Bidimensional fit to ^{2}H(γ,p)n cross-section values between 20 and 440 MeV

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All the ^{2}H(γ,p)n data in the energy range 20–440 MeV have been fitted to a simple phenomenological function. All differential cross-section data were used: The bremsstrahlung data were normalized to the total cross-section values obtained by fitting data provided by monochromatic photon beams. The results obtained give a good representation of the experimental points.

The ^{2}H(γ,p)n process is one of the most extensively studied among all nuclear photoreactions, because of its importance for our understanding of the nuclear properties. However, in spite of the considerable effort spent on these studies, the knowledge of the cross section of the process was still unsatisfactory until 1985. In fact, the discrepancies among the various data sets[1–17] were so great, particularly in the energy region between the pion emission threshold and the $\Delta(1232)$ resonance, to make a reliable comparison between theory and experiment impossible. This experimental situation existing before 1985 is summarized in Fig. 1, where the total cross-section values of the ^{2}H(γ,p)n, obtained through direct measurements or by integrating angular distributions, are plotted between 15 and 400 MeV. Error bars include both statistical and systematic errors added linearly. Notice that all these data were produced using bremsstrahlung beams. However, despite the large spread in absolute values, the relative angular distributions from most experiments and for any photon energy are rather similar and consistent among each other inside the statistical errors (see Fig. 2 of Ref. 18). This suggests that the origin of the discrepancies among many of the experimental results, or at least part of it, is to be found in the overall normalization.

In recent years the availability of intense monochromatic photon beams and the development of advanced computational capabilities have led to renewed interest in the ^{2}H(γ,p)n reaction. In particular, there have been several new experiments[19–26] which have provided data in fairly good agreement with each other within the total quoted errors, over an extended photon energy range. This is clearly shown in Fig. 2 where the total cross-section values of the process obtained with monoenergetic photons, or through direct measurements or by integrating angular distributions, are plotted for photon energies from 15 up to 400 MeV. Error bars include both statistical and systematic errors added linearly. Moreover, there is also agreement with the results deduced from recent measurements of the inverse reaction,[27–30] so that a reasonable basis of experimental data is now provided for comparison with theory.

Therefore, it is now possible to determine a simple phenomenological form which gives a reasonable fit to all the

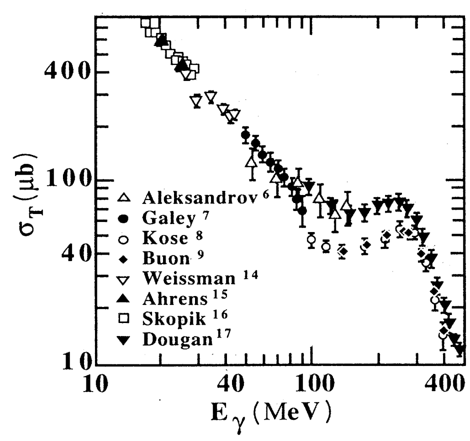

FIG. 1. The total cross section for the ^{2}H(γ,p)n reaction in the 15–400 MeV photon energy region: Experimental situation before 1985. Error bars include both statistical and systematic errors added linearly. (For the sake of clarity in the energy region 100–300 MeV only the higher and the lower values are shown.)

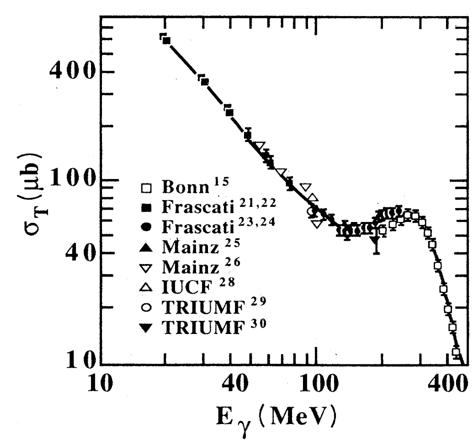

FIG. 2. The total cross-section value for the ^{2}H(γ,p)n reaction in the 15–400 MeV photon energy region obtained by using monochromatic photons. Error bars include both statistical and systematic errors added linearly. The solid curve represents the fit to Eq. (2).

existing cross-section data. The utility of this fit is manifold:

(i) It could provide the values of the differential cross section for any photon energy and over the whole angular interval (in particular, also at those angles, like 0° and 180°, where measurements are scarce, being difficult).

