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1. - INTRODUCTION

The main attempts in the analysis of the deuteron photodisintegration process below the pion threshold are to understand the nature of the interaction between the electromagnetic field and the nucleus, or inversely, assuming this interaction as known, to derive some knowledge about the deuteron. This dual approach is fruitful in evaluating the relative importance of the multipole fields in the interaction, the meson exchange contributions to the process, the D-state probability of the deuteron and the final state interaction of the n-p system⁽¹⁾.

Furthermore, it has been recently suggested⁽²⁾ that the deuteron photodisintegration can be used to criticize the traditional view of the nuclei as aggregates of almost-point nucleons interacting by meson exchange. As a matter of fact, an accurate analysis of the data at low and medium energy could exhibit evidence for the existence of subnuclear degrees of freedom. This point of view is supported by the recent successes of quantum chromodynamics in the description of hadron properties in terms of confined quarks and gluons. In this framework the nucleon-nucleon force at short distances must be considered as mediated by quark interchange and gluon exchange among quarks, rather than by meson exchange. As a consequence, the deuteron wave function can be expressed as a mixture of the traditional (n-p) component and of an unconventional 6 quarks state:

$$\begin{aligned} |d\rangle &= \alpha |pn\rangle + \beta |6q\text{-state}\rangle \\ |6q\text{-state}\rangle &= a |3q, [1]_C\rangle + 3q, [1]_C\rangle + b |3q, [8]_C\rangle + |3q, [8]_C\rangle \end{aligned} \quad (1.1)$$

where $[1]_C$ and $[8]_C$ denote the color-singlet and octet respectively⁽³⁾. Furthermore the $|6q\text{-state}\rangle$ bag is assumed to have a size of the order of the nuclear core (0.4 fm)⁽⁴⁻⁶⁾.

Recently E. Hadjimichael and D.P. Saylor⁽²⁾, after a critical examination of the low-energy total cross sections of the ${}^2\text{H}(\gamma, n)p$ reaction, concluded that the standard theory is inadequate. In their model a hole of radius $r_0 = 1.57$ fm was punched in $|pn\rangle$ and the hole was filled with a non specified non-nucleonic state, contributing approximately 20% to $|d\rangle$. Furthermore, the two contributions to the total cross section have been added incoherently. Some of the assumptions utilized in ref. (2), as the previously mentioned incoherent sum

and the value assumed for the radius of the hole, seem to be questionable. On the other hand, H. Arenhövel⁽⁷⁾ claims that the existing experimental data on the total cross-section do not exhibit any clear evidence for a substantial criticism of the standard theory. Aim of the present paper is to deeper the problem by a critical analysis of existing data on both total and differential cross sections in the range $6 \leq E_\gamma \leq 140$ MeV.

Section 2 will be devoted to a short description of the standard theory. In section 3 the procedure employed to analyze the experimental data will be briefly presented. Finally, a detailed comparison between theory and experiments will be performed in Section 4.

2. - THE STANDARD THEORY

The theoretical scheme we will present in this section is derived from the classical Partovi's work⁽⁸⁾ and from the more recent presentation due to H. Arenhövel⁽⁹⁻¹¹⁾.

As usual, the differential cross section for the $^2\text{H}(\gamma, n)p$ reaction can be written in the form:

$$\left(\frac{d\sigma}{d\Omega}\right) \propto |\langle \psi_{np} | T | \psi_D \rangle|^2, \quad (1.2)$$

where ψ_D is the non relativistic deuteron ground state wave function and ψ_{np} represents the n-p system in the continuum, including final state interactions. Moreover T is the interaction hamiltonian between the e.m. field and the nucleons which is usually expanded in terms of 2^L -pole electric and magnetic contributions ($T_{El}^{(L)}$, $T_{Mag}^{(L)}$).

While for the magnetic terms the role played by the exchange effects seems to be sufficiently settled, for the electric part, which is dominant in this energy range, the situation is still under discussion. The 2^L -pole electric operators can be expressed in the form⁽¹¹⁾:

$$T_{El}^{(L)} = T_a^{(L)}(q, \vec{j}) + T_b^{(L)}(q, \vec{j}), \quad (2.2)$$

where $\vec{j}(\vec{x})$ is the nuclear current density operator, q is the photon momentum transfer and:

$$T_a^{(L)}(q, \vec{j}) = \frac{1}{iq\sqrt{L(L+1)}} \int \vec{\nabla} \left\{ \left(1 + x \frac{d}{dx}\right) j_L(qx) Y^{(L)}(\hat{x}) \right\} \cdot \vec{j}(\vec{x}) d\vec{x}, \quad (3.2)$$

$$T_b^{(L)}(q, \vec{j}) = \frac{1}{i\sqrt{L(L+1)}} \int q \vec{x} j_L(qx) Y^{(L)}(\hat{x}) \cdot \vec{j}(\vec{x}) d\vec{x} \quad (4.2)$$

In the well known "long wave approximation (LWA)", valid for $qx \ll 1$, $T_a^{(L)}(q, \vec{j})$ is the leading contribution.

