously by a 10×10 in.^{2} NaI(Tl) crystal placed at the end of the beam line. Taking into account that our beam has a macroscopic duty factor of 100%, we had no pileup problems at the intensities available.

The experimental apparatus was that previously used for a high-precision measurement of deuteron photodisintegration.[37] The target container was a very thin (0.16 mm) aluminum cylinder of 15 cm length and 1.5 cm diameter, with two Lexan end caps at the bases for the passage of the beam. It was surrounded by a NE213 liquid scintillator, 6.75 cm thick, held in an anticorodal box and viewed by two photomultipliers. The target was helium gas at a pressure of ~ 30 bars. Both gas and scintillator were maintained at the same pressure by a mechanical device. Pressure and temperature were continuously measured and recorded during the running time. The ^4He density was determined by the method described in Ref. 38.

III. DATA ANALYSIS

In this section we describe in detail the derivation of the $^4He(\gamma,p)^3H$ cross sections from the collected data.

A. Electromagnetic background rejection

The details of this step of the data analysis are published elsewhere.[39] The total charge pulses from the two photomultipliers, their sum (head value) and their corresponding tail contributions (tail value) were acquired. The event processing was triggered by a threefold coincidence among the two pulses from the photomultipliers of the proton detector and a signal indicating the passage of an electron bunch through the laser cavity.[28] To decrease the number of events to be recorded (i.e., the data acquisition dead time), a very conservative on-line γ suppression was operated using a pulse shape analyzer ORTEC 552 together with a PSA system, namely a time-to-digital converter. A window in the gamma region was fixed using an Am-Be source. A time-to-pulse-height converter was used to trigger the circuit that clears the analog-to-digital converter (ADC) and the time-to-digital converter CAMAC modules. Background contributions come both from the interactions of photons with the detector materials and from the bremsstrahlung component of the beam. The first contribution was evaluated by alternating empty and full target runs; the second one was measured directly by turning off the laser light and running the bremsstrahlung beam alone. Data to be subtracted are normalized to the same photon flux in case of

TABLE I. Detection efficiencies of our apparatus for the different photodisintegration channels.

$\langle E_\gamma \rangle$ (MeV)	Proton threshold (MeV)	$^4He(\gamma,p)^3H$	$^4He(\gamma,n)^3He$	$^4He(\gamma,d)d$	$^4He(\gamma,pn)d$	$^4He(\gamma,2p2n)$
28.6±0.1	3	0.68	0.14	0.00	0.00	0.00
29.6±0.1	3.4	0.72	0.12	0.00	0.00	0.00
30.4±0.2	4.6	0.77	0.10	0.00	0.00	0.00
31.6±0.2	4.8	0.81	0.09	0.00	0.00	0.00
32.5±0.2	5.0	0.79	0.08	0.00	0.00	0.00
34.1±0.2	6.0	0.82	0.07	0.00	0.00	0.00
37.5±0.3	8.0	0.83	0.05	0.07	0.00	0.00
42.4±0.3	11.0	0.81	0.04	0.36	0.08	0.05
44.9±0.5	13.5	0.75	0.03	0.41	0.09	0.07
58.1±0.7	21.0	0.81	0.02	0.72	0.16	0.21

empty target runs, and to the total electron flux in the storage ring in the case of the bremsstrahlung runs.

To obtain a better background rejection we used a particular off-line procedure.[39] First a tentative line was drawn in the head/tail plane to separate the γ and p regions (zero line). Then, the zero line wad shifted in the head axis direction; the amount of the shift is characterized by a variable x giving the number of shift channels. Thus, we were able to construct the integral counts yield (after the empty target and bremsstrahlung subtraction) as a function of x $[F(x)]$; obviously, by varying x in both directions we passed from a proton loss to a large photon contamination. Finally, we separated electromagnetic background and proton contribution to the yield by means of a proper fit, allowing us to distinguish their different x behavior $[F(x)=F_p(x)+F_\gamma(x)]$.[39] This procedure was repeated with different software thresholds on the head value to minimize the systematic errors in the background subtraction. A similar procedure was repeated using the PSA system and the results were compared.

Using the matched head/tail and PSA methods we reach a typical separation efficiency between electromagnetic background and proton signal of about 97–98 percent.[39]

B. Apparatus efficiencies and the subtraction of other photodisintegration channel contributions: Monte Carlo calculations

The detection efficiencies of our apparatus for the different ^{4}He photodisintegration channels were evaluated by means of a Monte Carlo calculation, taking into acount the real geometric structure of the apparatus, the absorbing materials, and the finite dimensions of the beam.