(ii) It could allow a better comparison between theoretical and experimental results. In fact, often, one uses data taken at slightly different energies and angles, and averaged over different energy and angular intervals without making the necessary shifts in the data according to the theoretical variation of the cross section (the order of magnitude of the errors for the total cross sections varies from 3% to 1% per MeV in the range 20–100 MeV and is $\leq 1\%$ at higher photon energies, and is $\approx 1\%$ per degree for the differential cross section at 100 MeV).

(iii) It could be used for calculations, such as distorted-wave impulse approximation calculations of (p,γ) processes or the contribution of the quasideuteron photoabsorption mechanism, which require the two-body cross section as input.

Such phenomenological fits were obtained by De Pascale *et al.*,[31] for photon energies up to 120 MeV, and by Thorlacius and Fearing,[32] in the photon energy range 10–625 MeV. The purpose of this Brief Report is to give an improved version of these existing fits, taking advantage of the new monochromatic data made available after those works and by using a more consistent fitting procedure, while retaining the phenomenological function used in Ref. 32. Precisely, we selected the experiments carried out with monoenergetic photons in order to derive the absolute values of the total cross section, and we used the whole available angular distribution measurements, suitably normalized, to obtain a phenomenological representation of the $^2H(\gamma,p)n$ differential cross-section data, valid in the energy range from 20 to 440 MeV.

The differential cross section in the center of mass was represented by the usual form:

$$\frac{d\sigma}{d\Omega}=\sum_i A_i(E_\gamma)P_i(\cos\vartheta) , \qquad (1)$$

where ϑ is the angle between the incoming photon and the outgoing proton in the center-of-mass (c.m.) system, E_γ is the laboratory photon energy, and $P_i(\cos\vartheta)$ are the Légendre polynomials. As a first step, using a least-squares method, we fitted to the form (1) (with $i=0.1,2,3$) the angular distributions provided by all those experiments[1–17,19,21,23–26] that have measured the differential cross section at least at five angles for each photon energy. The data of Refs. 23 and 24 were combined so as to give a more complete angular distribution. This is allowed because those data were produced by the same authors using the same photon beam.

As a second step, we fitted to the phenomenological function[32]

$$A_{0m}(E_\gamma)=C_1e^{C_2E_\gamma}+C_3e^{C_4E_\gamma}+\frac{C_5+C_6E_\gamma}{1+C_8(E_\gamma-C_7)^2} \qquad (2)$$

the values of $A_0(E_\gamma)$ obtained only from monochromatic experiments, or through direct measurements of the total cross section[22] (being $A_0=\sigma_T/4\pi$) or through the previously described fit to the angular distributions.[19,21,23,24] The result of this fit is shown in Fig. 2 as a solid curve. In the figure are also shown the preliminary results from Mainz[25,26] and those from recent radiative capture experiments.[28–30] As it is seen, the fit is obviously quite good: The value of the normalized χ^2 is 0.538 (the number of data is 49) and the relevant probability is 98%.

