Relativistic and Mesonic Corrections to the Forward Cross Section for $d(\gamma,p)n$

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The discrepancy between the theoretical and the experimental values of the forward deuteron photodisintegration cross section is found to be sensibly reduced by the inclusion of the relativistic corrections (Darwin-Foldy and spin-orbit terms) in the charge density. On the contrary, the pionic corrections calculated in the pseudoscalar πNN coupling are in the opposite direction.

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As is well known, there is a large discrepancy between the experimental and the theoretical values of the differential cross section at 0°, $d\sigma/d\Omega(0°)$, for the emitted protons in deuteron photodisintegration. The results obtained by Hughes *et al.*[1] for photon laboratory energies between $E_\gamma = 20$ and 120 MeV were systematically lower, by about 30% to 40%, than those given by the impulse-approximation (IA) theory[2] with old realistic potentials predicting a D-state deuteron percentage $P_D \simeq 7\%$, such as the Hamada-Johnston potential. The discrepancy was practically unchanged even after the inclusion of the exchange-current contributions as in the calculation of Arenhövel *et al.* quoted in Ref. 1. Moreover, very recently the result of Hughes *et al.*[1] at $E_\gamma \simeq 40$ MeV has been confirmed by Gilot *et al.*[3] in a measurement of the differential cross section of the inverse reaction, the n-p radiative capture.

The first attempts to obtain theoretical values in agreement with those measured were concentrated on the NN interaction. In fact, $d\sigma/d\Omega(0°)$ is very sensitive to the noncentral parts of the NN potential, essentially to the tensor part. The cross section should be exactly zero in $E1$ approximation (neglecting the magnetization current) with noninteracting final states and with a vanishing P_D.[4] By studying the influence of the tensor force on $d\sigma/d\Omega(0°)$, several authors[4-6] have shown that NN potentials predicting a lower P_D sensibly reduce the discrepancy with experiment. But too strong of a reduction of the strength of the tensor force is not realistic because it has the consequence of worsening the fit to other experimental data, such as the deuteron quadrupole moment. Rather, it should be necessary to modify the shape of the tensor force, whose isovector part seems to be too strong in the intermediate range.[7]

Obviously a second way for modifying the value of the cross section consists of changing the transition operators. The first attempts in this direction were by Gari and Sommer[8] and Hadjimichael,[9] who studied the effect on $d\sigma/d\Omega(0°)$ of the two-body contributions ($\rho_{[2]}$) to the charge density coming from the pair process in Fig. 1, calculated with use of the pseudoscalar (ps) πNN coupling. Their results seemed to go in the right sense, leading to a consistent reduction (of about 10%) of the theoretical cross section. But these findings have been completely reversed by Jaus and Woolkock,[10] who compare the effect on $d\sigma/d\Omega(0°)$ of $\rho_{[2]}$ evaluated in pseudovector (pv) and ps πNN coupling. Indeed, they find that $d\sigma/d\Omega(0°)$ diminishes by (2–5)% in pv coupling, while it increases by (4–5)% in ps coupling, in the photon energy range 20–40 MeV. These authors take into account many local and nonlocal contributions to $\rho_{[2]}$ deriving from the exchange of one and two pions and with nucleon- and Δ_{33} intermediate states. However, the dominant contribution in ps coupling turns out to be that of the pair process. In their calculations, Jaus and Woolkock[10] include only the $E1$ transitions in the long-wavelength (LW) approximation.

Besides the two-body mesonic corrections to

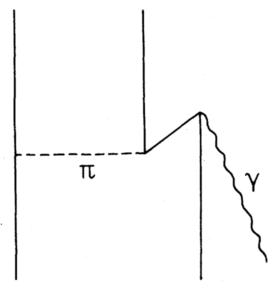

FIG. 1. Pair-excitation process.

the charge density, there are the one-body relativistic corrections (ρ_R), which, to our knowledge, have never been considered until now in deuteron photodisintegration. Our aim in this paper is to give an evaluation of the relativistic effects on $d\sigma/d\Omega(0°)$. We limit ourselves to the so-called Darwin-Foldy and spin-orbit terms,[11] even if a fully consistent relativistic treatment to the order $1/M^2$ (M being the nucleon mass) should also include other kinematic and dynamic corrections to the charge density coming from the relativistic transformation of the wave functions.[12]

In this paper we also report on the results for $d\sigma/d\Omega(0°)$ when the mesonic charge density in ps coupling is considered without limiting the calculation to the LW $E1$ approximation.

We find that these relativistic corrections sensibly reduce the discrepancy between the theoretical and experimental values of $d\sigma/d\Omega(0°)$. On the contrary, the mesonic corrections in ps coupling go in the wrong direction, increasing the theoretical cross section, in agreement with the findings of Jaus and Woolkock.[10]

In summary, we are interested in showing the effect on $d\sigma/d\Omega(0°)$ of the one-body relativistic charge density ρ_R and of the two-body pionic charge density $\rho_{[2]}$, calculated in ps coupling. For ρ_R and $\rho_{[2]}$ we limit ourselves to the Darwin-Foldy and spin-orbit terms, and to the dominant pair-process contributions, respectively.