By using the standard charge conservation theorem:

$$\vec{\nabla} \cdot \vec{j} = i [H, \rho] \quad (5.2)$$

where H and ρ are the nuclear hamiltonian and the nuclear charge density operator. $T_a^{(L)}$ can be put in the form:

$$T_a^{(L)}(q, \vec{j}) \equiv T_a^{(L)}(q, \rho) = \frac{1}{q\sqrt{L(L+1)}} \left[H, \int \rho(\vec{x}) \left(1 + x \frac{d}{dx}\right) j_L(qx) Y^{(L)}(\hat{x}) d\vec{x} \right] \quad (6.2)$$

Expression (6.2) summarizes the "Siegert theorem" and allows to strongly simplify the calculation of the matrix element $T_a^{(L)}$.

The operators ϱ and \vec{j} can be expanded as a sum of n-body contributions:

$$\varrho = \sum_n \varrho_n, \quad \vec{j} = \sum_n \vec{j}_n \quad (7.2)$$

In the non relativistic approximation, the one-body operators assume the well known form:

$$\varrho_1 = \sum_\alpha e_\alpha \delta(\vec{x} - \vec{r}_\alpha) \quad (8.2)$$

$$\vec{j}_1 = \sum_\alpha \left\{ \frac{e_\alpha}{2M} \left[\vec{p}_\alpha \delta(\vec{x} - \vec{r}_\alpha) \right] + \frac{\mu_\alpha}{2M} \vec{v} \times (\vec{\sigma}_\alpha \delta(\vec{x} - \vec{r}_\alpha)) \right\} \quad (9.2)$$

Since in the lowest non relativistic order ϱ is not affected by exchange effects, in almost all the available calculations it has been assumed:

$$\varrho = \varrho_1 \quad (10.2)$$

and this assumption is often called "Siegert hypothesis": however this can never be considered as an exact statement.

By also assuming $\vec{j} = \vec{j}_1$, so that

$$T_{EI}^{(L)} \equiv T_a^{(L)}(q, \varrho_1) + T_b^{(L)}(q, \vec{j}_1), \quad (11.2)$$

one obtains the standard Partovi's "Normal approximation", also called "Impulse approximation". It allows for introducing in the theory a large part of the two-body or exchange current effects. In fact, by putting in the usual way, $H = T + V_2$, eq. (5.2) splits in two parts:

$$\begin{aligned} \text{a) } \vec{v} \cdot \vec{j}_1 &= i [T, \varrho_1], \\ \text{b) } \vec{v} \cdot \vec{j}_2 &= i [V_2, \varrho_1]. \end{aligned} \quad (12.2)$$

Effects due to \vec{j}_2 are evidently introduced in $T_{EI}^{(L)}$ through the $[V_2, \varrho_1]$ commutator appearing in $T_a^{(L)}(q, \varrho_1)$.

Further contributions due to \vec{j}_2 can be introduced through $T_b^{(L)}(q, \vec{j}_2)$. Explicit forms of $\vec{j}_2(\vec{x})$ can be derived from the field theory in different ways. The most relevant physical effects can be associated with the Feynman graphs shown in Fig. 1. Diagrams I and II define the so called "Meson exchange currents (MEC)", while diagrams III the "Isobaric currents (IC)". In this way one obtains the approximation

$$T_{EI}^{(L)} = T_a^{(L)}(\varrho_1) + T_b^L(\vec{j}_1) + T_b^L(\vec{j}_2) \quad (13.2)$$

often called "Normal+MEC+IC approximation". The most complete works at present available include only the simplest π^- , pair - and Δ -contributions, so that:

$$\vec{j}_2 = \vec{j}_\pi + \vec{j}_{\text{pair}} + \vec{j}_\Delta. \quad (14.2)$$

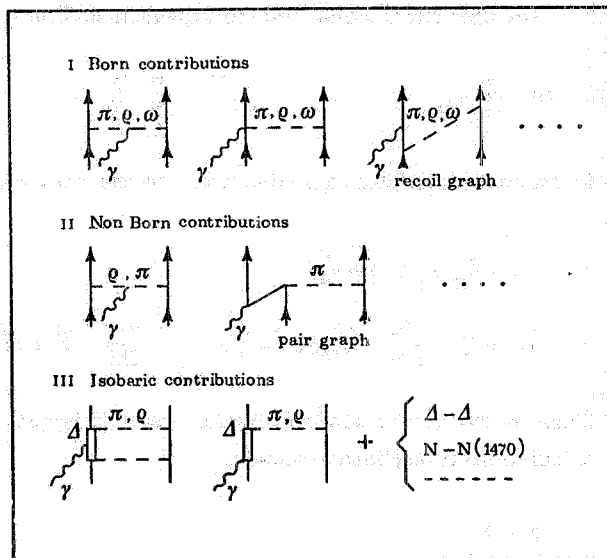


FIG. 1 - Feynman graphs contributing to the two-body nuclear exchange current operators.

