Phenomenological fit to deuteron photodisintegration data in the medium energy region

A. E. Thorlacius and Harold W. Fearing
TRIUMF, Vancouver, British Columbia, Canada V6T 2A3
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Recent data on the photodisintegration of the deuteron in the energy range 10–625 MeV have been fit to a simple phenomenological function. The result provides a representation of the cross section which should be useful for interpolating between measured points or for providing simple input for calculations such as impulse approximation calculations of (p,γ) reactions.

The deuteron photodisintegration reaction, $\gamma + d \rightarrow n + p$, is one of the most fundamental of the few-nucleon reactions. It has been attracting renewed interest as a result of new experiments in both the $\gamma + d$ and the $n + p$ directions and of some new theoretical calculations.[1] In order to provide a qualitative understanding of the reaction, useful, for example, for planning new experiments, it would be helpful to have a simple phenomenological form which gives a reasonable fit to the existing cross section data and provides a convenient interpolation in energy between existing experiments. Such a form is essential also for calculations such as distorted wave impulse approximation calculations of (p,γ) processes[2,3] which require the two body cross section as input.

At lower energies, $E_\gamma < 120$ MeV, De Pascale *et al.*[4] have obtained such a phenomenological fit. However, until recently discrepancies among data sets in the medium energy region were so great that such a fit in that range was not really practical. Now, however, there have been several new experiments[5–8] which are in fairly good agreement with each other and so obtaining a meaningful fit to the data in this energy region has become a possibility.

Thus the purpose of this note is to obtain a phenomenological representation of the $\gamma + d \rightarrow n + p$ differential cross section data valid in the full energy range 10 to about 625 MeV.

The representation used for the differential cross section in the center of mass takes the form,

$$d\sigma/d\Omega = \sum_{i=0}^{4} A_i(E_\gamma) P_i(\cos\theta) \ , \tag{1}$$

where θ is the angle between the incoming photon and outgoing proton momenta in the center of mass and E_γ is the laboratory photon energy in GeV. Note that the sum was truncated at $i = 4$. This form was chosen because the orthogonality of the Legendre polynomials ensures the relative independence of the fitted coefficients A_i. Other expansions, particularly just a simple power series in $\cos\theta$ have often been used. However, the analogous A_i's in such an expansion are strongly correlated and, as it turns out, are much less smooth as a function of energy than those of the Legendre expansion.

For most experiments where a reasonably complete angular distribution has been measured, results have been reported as a tabulation of the coefficients obtained by fitting the data to the Legendre expansion above or to some other expansion. In those cases where another expansion was originally used, appropriate linear combinations were taken so as to obtain the form above, and the usual rules were used to carry through the errors. For most of the modern experiments it was necessary to fit the raw data to the cross section form above to obtain the A_i's. The errors in the parameters A_i are standard errors given by the fitting program, except that for the Frascati data[6] at 180 and 220 MeV they were arbitrarily increased to be comparable to errors for the lower energies. This was necessary since for these cases there were almost as many A_i's as data points in the angular distribution, so that the standard errors produced by the fitting program were unreasonably small. In all cases the quoted systematic error in the experiment was added in quadrature to the statistical errors given for the A_i's. Time reversal invariance was always assumed to relate data for $n + p \rightarrow \gamma + d$ to that for the photodisintegration reaction.

Thus the "data" to be fit consisted of the set of A_i's, the coefficients of the Legendre expansion above, corresponding to the various experiments and given as a function of the photon energy. These were fit, using a least squares method, to the following phenomenological functions:

$$\begin{aligned} A_0 &= C_1 \exp(C_2 E_\gamma) + C_3 \exp(C_4 E_\gamma) \\ &\quad + (C_5 + C_6 E_\gamma)/[1 + C_8 (E_\gamma - C_7)^2] \ , \\ A_i &= C_1 \exp(C_2 E_\gamma) + C_3 \exp(C_4 E_\gamma), \quad i = 1, 2, 3, 4 \ , \end{aligned} \tag{2}$$

where an index associating the C_j's with the appropriate A_i's has been suppressed. These particular forms were chosen because they were easy to use, needed only a small number of parameters, and gave a good fit.

In principle, it would be more direct, and thus probably better, to combine Eqs. (1) and (2) above and fit each individual cross section data point directly. This might avoid possible compounding of errors and would allow the inclusion of data sets, such as the data at 0°,[9] 90°,[10] or 180° (Ref. 11) or that from Tokyo,[12] which do not cover a large enough angular range to give a set of A_i's. If there were a larger pool of new data, or if the older data were more consistent, then this method would certainly be appropriate and preferable. Given the current difficulties with the data, however, it seems too sophisticated an approach at present, one which would probably give, within errors, results not too different from the simpler method used here.