In Table I we report our detection efficiencies at the head threshold values used for each energy in the data analysis described below. As is well known, the neutrons from ^{4}He$(\gamma,n)^3$He produce an energy spectrum highly peaked at very low values in comparison with the proton spectrum. The largest part of these neutrons is removed using the software threshold (see Table I) on the ADC channels (head value); then, using the experimental data of Ref. 15 and the efficiencies reported in Table I, we can evaluate and subtract from our data the residual neutron contamination.

The three- and four-body processes, with thresholds at 26.1 and 28.4 MeV, respectively, and the ^{4}He$(\gamma,d)d$ process have very small cross sections compared with ^{4}He$(\gamma,p)^3$H, throughout the energy range explored here[34,40–42] [only $\sigma(\gamma,pnd)$ reaches about $\frac{1}{3}$ of $\sigma(\gamma,p)$ at $E_\gamma \sim 60$ MeV, but our efficiency for this three-body channel is poor, as shown in Table I]. Furthermore, the cut in the amplitude spectrum also decreases this source of contamination (particularly at $E_\gamma < 40$, see Table I). Finally, the residual contamination is estimated from the experimental values in the quoted references and the efficiencies of Table I, and is subtracted from our data.

Furthermore, over a long period of time the long-term stability of the proton detection efficiency [well known from the previous ^{2}H$(\gamma,p)n$ experiment but a critical parameter at low energy] has been verified by measuring the deuteron photodisintegration cross section at mean photon energies 15.3 and 19.1 MeV using the same apparatus, beam, and analysis procedure (obviously no subtraction of contributions due to other photodisintegration channels is necessary in this case). In these cases the proton energies at 90° in the laboratory system are close to those in the ^{4}He$(\gamma,p)^3$H reaction for mean photon ener-

TABLE II. Experimental results for the ^{2}H$(\gamma,p)n$ reaction.

Mean energy $\langle E_\gamma \rangle$ (MeV)	Our results for ^{2}H$(\gamma,p)n$ $\sigma(\gamma,p)$ (μb)
15.3±0.2	924±10
19.1±0.2	625±15

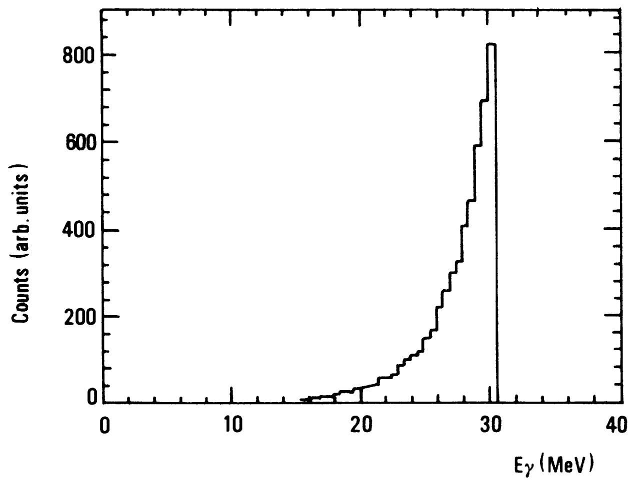

FIG. 1. Beam profile at $E_{\text{maximum}}=30.6$ MeV collected by the pair spectrometer.

TABLE III. Basic information on the photon beam during data taking. The error values on the mean energy values include both statistical and systematic errors. FWHM denotes full width at half maximum.

E_{maximum} (MeV)	FWHM/E_{peak} (%)	Mean energy $\langle E_\gamma \rangle$ (MeV)
30	6.2	28.6±0.1
30.6	4.3	29.6±0.1
32	5.3	30.4±0.2
33	6.2	31.6±0.2
34	5.0	32.5±0.2
36	5.0	34.1±0.2
40	6.8	37.5±0.3
45	9.0	42.4±0.3
50	9.0	44.9±0.5
65	6.2	58.1±0.7

TABLE IV. $\sigma(\gamma,p)$: our experimental results on $^4He(\gamma,p)^3H$; only statistical errors are quoted. $\sigma(\gamma,n)$: from the Calarco evaluation (Ref. 1). The quoted errors on the R_γ values are a mean evaluation obtained by taking into account both statistical and systematic errors on the measured $\sigma(\gamma,p)$ and on the evaluation of Calarco *et al.* for the $\sigma(\gamma,n)$. The asterisk means that the 58.1-MeV datum is a mean estimation from the data of Gorbunov (Ref. 18) and Arkatov *et al.* (Ref. 17).