The measurement of the neutron asymmetry performed at Frascati⁽¹²⁾ with polarized photons definitely shows the need for the explicit inclusion (through $T_B^L(j_2)$) of the MEC contributions to the electric multipoles, at least those connected to one pion exchange.

Particular attention will be devoted to compare calculations performed with interactions giving different values of the deuteron D-state percentage (P_D). Such a procedure is suggested by the fact that high- P_D interactions seem not to reproduce the experimental cross sections for forward proton emission⁽¹³⁾ and the neutron asymmetry recently measured at $E_\gamma = 19.8$ MeV by polarized photons⁽¹⁴⁾. A great deal of theoretical works⁽¹⁵⁻²¹⁾ has been devoted to this problem and it was established that the observed disagreements are, almost in part, related to the strength of the isovector tensor force.

Before leaving this section, let us note that, as it has been recently suggested⁽²¹⁾, also relativistic correction to $q_1(q_1^{rel})$ and exchange contributions (q_2^{exc}) could play a significant role in the theoretical description of the forward scattering processes. Thus, we are forced to conclude that the limits of validity of the Siegert hypothesis must be exhaustively explored before that the standard theory can be settled in a final form.

3. - PARAMETRIZATION AND FITTING OF THE EXPERIMENTAL DATA

In the present paper we present the results obtained by fitting the worldwide experimental data on the deuteron photodisintegration process between 6 and 140 MeV. The fitting expression for the differential cross section in the centre of mass frame, takes the usual form:

$$\frac{d\sigma}{d\Omega}(\theta, \vartheta) = I_0(\theta) + P I_1(\theta) \cos 2\vartheta = \sum_i A_i(E_\gamma) P_i(\cos \theta) + \quad (1.3)$$

$$+ P \cos 2\vartheta \sum_K B_K(E_\gamma) P_K(\cos \theta) \quad ,$$

where θ is the angle between the proton and photon momenta in the CM system and ϑ is the angle between the polarization and reaction planes; P represents the degree of linear polarization of the photon beam. If neutrons are detected, $\theta = \theta_p$ must be replaced with $\theta_n = \pi - \theta$.

Since the bulk of experimental data have been obtained with unpolarized photons ($P=0$), our attention will be mainly devoted to the first term of eq. (1.3). The idea is to give the best experimental evaluation at present

available for the coefficients A_i . Direct comparison with current theories will measure our present understanding of the physics involved in the process.

The various A_i coefficients are determined by the strength of different multipoles. However, to have a cleaner analysis in terms of multipole contributions, it is convenient to express the differential cross section for unpolarized photons as a power series of $\cos \theta$. Including terms up to the dipole-octupole interference ($i \leq 4$), one can put the first term of the eq. (1.3) in the form

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{unp.}} = a + b \sin^2 \theta + c \cos \theta + d \cos \theta \sin^2 \theta + e \sin^4 \theta, \quad (2.3)$$

using the following transformations:

$$\begin{aligned} a &= A_0 + A_2 + A_4, & b &= -\frac{3}{2}A_2 - 5A_4, \\ c &= A_1 + A_3, & d &= -\frac{5}{2}A_3, & e &= \frac{35}{9}A_4. \end{aligned} \quad (3.3)$$

As pointed out by Y. M. Shin⁽¹⁾, the meaning of the coefficients in eq. (2.3) is intuitively clearer than those of Eq. (1.3).

A detailed analysis of the available theoretical calculations^(1,8) obtained under the Siegert hypothesis allows the following conclusions:

- a) The coefficient a comes mainly from $(i \rightarrow f)\sigma L$ transitions of the kind $({}^3D_1 \rightarrow {}^3P)E1$ and $({}^3D_1 \rightarrow {}^3F)E1$, while $({}^3S_1 \rightarrow {}^1S_0)M1$ and $({}^3D_1 \rightarrow {}^3S_1)E2$ play only a marginal role. Thus, a is strongly dependent on P_D and its knowledge seems to be a sensible probe for the strength of the tensor interaction.
- b) In the lowest energy part of the examined range ($E_\gamma \leq 80$ MeV), the coefficient b is strongly dominated by the $({}^3S_1 \rightarrow {}^3P)E1$ transitions. Since $T_{E1}^{(1)}$ is a long range operator, the $E1$ matrix elements are not expected to be strongly dependent on the short range properties of the interaction: consequently b is essentially determined by the δ_p phase-shifts.
- c) Important contributions to the coefficient c come from the interference of the $({}^3D_1 \rightarrow {}^3P)E1$ with the $({}^3D_1 \rightarrow {}^3S_1)E2$ transitions and from the interference of the $({}^3D_1 \rightarrow {}^3D_1)M1$ (orbital) and $({}^3S_1 \rightarrow {}^3S_1)M1$ (spin) transitions with other multipoles. Thus, also the coefficient c is an useful probe for the strength of the tensor force. In the past some authors have experimentally found negative values of c , in spite of the theoretical calculations. One has to remind that the only term giving a negative c coefficient is related to the $({}^3D_1 \rightarrow {}^3D_1)M1$ (orbital) transitions but this would require a very anomalous enhancement of this term.
- d) Finally, d comes almost entirely from $({}^3S_1 \rightarrow {}^3P)E1 + ({}^3S_1 \rightarrow {}^3D)E2$ interference.

All the data included in the fit have been taken from refs. (13, 14, 22-39). In particular, data from refs. (36,37) disagree of 10-20% with respect to the average of the others and nevertheless have been included in the fit in relative units. The systematic errors quoted by the authors have been linearly added to the statistical Lab system according to the dependences suggested in ref. (40), with the addition of some polynomial terms. Furthermore the coefficient A_4 in the region $E_\gamma \geq 60$ MeV has been found to be largely dependent upon the parametrization used and almost undetermined ($\Delta A_4/A_4 \approx 0.5$). For these reasons it has been fixed to the theoretical value given by the RSC potential under the "Normal+MEC+IC approximation"⁽⁴²⁾.

The obtained results for the coefficients A_i ($i=0,3$) are reported in Table I together with the values assumed for A_4 and in Figs. 2 and 3. The χ^2 per degree of freedom is 1.45 and the total number of data is 396.

TABLE I - Fitted values for the coefficients A_i ($i=0, 1, 2, 3$). The values for the A_4 coefficient come from ref (42).

E_γ (MeV)	A_0 ($\mu\text{b}/\text{sr}$)	A_1 ($\mu\text{b}/\text{sr}$)	A_2 ($\mu\text{b}/\text{sr}$)	A_3 ($\mu\text{b}/\text{sr}$)	A_4 ($\mu\text{b}/\text{sr}$)
10	110.6 ± 3.5	13.8 ± 2.2	-105.9 ± 3.9	-13.6 ± 1.3	-0.9
20	45.5 ± 1.4	8.9 ± 1.0	-40.0 ± 1.3	-8.63 ± 0.77	-0.85
30	25.7 ± 0.9	6.09 ± 0.80	-20.14 ± 0.85	-5.77 ± 0.66	-0.70
40	17.2 ± 0.7	4.60 ± 0.65	-11.84 ± 0.60	-4.16 ± 0.59	-0.59
50	12.7 ± 0.7	3.68 ± 0.58	-7.66 ± 0.54	-3.18 ± 0.54	-0.51
60	10.0 ± 0.6	3.08 ± 0.55	-5.31 ± 0.53	-2.52 ± 0.50	-0.45
70	8.34 ± 0.60	2.66 ± 0.54	-3.87 ± 0.55	-2.05 ± 0.48	-0.39
80	7.19 ± 0.60	2.36 ± 0.53	-2.95 ± 0.56	-1.69 ± 0.47	-0.34
90	6.38 ± 0.60	2.13 ± 0.53	-2.33 ± 0.56	-1.40 ± 0.47	-0.30
100	5.80 ± 0.60	1.95 ± 0.54	-1.89 ± 0.55	-1.16 ± 0.48	-0.26
110	5.38 ± 0.60	1.79 ± 0.56	-1.58 ± 0.53	-0.94 ± 0.50	-0.23
120	5.07 ± 0.60	1.66 ± 0.59	-1.35 ± 0.50	-0.75 ± 0.52	-0.20
130	4.84 ± 0.60	1.55 ± 0.63	-1.16 ± 0.48	-0.57 ± 0.55	-0.18
140	4.67 ± 0.60	1.43 ± 0.67	-1.01 ± 0.45	-0.40 ± 0.59	-0.15