There are actually a lot of data for the photodisintegration process. However, much of the data, particularly that from older experiments, disagree by amounts large compared to the claimed errors, particularly in the medium energy re-

gion. Thus it has been difficult to obtain useful representations of the data. More recently, however, there have been a series of experiments carried out in both the $\gamma + d \rightarrow n + p$ and the $n + p \rightarrow \gamma + d$ directions which give results which are approximately consistent.[5-8]

In view of the inconsistencies in the total data set, fits have been made to three different selected groups of data. These groups correspond to different ways of handling discrepancies among data sets.

Group I consists of all of the more modern data, including that of Indiana University Cyclotron Facility (IUCF),[5] TRIUMF,[7] Frascati,[6] and Bonn.[8] The Lund[13] data were used for 400 MeV $< E_\gamma <$ 625 MeV only and the De Pascale *et al.*[4] fit was used at energies less than 120 MeV. The TRIUMF and Frascati data were combined with the IUCF data at $E_\gamma = 100$ and 140 MeV so as to give a sufficiently complete angular distribution to obtain a fit to the A_i's. The 180° point from another Bonn group, Althoff *et al.*,[11] was combined with the Bonn[8] data at smaller angles so as to give a more complete angular distribution. A_4 was taken as a constant above 425 MeV, where it cannot be determined from the data. In the De Pascale[4] fit A_4 was taken from theory, so for the present purposes an arbitrary error of 50% was assigned to these theoretical values. This set of data includes all of the published modern experiments at medium energy, gives a relatively smooth cross section curve with energy, and reputedly agrees with unpublished data from Bates.[14]

Group II consists of all available medium energy data,[5-8,13,15-20] accepted uncritically. The fit of De Pascale *et al.*[4] was again used for the lower energies and data included in that fit were dropped so as to avoid double counting.

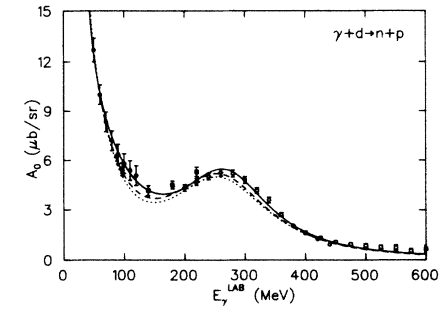
Group III consists of all data included in Group II except that of Sober *et al.*[19] and that of Lund[13] for $E_\gamma < 400$ MeV. The Lund data provide one of the most complete data sets from a single experiment and agree with other data at higher energies. However, in the 200–400 MeV range they seem to be significantly higher than most other data, as do the data of Sober.

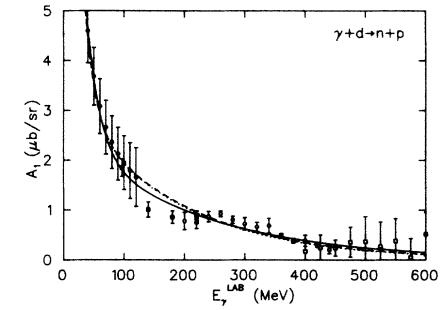
The values of the coefficients C_i of Eq. (2) obtained from fitting the three groups of data described above are tabulated in Table I. The errors given are again the standard errors produced by the fitting program, but are here probably just suggestive of the uncertainty of the fits as the coefficients were in some cases strongly correlated and there often were several rather different but almost equally good fits. Figure 1 shows the resulting values of the A_i's plotted against the data of Group I. The fit is obviously quite reasonable. Shown also in the figure are the curves obtained by fitting Groups II and III, which contain data not plotted in the figure. While the differences are not large, they are noticeable, reflecting the fact that some of the older data differ significantly from the modern sets.

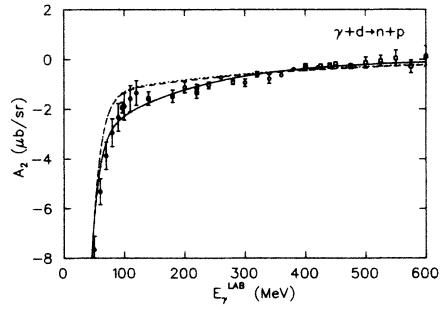
Figure 2 shows the cross sections resulting from these A's used in Eq. (1). Again only the data of Group I are shown.