$\langle E_\gamma \rangle$ (MeV)	Our results on $\sigma(\gamma,p)$ (mb)	Calarco $\sigma(\gamma,n)$ (mb)	$R_\gamma=\sigma(\gamma,p)/\sigma(\gamma,n)$
28.6±0.1	1.15±0.03	$1.12^{+0.12}_{-0.16}$	1.03±0.16
29.6±0.1	1.13±0.03	$1.12^{+0.12}_{-0.21}$	1.01±0.17
30.4±0.2	1.15±0.02	$1.12^{+0.12}_{-0.21}$	1.03±0.17
31.6±0.2	1.15±0.03	$1.12^{+0.12}_{-0.16}$	1.03±0.15
32.5±0.2	1.06±0.02	$1.12^{+0.12}_{-0.16}$	0.95±0.14
34.1±0.2	1.25±0.01	1.12±0.12	1.12±0.13
37.5±0.3	0.92±0.02	1.00±0.10	0.92±0.12
42.4±0.3	0.83±0.01	$0.82^{+0.06}_{-0.09}$	1.01±0.11
44.9±0.5	0.82±0.01	0.68±0.07	1.21±0.14
58.1±0.7	0.44±0.01	0.30±0.08*	1.47±0.40

gies 28.6 and 31.1 MeV. The values obtained are reported in Table II, where only statistical errors are quoted. They are in complete agreement with our previous data and with the most recent theoretical calculations.[37,43]

C. Mean photon energy calculation

It is necessary to estimate correctly the mean energy corresponding to the Ladon beam spectrum for the different maximum photon energies. As an example, in Fig. 1 we show the experimental beam profile as measured by the pair spectrometer at a maximum photon energy of 30.6 MeV. In Table III we summarize some of the photon beam characteristics observed during these measurements.

The photon energy mean value is calculated by means of the following expression:

$$\langle E_\gamma \rangle = \frac{\sum_i \sigma_i N_i \epsilon_i(S) E_i}{\sum_i \sigma_i N_i \epsilon_i(S)} ,$$

where σ_i is estimated from the fit corresponding to our $^4He(\gamma,p)^3H$ total cross-section measurements at the photon energy E_i, N_i is the weight for the ith channel of the pair spectrometer beam profile, and $\epsilon_i(S)$ is the absolute detection efficiency for the $^4He(\gamma,p)^3H$ channel at the threshold S on the head value. Note that if one uses Calarco's value for σ_i the estimated mean energy will have a slightly lower value.

This calculation was performed for each run. We then estimated the mean value for each energy, weighting each run with its photon dose. We have estimated a systematic error in the determination of the mean energy equal to about 10% of the difference between the maximum and the mean value. The errors in the photon mean energy

TABLE V. Systematic errors; the total is obtained by summing all errors in quadrature.

$\langle E_\gamma \rangle$ (MeV)	^{4}He density (%)	NaI(Tl) efficiency (%)	Apparatus detection efficiency (%)	Error source Energy calibration efficiency (%)	Bremsstrahlung subtraction (%)	p/γ separation (%)	Total (%)
28.6±0.1	<0.1	1.1	6.0	1.2	2.7	3.5	7.5
29.6±0.1	<0.1	1.0	5.1	1.0	2.5	2.5	6.4
30.4±0.2	<0.1	1.2	4.4	1.0	2.5	2.0	5.7
31.6±0.2	<0.1	1.0	3.9	1.2	2.5	2.0	5.3
32.5±0.2	<0.1	1.5	3.8	1.0	2.5	2.0	5.3
34.1±0.2	<0.1	1.0	2.9	1.0	2.2	2.0	4.4
37.5±0.3	<0.1	1.2	2.6	1.0	2.2	2.0	4.2
42.4±0.3	<0.1	1.0	2.6	1.0	2.0	2.0	4.1
44.9±0.5	<0.1	1.0	2.6	1.0	2.0	2.3	4.2
58.1±0.7	<0.1	1.2	2.6	1.0	2.0	2.3	4.3