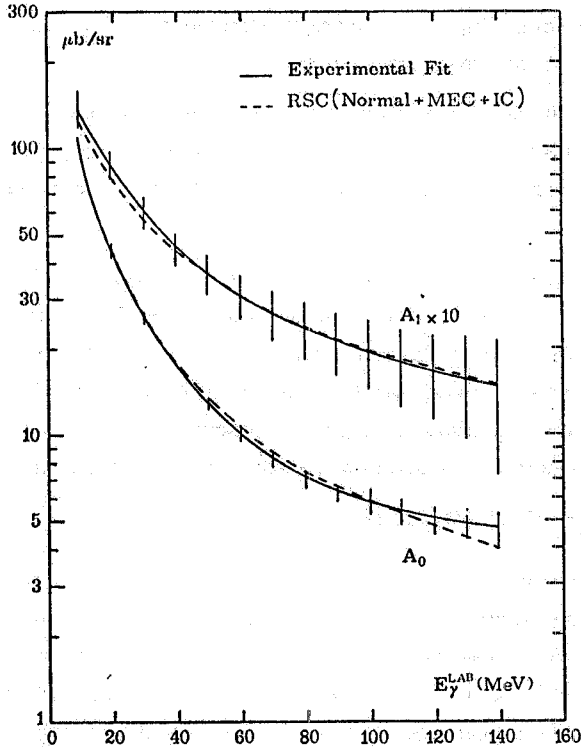


FIG. 2 - Obtained results for the coefficients A_i ($i=0,1$). The full lines represent the present fit and the vertical bars account for the statistical uncertainties. The dashed curves are the theoretical results (42) given by the RSC calculations (N+MEC+IC).

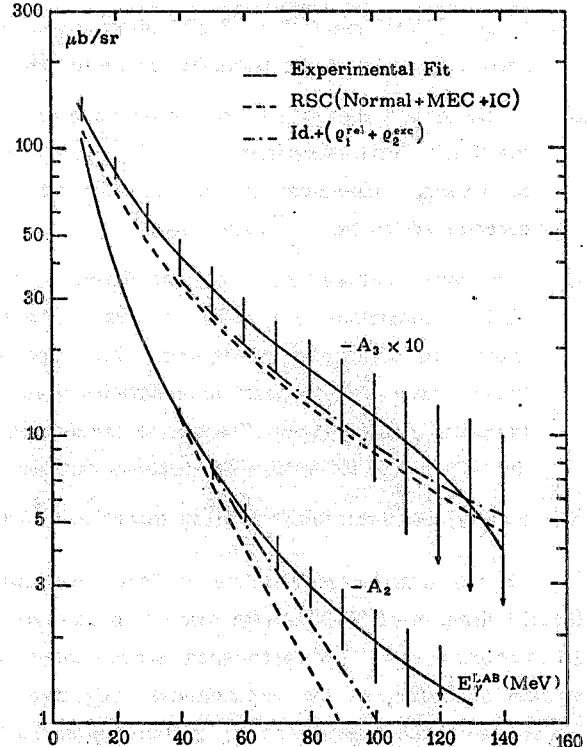


FIG. 3 - The same as Fig. 2 for the coefficients A_i ($i=2,3$). The dot-dashed curves include relativistic corrections to e_1 and pion-exchange contributions to e_2 (42).

The results of our analysis can be also expressed in terms of the a, b, c, d coefficients given by eq. (3.13). While the procedure furnishes unique results for a and d, the extraction of b and c is very delicate: for $E_\gamma \geq (70-80)$ MeV, b is strongly dependent upon $e (e = \frac{35}{9} A_4)$ and the large dispersion of the data points around $\theta=0$ and $\theta = \pi$, makes the determination of c very doubtful below 40 MeV. The obtained values are reported in Table II and

TABLE II - Fitted values for the a, b, c, d coefficients. The values for the coefficient e come from ref. (42).

E_γ (MeV)	a ($\mu\text{b}/\text{sr}$)	b ($\mu\text{b}/\text{sr}$)	c ($\mu\text{b}/\text{sr}$)	d ($\mu\text{b}/\text{sr}$)	e ($\mu\text{b}/\text{sr}$)
10	3.88 ± 0.63	163.3 ± 4.7	0.22 ± 0.15	34.0 ± 3.2	-4.0
20	4.63 ± 0.46	64.2 ± 1.4	0.32 ± 0.22	21.6 ± 1.9	-3.8
30	4.86 ± 0.38	33.7 ± 0.8	0.38 ± 0.24	14.4 ± 1.7	-3.1
40	4.77 ± 0.34	20.7 ± 0.6	0.44 ± 0.25	10.4 ± 1.5	-2.7
50	4.54 ± 0.31	14.0 ± 0.5	0.50 ± 0.25	7.94 ± 1.30	-2.3
60	4.30 ± 0.28	10.2 ± 0.5	0.56 ± 0.25	6.30 ± 1.20	-2.0
70	4.08 ± 0.26	7.77 ± 0.41	0.61 ± 0.26	5.12 ± 1.20	-1.7
80	3.89 ± 0.24	6.16 ± 0.38	0.67 ± 0.26	4.22 ± 1.20	-1.5
90	3.75 ± 0.24	5.03 ± 0.37	0.73 ± 0.27	3.50 ± 1.20	-1.3
100	3.64 ± 0.24	4.20 ± 0.35	0.79 ± 0.27	2.89 ± 1.20	-1.1
110	3.56 ± 0.25	3.58 ± 0.34	0.85 ± 0.28	2.35 ± 1.20	-1.0
120	3.51 ± 0.27	3.10 ± 0.32	0.91 ± 0.28	1.87 ± 1.30	-0.9
130	3.48 ± 0.29	2.72 ± 0.32	0.96 ± 0.29	1.42 ± 1.40	-0.8
140	3.47 ± 0.31	2.42 ± 0.30	1.03 ± 0.30	1.00 ± 1.50	-0.7