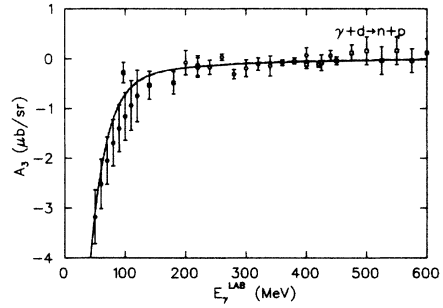
TABLE I. The coefficients and their standard errors, arising from the fit to Eq. (2) for the three groups of data, expressed in exponential form, i.e., so that $x \pm n$ denotes $x \times 10^{\pm n}$. The units are μb/sr for coefficients C_1, C_3, C_5; GeV^{-1} for C_2, C_4; μbGeV^{-1}/sr for C_6; GeV for C_7; and GeV^{-2} for C_8.

		Group I	Group II	Group III
A_0:	C_1	2.61+2 ± 2.88+1	2.77+2 ± 5.98+1	2.92+2 ± 6.04+1
	C_2	−1.10+2 ± 9.83+0	−1.23+2 ± 2.04+1	−1.32+2 ± 2.04+1
	C_3	2.46+1 ± 4.63+0	3.50+1 ± 8.86+0	4.03+1 ± 8.34+0
	C_4	−1.71+1 ± 2.71+0	−2.34+1 ± 3.60+0	−2.54+1 ± 3.13+0
	C_5	5.76+0 ± 1.10+0	6.34+0 ± 9.62−1	5.78+0 ± 8.51−1
	C_6	−2.05+0 ± 3.97+0	−4.77+0 ± 3.75+0	−3.30+0 ± 3.40+0
	C_7	2.67−1 ± 4.42−3	2.60−1 ± 5.47−3	2.58−1 ± 5.35−3
	C_8	1.13+2 ± 1.83+1	9.23+1 ± 1.52+1	9.16+1 ± 1.39+1
A_1:	C_1	1.68+1 ± 3.39+0	1.99+1 ± 6.74+0	1.95+1 ± 6.40+0
	C_2	−4.66+1 ± 7.55+0	−6.00+1 ± 1.43+1	−5.91+1 ± 1.38+1
	C_3	2.56+0 ± 2.88−1	3.33+0 ± 2.72−1	3.35+0 ± 2.75−1
	C_4	−4.72+0 ± 3.82−1	−5.63+0 ± 3.24−1	−5.76+0 ± 3.31−1
A_2:	C_1	−2.03+2 ± 1.55+1	−1.76+2 ± 1.71+1	−1.74+2 ± 1.69+1
	C_2	−8.12+1 ± 3.47+0	−7.14+1 ± 3.74+0	−7.09+1 ± 3.73+0
	C_3	−4.05+0 ± 4.55−1	−1.67+0 ± 2.07−1	−1.62+0 ± 2.20−1
	C_4	−5.99+0 ± 4.09−1	−3.32+0 ± 4.24−1	−3.41+0 ± 4.62−1
A_3:	C_1	−1.77+1 ± 1.64+0	−1.77+1 ± 2.14+0	−1.79+1 ± 2.10+0
	C_2	−3.74+1 ± 4.09+0	−3.81+1 ± 4.56+0	−3.83+1 ± 4.36+0
	C_3	−5.07−1 ± 4.46−1	−6.46−1 ± 3.81−1	−5.92−1 ± 3.47−1
	C_4	−5.40+0 ± 2.89+0	−6.57+0 ± 2.32+0	−6.29+0 ± 2.29+0
A_4:	C_1	−2.05+0 ± 1.36−1	−2.65−0 ± 2.17+0	−2.65+0 ± 2.17+0
	C_2	−7.05+0 ± 1.43+0	−2.50+0 ± 1.83+0	−2.50+0 ± 1.83+0
	C_3	9.40−1 ± 2.04−1	1.91+0 ± 2.30+0	1.91+0 ± 2.30+0
	C_4	−2.05+0 ± 1.07+0	−9.96−1 ± 1.78+0	−9.96−1 ± 1.78+0