As said before, the measurements of relative angular distributions are independent of the incident photon spectrum and intensity, and, therefore, they are more reliable than absolute measurements. Then, in order to have available a very large and consistent set of data to be phenomenologically fitted, all the differential cross-section values, $(d\sigma/d\Omega)^{\exp}$, obtained by using either monochromatic or nonmonochromatic photon beams, were renormalized to the monochromatic absolute values $A_{0m}(E_\gamma)$ given by Eq. (2):

$$\left[\frac{d\sigma}{d\Omega}\right]^*=\left[\frac{d\sigma}{d\Omega}\right]^{\exp}\frac{A_{0m}(E_\gamma)}{A_0^{\exp}(E_\gamma)} \qquad (3)$$

being $A_0^{\exp}(E_\gamma)$ the values of the coefficients of lower order, obtained by fitting the experimental data to the form (1). Thus the data to be fitted consisted of a large set of differential cross-section values (913 values) measured at various proton (neutron) angles and at photon energies from 20 up to 440 MeV. Each individual cross-section data point was directly fitted by using a least-squares method and combining Eqs. (1) and (2) together with the

TABLE I. The coefficients and their standard errors arising from the fit to Eqs. (2) and (3). The units are μb/sr for C_1, C_3, and C_5; GeV^{-1} for C_2 and C_4; μb·GeV^{-1}/sr for C_6; GeV for C_7; and GeV^{-2} for C_8.

A_0	C_1	27.57±0.01
	C_2	−21.69±0.01
	C_3	143.19±0.56
	C_4	−84.93±0.30
	C_5	9.69±0.01
	C_6	−16.34±0.02
	C_7	0.29±0.01
	C_8	68.46±0.31
A_1	C_{11}	21.62±0.57
	C_{21}	−59.42±0.90
	C_{31}	3.33±0.01
	C_{41}	−5.70±0.01
A_2	C_{12}	−128.60±0.59
	C_{22}	−63.30±0.16
	C_{32}	−2.53±0.02
	C_{42}	−4.41±0.04
A_3	C_{13}	−20.14±0.30
	C_{23}	−50.01±0.50
	C_{33}	−2.40±0.03
	C_{43}	−9.81±0.20
A_4	C_{14}	−1.48±0.04
	C_{24}	−9.75±0.34
	C_{34}	0.27±0.01
	C_{44}	−0.12±0.06

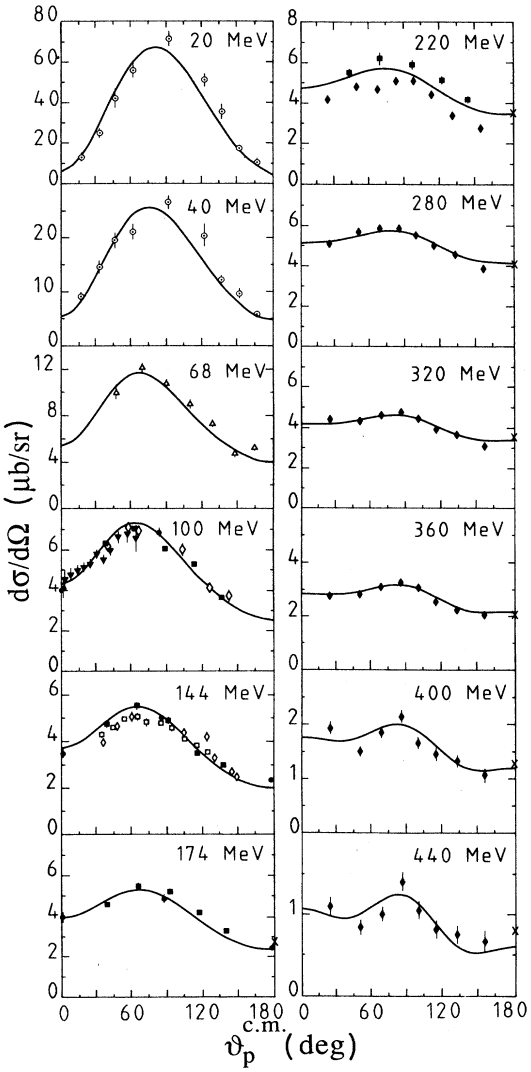

FIG. 3. Comparison of the fit to the differential cross-section data of the $^2H(\gamma,p)n$ reaction for the given energies: (♦) Ref. 19; (⊙) Ref. 21; (■) Ref. 23; (●) Ref. 24; (□) Ref. 25; (△) Ref. 26; (▼) Ref. 28; (◇) Ref. 29; (○) Ref. 33; (×) Ref. 34.