Figs. 4 and 5 but the quoted errors must be considered necessarily as indicative since they sensibly depend even upon the parametrization used.

To give an idea of the goodness of the fit, a direct comparison between the fit and the total cross section experimental data ($\sigma_{T=4\pi A_0}$) is shown in Fig. 6. Furthermore the fit curve is in substantial agreement with the estimates of the total cross section obtained in the limit $q^2 \rightarrow 0$ from the electrodisintegration data in the region $E_\gamma \leq 30$ MeV⁽⁴¹⁾.

Finally Figs. 7A and 7B show how the situation looks like for the reproduction of the differential cross section data in the low and high energy region respectively.

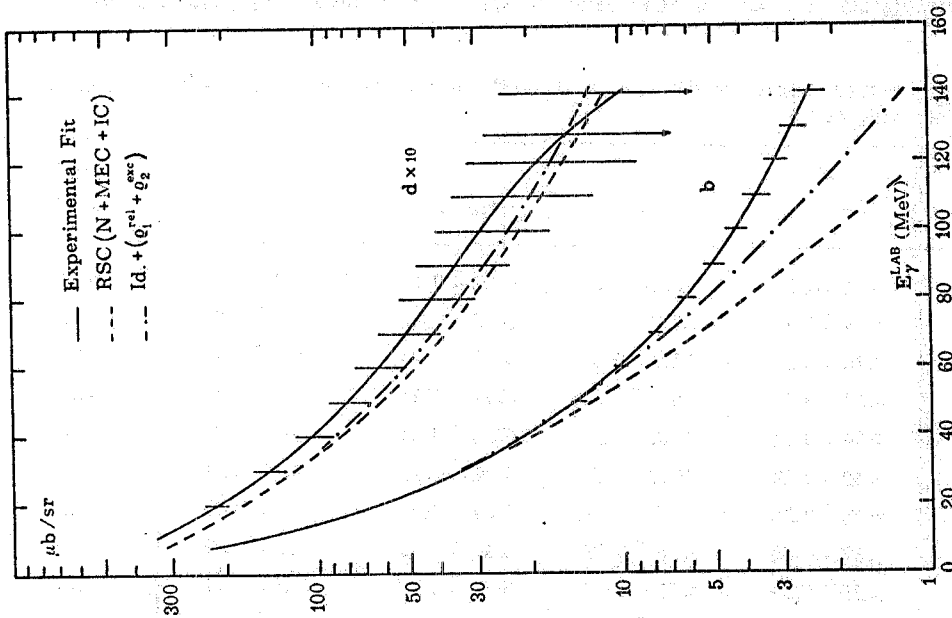


FIG. 5 - Obtained results for b and d. Full and dashed curves represent the fit and the RSC calculations. The dot-dashed curve include relativistic corrections to Q_1 and π -exchange contributions to Q_2 .