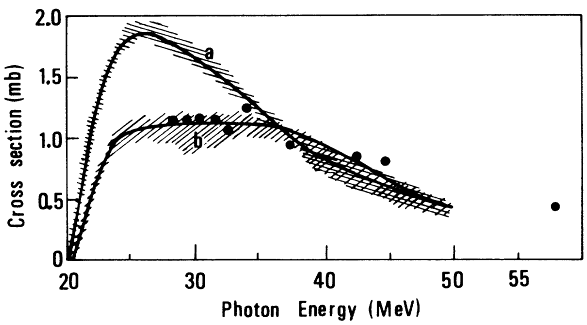

FIG. 2. Continuous lines are the evaluation of Calarco *et al.* (Ref. 1) for the ^{4}He(γ,p)^{3}H (curve a) and ^{4}He(γ,n)^{3}He (curve b), cross sections (dashed areas take into account the experimental uncertainties). Filled circles are our results for the ^{4}He(γ,p)^{3}H cross section including the statistical errors. Additional systematic errors are reported in Table V.

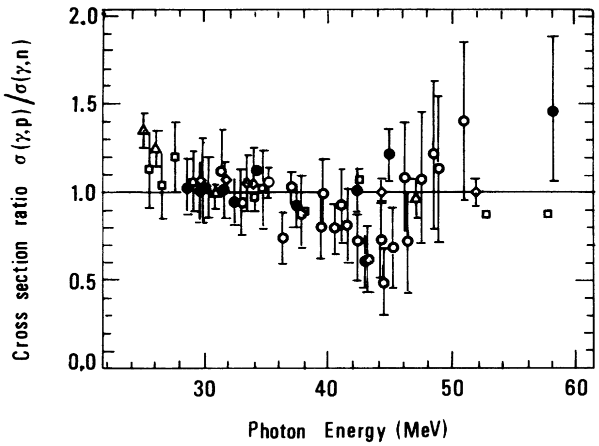

FIG. 3. R_γ as a function of the photon energy. Filled circles: evaluation of Table IV; open squares: Gorbunov (Ref. 18); open circles: Phillips *et al.* (Ref. 32); open diamonds: Dodge and Murphy (Ref. 33); open triangles: Balestra *et al.*, (Ref. 34).

quoted in the tables take into consideration both statistical and systematic uncertainties.

IV. RESULTS ON THE ^{4}He(γ,p)^{3}H CROSS SECTION AND DISCUSSION

The measured total cross sections are listed in Table IV, where only statistical errors are quoted. In Table V our estimates of the systematic errors affecting the measurements are indicated.

Results for the ^{4}He(γ,p)^{3}H process are also shown in Fig. 2 together with the evaluation of Calarco *et al.*[1] for the ^{4}He(γ,p)^{3}H and ^{4}He(γ,n)^{3}He cross sections.

In this context, the comparison between our results and the ^{4}He(γ,n)^{3}He evaluation by Calarco from the data of Berman *et al.* does not show substantial deviations from the standard theoretical expectations.[2,13,14,44] The ratio R_γ is near unity from $\langle E_\gamma \rangle = 28.6$ up to 42.4 MeV and could rise slightly above this energy. The ratio R_γ is shown in Fig. 3 together with the existing direct determinations of $\sigma(\gamma,p)/\sigma(\gamma,n)$.[18,32–34] In these last references[18,32–34] we give credibility to the R_γ ratio, even though they found $\sigma(\gamma,p)$ and $\sigma(\gamma,n)$ both higher than our measurements and those of Berman *et al.* In fact, the simultaneous measurement of both the cross sections could allow a good determination of R_γ even if non-negligible systematic uncertainties are present in the absolute value of the two different cross sections.

The mean value of R_γ, $\langle R_\gamma \rangle = 1.01 \pm 0.06$, at energies between 28.6 and 42.4 MeV (including both statistical and systematic errors), implies an isospin mixing between the $J^P = 1^-$, $T=0$ and $T=1$ states explainable by a small breaking of charge symmetry due to the electromagnetic force.

In conclusion, our ^{4}He(γ,p)^{3}H measurements in the energy interval between 28.6 and 58.1 MeV, compared with the most recent corresponding ^{4}He(γ,n)^{3}He data, do not seem to indicate an important charge symmetry breaking in ^{4}He due to nuclear forces. These results are in agreement with the previously mentioned measurement of the R_π value at excitation energies in the range $\sim$23–30 MeV.[35]

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