By Fourier transformation of the momentum-space expression of ρ_R in Ref. 11, the one-body charge density $\rho_{[1]}$, in configuration space, assumes the form

$$\rho_{[1]}(\vec{x}) = e\sum_i \left[\hat{e}_i\left(1+\frac{\nabla_x^2}{8M^2}\right)\delta(\vec{x}-\vec{r}_i) + \frac{2\hat{\mu}_i-\hat{e}_i}{4M^2}\nabla_x\delta(\vec{x}-\vec{r}_i)\cdot\vec{\sigma}_i\times\vec{p}_i\right], \qquad (1)$$

where $\vec{\sigma}_i$ and $\vec{p}_i$ are the spin and momentum operators of the ith nucleon, and $\vec{r}_i$ is its coordinate in the center-of-mass frame. For real photons,

$$\hat{e}_i = \tfrac{1}{2}[1+\tau_z(i)], \quad \hat{\mu}_i = \tfrac{1}{2}[\mu_S + \mu_V\tau_z(i)],$$

$\mu_S \simeq 0.88$ and $\mu_V \simeq 4.71$ being the isoscalar and isovector magnetic moments of the nucleon, and $\tau_z(i)$ the z component of the isospin vector $\vec{\tau}_i$.

The pair-process contribution to the charge density was calculated for the first time by Kloet and Tjon and reported afterwards by several authors.[13] Transforming to configuration space, as indicated in the Appendix of Ref. 14, we have

$$\rho_{[2]}(\vec{x}) = -\frac{e}{2M} f_{\pi NN}^2 \vec{\sigma}_1\cdot\nabla_x\left[(\mu_S\vec{\tau}_1\cdot\vec{\tau}_2+\mu_V\tau_{2z})\vec{\sigma}_2\cdot\frac{\vec{r}_2-\vec{x}}{|\vec{r}_2-\vec{x}|}Y_1(\mu|\vec{r}_2-\vec{x}|)\delta(\vec{r}_1-\vec{x})\right] + (1\rightleftarrows 2), \qquad (2)$$

where we did not use any form factor at the πNN vertex. In (2) $f_{\pi NN}^2 \simeq 0.08$ is the πNN coupling constant, μ is the pion mass, and

$$Y_1(x) = (e^{-x}/x)(1+x^{-1}).$$

As far as the nuclear current density is concerned, we have considered only the usual convective and spin magnetization currents, neglecting the meson-exchange currents (MEC) as well as the isobar configuration admixtures (IC) to the normal wave functions. The reasons for this are that our treatment of the mesonic and relativistic corrections is far from being complete and, moreover, that the MEC and IC contributions to $d\sigma/d\Omega(0°)$ were calculated by Arenhövel and Fabian (quoted in Ref. 1) and found to be very small except at the threshold.

Finally, we refer to the classic paper of Partovi[2] for the expression of the differential cross section. The procedure for obtaining from ρ_R and $\rho_{[2]}$ the electric multipole operators and the new contributions to the reduced matrix elements $I^L(\lambda j)$, defined by Partovi, is straightforward and will not be given in this Letter.

Furthermore, because of the sensitivity of $d\sigma/d\Omega(0°)$ to the form of the NN interaction, we have considered two potential models, giving different P_D: the Reid soft-core potential (RSC)[15] ($P_D = 6.47\%$), and version B of the super-soft-core potential (SSB) of de Tourreil and Sprung[16] ($P_D = 4.25\%$).

Our results are compared with the experimental values[1,3] in Figs. 2 and 3 for the RSC potential and SSB potential, respectively. The solid lines represent the values obtained in Partovi's theory, the dashed lines show the variations induced by $\rho_{[2]}$, and the dot-dashed lines show those induced by ρ_R. Finally, the dotted lines correspond to the inclusion of both $\rho_{[2]}$ and ρ_R.

The first comment concerns the convergence of the multipole expansion. We have found that, in order to have three significant digits in $d\sigma/d\Omega(0°)$, it is necessary to include in the calculation all the electromagnetic multipoles through $L=3$ for $E_\gamma \simeq 20$ MeV, $L=4$ for $E_\gamma \simeq 60$ MeV, and $L=5$ for higher energies. Actually, the maximum multipole order to be included for the contributions due to ρ_R and $\rho_{[2]}$ turns out to be lower on the average, by one and two units, respectively.