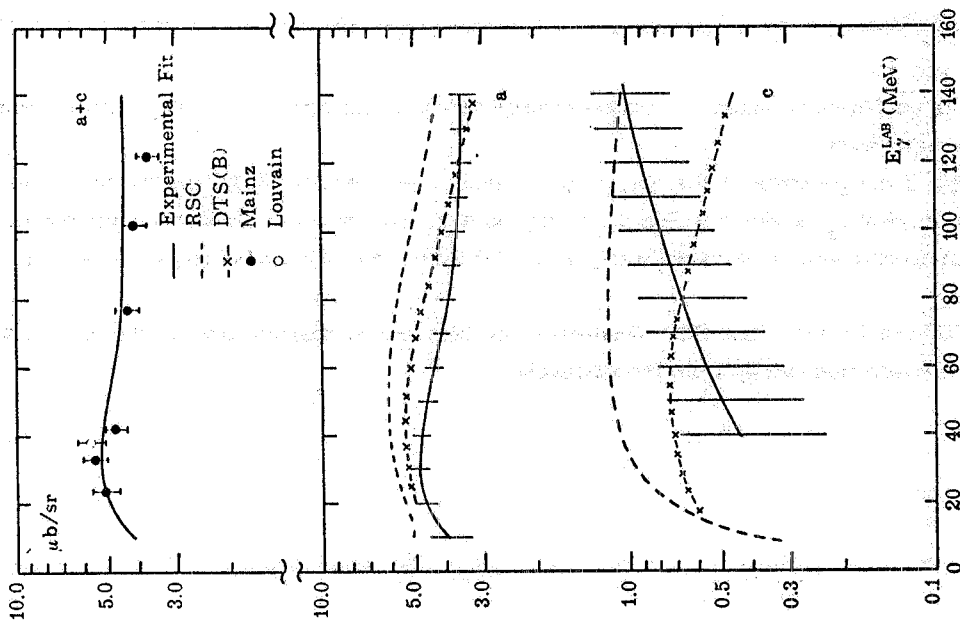


FIG. 4 - Obtained results for a, c, a+c. Full, dashed and cross-dashed curves represent the fit, the RSC and the DTS-version B calculations, respectively. Dots and circles are the Mainz and Louvain experimental results.

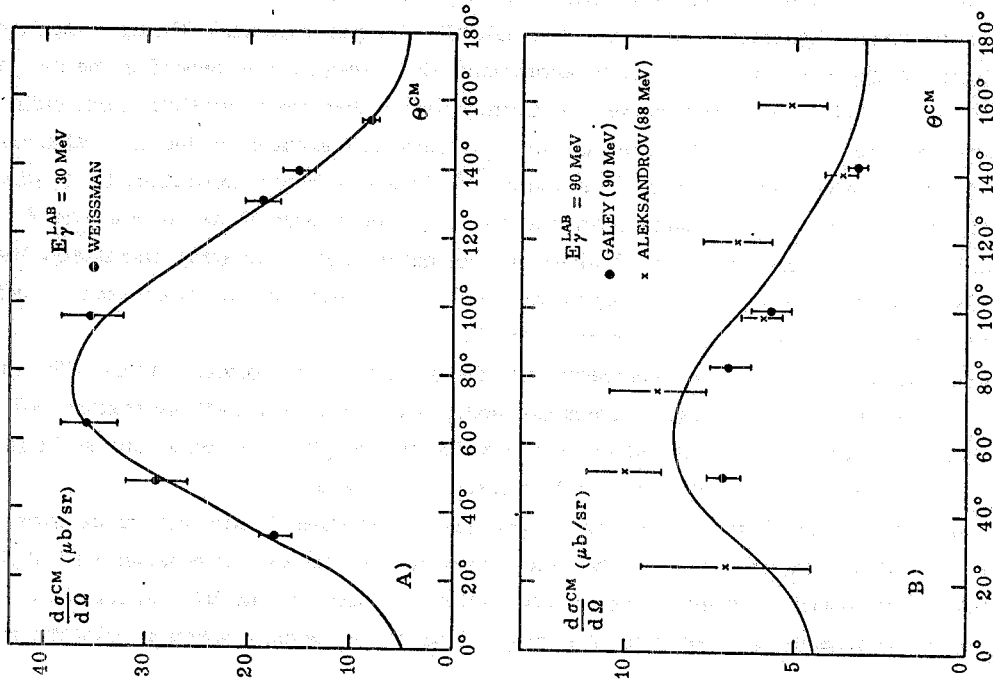


FIG. 7 - Typical results for the differential cross sections in the low (7A) and high (7B) energy regions.