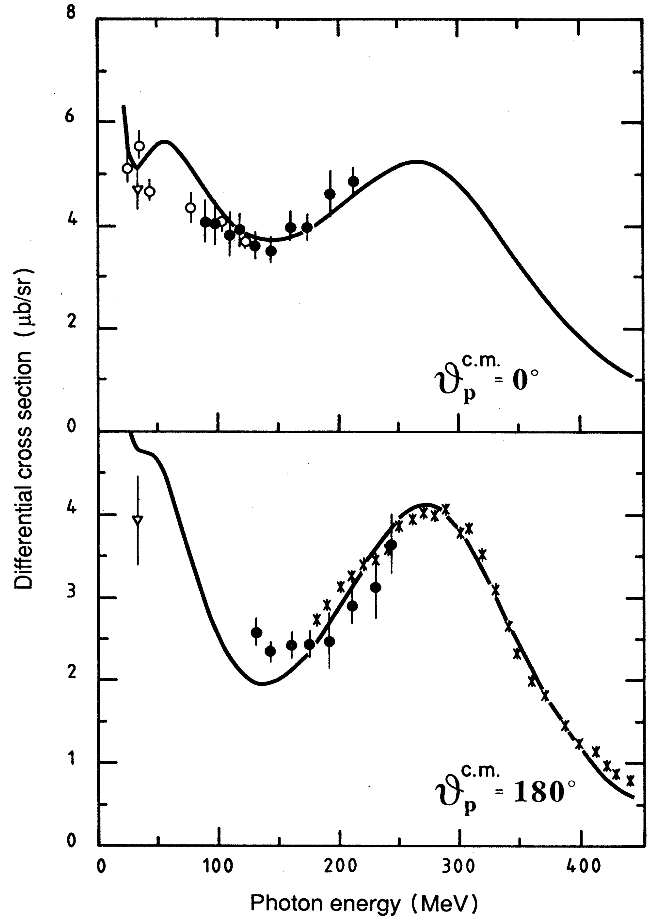

FIG. 4. Comparison of the fit to the experimental excitation functions at $\vartheta_p = 0°$ and 180°: (●) Ref. 24; (▽) Ref. 27; (○) Ref. 33; (×) Ref. 34.

following representation for the $A_i^{32} (i=1,4)$:

$$A_i(E_\gamma) = C_{1i} e^{C_{2i} E\gamma} + C_{3i} e^{C_{4i} E\gamma}, \quad i=1-4 . \tag{4}$$

This bidimensional fit avoids possible compounding of errors that can arise by following the usual two-step fit[31,32] and allows the inclusion of careful data sets, such as the data at 0°,[33] which do not cover a large enough angular region to give an accurate $A_0^{\exp}$.

The values of the coefficients C_i of Eq. (2) and C_{ij} $(i,j=1,2,3,4)$ of Eq. (3) are given in Table I. The errors given are the standard errors produced by the fitting program. Figure 3 shows how the situation looks for the reproduction of the differential cross-section data for the given energies, while Fig. 4 shows the excitation function at 0° and 180°, in the whole energy range explored. In the figures are also shown other recent data[27–29,34] that were not used for the fit. The error bars take into account only the statistical errors. As seen, the fit gives a nice representation of the experimental points. To estimate quantitatively the goodness of this fit, we calculated the reduced χ^2 value with respect to all the monochromatic photon data (including also the Tokyo[20] results), and the data from radiative capture experiments[28–30] that we did not use in the fitting procedure. We obtained the values 0.9 and 98%, respectively, for the χ^2 and the relevant probability.

In summary, the inclusion of new monochromatic data, together with the use of a more accurate fitting procedure, provides a good fit to the differential cross-section data for deuteron photodisintegration. This fit gives the behavior of the differential cross section over the whole angular and energetic regions and makes possible an easier comparison of theory with experiments.

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