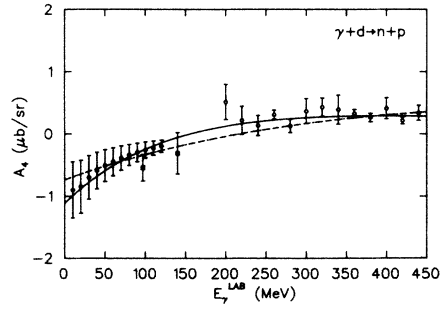
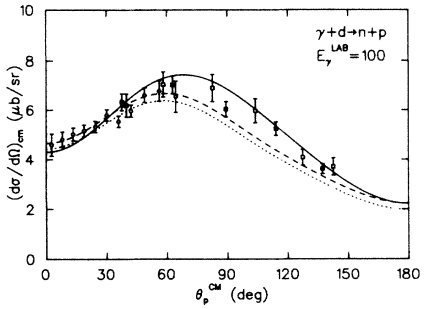
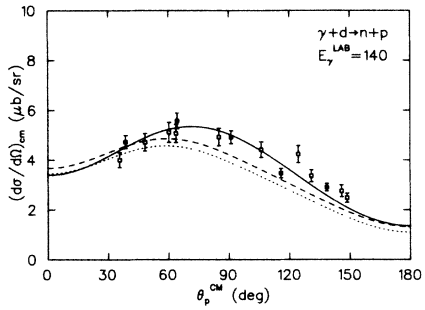
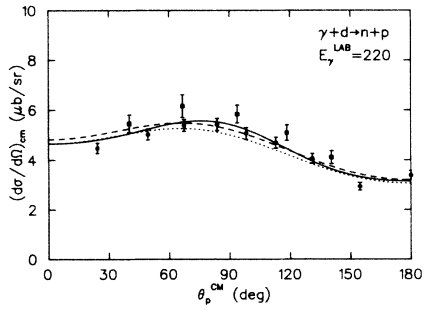
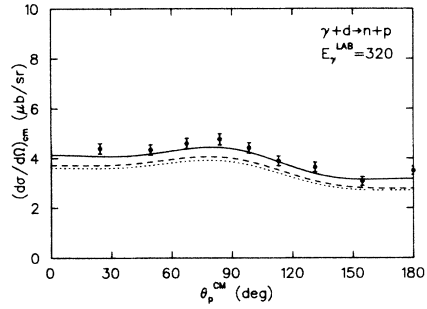


FIG. 1. Comparison of the curves fitted to A_i's to the data of Group I. The smooth curve is the fit to Group I, the dashed curve is the fit to Group II, and the dotted curve is the fit to Group III. The open boxes refer to the Lund (Ref. 13) data, the open circles refer to the Bonn (Refs. 8 and 11) data, the closed boxes refer to IUCF, Frascati, and TRIUMF (Refs. 5–7) data combined, and the closed circles refer to the De Pascale *et al.* (Ref. 4) fit to lower energy data.









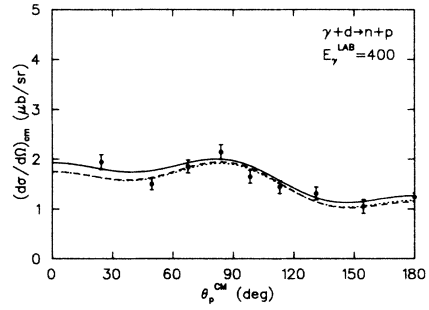


FIG. 2. Comparison of cross sections predicted at specific energies (in MeV) from the expressions fitted to the three groups of data to the actual data of Group I. The smooth curve is the fit to Group I, the dashed curve is the fit to Group II, and the dotted curve is the fit to Group III. The open boxes refer to the TRIUMF (Ref. 7) data, the open circles refer to the IUCF (Ref. 5) data, the closed boxes refer to the Frascati (Ref. 6) data, and the closed circles refer to the Bonn (Refs. 8 and 11) data.

The fits are quite consistent with the data, especially if one takes into account the fact that such fits come from an average or smoothing over an energy range but are plotted in each case at single energies against data which may come from often only one experiment, and which may differ from the energy average set in a systematic way. For example, the Group I curve at 100 MeV seems to fall slightly below the data in the forward direction. This difference can be traced to negative contributions from A_2, A_3, and A_4. However, the plotted data in the forward direction are all from IUCF[5] and one can see from Fig. 1 that the values for A_3 and to a lesser extent A_2 for that experiment alone are not as negative as for the average of other experiments in the nearby energy range as given by the fitted curve. Similar explanations apply for some of the other differences. The results from the fits to Group II and III data are shown also. One can see the kind of differences introduced by different choices of the data set.

The coefficients of Table I together with the formulas of Eqs. (1) and (2) provide a satisfactory phenomenological fit to the available deuteron photodisintegration data in the medium energy region. This fit makes possible a qualitative survey of the reaction cross section and provides a useful representation and interpolation of the data for use in other calculations. The Groups I, II, and III fits reflect different selections from a somewhat inconsistent data set, with the Group I fit emphasizing a selection of the more modern and more consistent data.

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