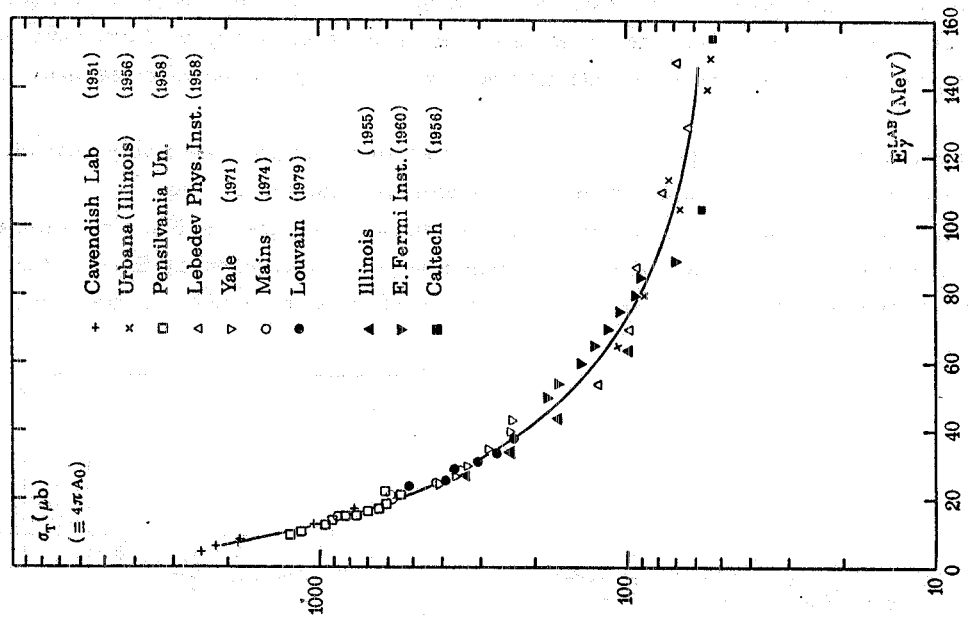


FIG. 6 - Comparison between the fit and the experimental data for the total cross section.

4. - DISCUSSION OF THE RESULTS

The dashed curves in Figs. 2 and 3 report the results for the A_1 coefficients obtained in ref. (42) by using the RSC potential under the Siegert hypothesis and in the "Normal+MEC+IC approximation". The agreement for A_0 and A_1 is extremely satisfying everywhere. For A_2 no appreciable disagreement is evidenced in the low energy region, whereas for $E_\gamma > 50$ MeV the fitting curve is definitely higher than the theoretical calculation. This effect can be partially attributed to the great influence that the assumed behaviour for the A_4 coefficient can have on A_2 beyond 50 MeV. Furthermore preliminary estimates⁽⁴²⁾ of the relativistic corrections to ρ_1 (Darwin-Foldy and spin orbit terms) and pion exchange contributions to ρ_2 have been shown to enhance A_2 of a substantial amount. This effect is reported in Fig. 3 where the dot-dashed curve fills quite appreciably the gap between fit and theory beyond 50 MeV. A similar argument holds for A_3 where, on the other hand, no definite disagreement can be evidenced outside the quoted errors of the fit.

In Fig. 4 the fitted values for a and c are compared with the calculations performed with the RSC and the DTS-Version B potentials always under the Siegert hypothesis and in the "Normal+MEC+IC approximation". As it is very well known, these two potentials mainly differ for the different strength of the tensor force: the D-wave percentage is $P_D = 6.47\%$ and $P_D = 4.25\%$ for the RSC and DTS cases respectively.

According to our analysis the fitting curves for a and (a+c) coefficients turn out to be lower than theoretical expectations and as a significant result the best reproduction of the data is obtained with the DTS-potential. Even c, that is very poorly determined, seems to be better reproduced by the DTS-calculations.

As far as the other coefficients are concerned, d is proportional to A_3 , while b seems to miss theory only beyond $E_\gamma = 50$ MeV.

In conclusion of this analysis of the deuteron photodisintegration process below π - threshold, we can say that in the region $E_\gamma < 70$ -80 MeV the current theory including MEC+IC contributions seems to reproduce the data sufficiently well except for the differential forward cross section (a+c) where the observed discrepancies are of the order of the contributions we expect from $\rho^{rel.}$ and $\rho^{exc.}$. In the high energy region ($E_\gamma > 80$ MeV), the disagreements are more evident but, before giving particular significance to any of them, more complete calculations outside the limits imposed by the Siegert hypothesis and including relativistic corrections should be made available.

In addition, the spread of the data points (see Fig. 6) in this energy region makes very difficult to test theories with sufficient accuracy and thus more refined experiments are seriously required.

As a final remark on the claimed inadequacy of the present theory, we present in Fig. 8 the ratio between the experimental and theoretical total cross sections, calculated with the RSC potential. Even in this case no real effect can be envisaged such as to necessarily claim for the introduction in the theory of subnuclear degrees of freedom.

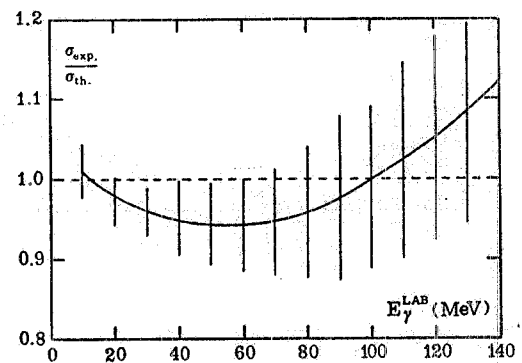


FIG. 8 - Ratio σ_{exp}/σ_{th} between the experimental and theoretical total cross sections calculated by the RSC potential.

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