As regards the effect of ρ_R, it is clearly seen from the figures that the relativistic corrections to the charge density markedly lower the theoretical values of $d\sigma/d\Omega(0°)$. If only ρ_R is added to the standard electromagnetic operators and the SSB potential is used, the theoretical points become even lower than the experimental ones above 80 MeV (see Fig. 3). The variations increase with photon energy, as expected on account of the momentum dependence of ρ_R. The percentage changes are similar for both the potentials used. For example, in the case of the RSC potential, they go from -3% at 10 MeV to -20% at 100 MeV. The spin-orbit term gives

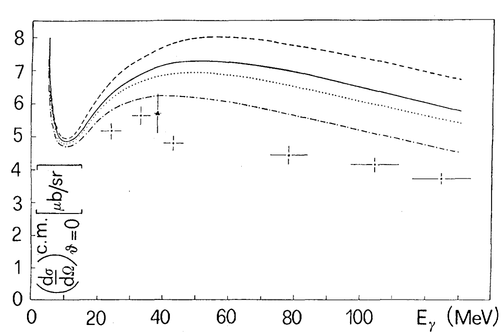

FIG. 2. Forward deuteron photodisintegration cross section, with the Reid soft-core potential. The full line represents the cross section in the impulse approximation. The dashed (dot-dashed) line gives the results when the two-body charge density $\rho_{[2]}$ (the relativistic charge density ρ_R) is included. The dotted line shows the cross section when both $\rho_{[2]}$ and ρ_R are included. The experimental points are from Ref. 1 (dots) and from Ref. 3 (triangle).

the dominant contribution because it allows transitions from the $^3S_1$ deuteron state to the singlet and triplet final states, whose importance is enhanced because of the small value of P_L. In fact, as discussed above, the main transitions in the standard theory are from the $^3D_1$ deuteron state.

As far as the effect of the pionic charge density in ps coupling is concerned, we find that $\rho_{[2]}$ induces positive corrections in $d\sigma/d\Omega(0°)$. Thus, our results are in disagreement with those of Gari and Sommer[8] and of Hadjimichael[9] but in agreement with those of Jaus and Woolkock.[10] The short-range behavior of the two-body electric multipole operators deriving from (2) enhances the importance of higher momentum transfers. In fact, when $\rho_{[2]}$ is added to the usual nonrelativistic charge density, the percentage variations of $d\sigma/d\Omega(0°)$ grow gradually from 2% at 10 MeV to 14% at 100 MeV for the RSC potential. Again, the variations with the SSB potential are similar.

With reference to the corrections induced by $\rho_{[2]}$, a remark about the paper of Jaus and Woolkock[10] is in order. The percentage variations just quoted are those obtained with consideration of all the electromagnetic multipoles through an appropriate order ($L=4$ on the average, as stated above) and all the retardation factors. We have also calculated $d\sigma/d\Omega(0°)$ in the LW $E1$ approximation, as in Ref. 10. In this limit the percentage variations are, of course, higher; at 20 MeV we obtain 7.1% instead of 4.6% and at 40 MeV 11.6% instead of 7.9%, always with the RSC potential. We must conclude that the other multipoles and the retardation factors neglected in Ref. 10 give nonnegligible contributions even in this low-energy region.

The dotted lines represent the theoretical results when both $\rho_{[2]}$ and ρ_R are considered. Since

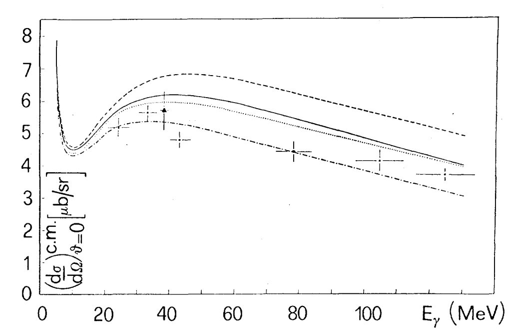

FIG. 3. The same as in Fig. 2, when the super-soft-core potential (version B) of de Tourreil and Sprung (Ref. 16) is used.

the two corrections are of opposite sign and that of ρ_R is higher, the resulting curves are slightly closer to the measured values than those obtained in the IA.

Jaus and Woolkock[10] have also found that $\rho_{[2]}$ evaluated in pv coupling reduces the discrepancy with the experiment. However, we cannot combine our results for ρ_R with their results for $\rho_{[2]}$ in pv coupling to give the overall effect in $d\sigma/d\Omega(0°)$ because their calculation is in LW $E1$ approximation and, moreover, because of the interference terms.

In conclusion, we think that our results on the relativistic corrections to $d\sigma/d\Omega(0°)$ are promising even if not conclusive because we have neglected the relativistic corrections coming from the distortions to the wave functions due to the nuclear motion. For a definite understanding of the measured $d\sigma/d\Omega(0°)$, a more accurate investigation of the isovector part of the tensor force has been suggested.[7] It seems to us that the study of the relativistic and exchange contributions to the electromagnetic operators is also worth pursuing.

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