Contributions to the $E2$ transition in the reaction ^{2}H(γ, n)p

A. Kassaee, L. N. Pandey, and M. L. Rustgi
Department of Physics and Astronomy, State University of New York, Buffalo, New York 14260

E. Hadjimichael
Physics Department, Fairfield University, Fairfield, Connecticut 06430
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We find that the contributions from meson-exchange currents and from single-nucleon relativistic-order effects do not sufficiently enhance the $E2$ multipole transition in ^{2}H(γ,n)p, to match the quality of previously obtained fits to data for the ratio of the differential cross section at forward and backward angles to that at 90°.

In an earlier paper,[1] we had analyzed experimental data at low energies, measured at Argonne,[2] of the ratio of the laboratory differential cross section for deuteron photodisintegration at laboratory angles 45°, 135°, and 155°, to that at 90°. We found that these data project out the contribution from the $E2$ transition amplitude to an extent that both a theoretical analysis and an experimental determination of this amplitude become feasible. We consider this an important outcome. It gives us a way to glean information on microscopic nuclear processes from a close examination of the $E2$ transition amplitude in an energy regime where theoretical constructs are most reliable.

We display a sample of the results of these calculations in Fig. 1, along with the experimental data. In this low-energy range, one normally thinks of the photodisintegration reaction as proceeding via the $E1$ transition, with the $M1$ transition fading soon after the reaction threshold, and the $E2$ and $M2$ amplitudes playing no role at all (see Ref. 1). Surprisingly, however, our results in Fig. 1 show a large and measurable difference between curve 1, which is the cross-section ratio when only the $E1$ and $M1$ amplitudes are taken into account, and curve 2, which includes contributions from the $E2$ transition. This difference is impressively large and obviously useful in analyzing the $E2$ multipole amplitude. These results are obtained with NN wave functions found using the Paris potential.[3] We have obtained very similar results with the super-soft core (SSC) potential[4] (See Ref. 1). Furthermore, line 2 changes to line 3 when the effect of meson-exchange currents is incorporated into the $E1$-$M1$ multipoles.

A second observation is that the complete results in Fig. 1, including the measurable contribution from the $E2$ multipole (line 2 or 3), do not yet agree with the experimental data at low energies. It was shown that, assuming the data to be correct, the discrepancy can be eliminated by enhancing the $E2$ multipole amplitude. Indeed, excellent agreement with the data was achieved, shown by line 5 in Fig. 1, by a radical phenomenological change in the magnitude and in the energy dependence of the coefficients c, d, and e, in the c.m. cross section,[5]

$$\sigma(\theta)_{\rm c.m.} = a + b\sin^2\theta - c\cos\theta - d\sin^2\theta\cos\theta + e\cos^2\theta\sin^2\theta \ , \quad (1)$$

i.e., precisely the coefficients that are strongly affected by the $E2$ transition amplitude.[1] Table I in Ref. 1 shows both the unmodified coefficients that yield curve 2, and the modified ones that produce curve 5.

Recently, the results of a new experiment on cross-

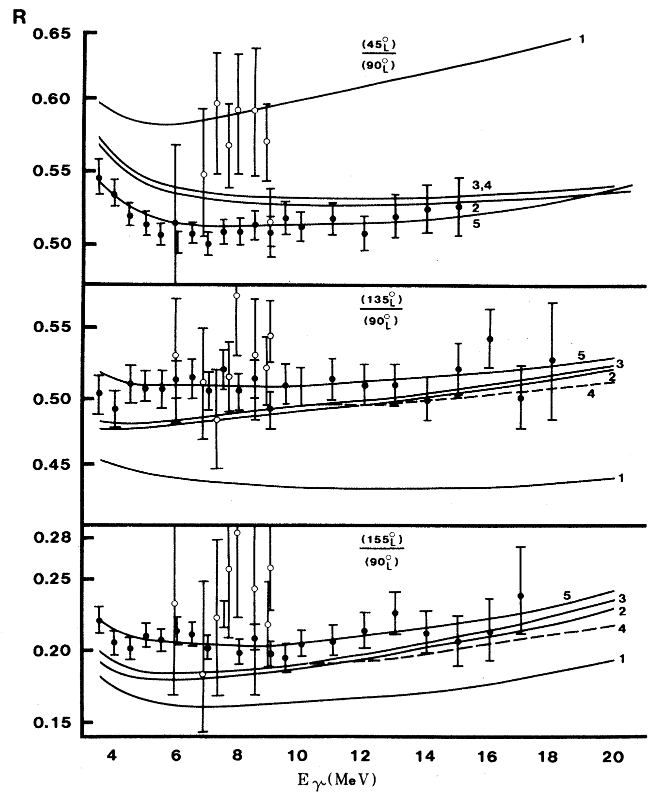

FIG. 1. Results for the differential cross-section ratio $R=\sigma_L(\theta_L)/\sigma_L(90°_L)$ for ^{2}H(γ,n)p. (a) $\theta_L=45°$; (b) $\theta_L=135°$; and (c) $\theta_L=155°$. Line 1 is the result when only the $E1$ and $M1$ amplitudes are included in the cross section. Line 2 additionally includes the $E2$ (and $M2$) amplitude. Line 3 shows the effect of the enhancement of the $E1$-$M1$ amplitude by MEC contributions. Line 4 is the result with the single-nucleon spin-orbit contribution and MEC contributions. Line 5 is the best-fit results from the phenomenologically enhanced $E2$ amplitude (see Ref. 1). The experimental data are from Ref. 2 (filled circles) and Ref. 6 (open circles).

section ratios in the range 6–9 MeV were published[6] and are shown by the open circles in Fig. 1. Because of the limited energy range and the relatively larger experimental uncertainties associated with these data points, the experimental situation is hardly clarified by this new information, and the theoretical issues raised here remain relevant.

In the present work, we attempt to discover if corrections to the nuclear current from relativistic order terms in the single-nucleon charge density, i.e., the spin-orbit term, and from microscopically calculated mesonic-exchange currents (MEC's) could produce $E2$ multipole amplitudes that would yield the correct size and energy dependence of the coefficients c, d, and e, and thus achieve agreement with the Argonne data.

We recall that the single-nucleon spin-orbit contribution to the deuteron charge density is

$$\rho_{so}(\mathbf{k}\cdot\mathbf{x}_i) = -\tfrac{1}{2}\sum_{i=1}^{2}\frac{[(F_1^s+\tau_{iz}F_1^v)+4M(F_2^s+\tau_{iz}F_2^v)]}{4M^2}e^{i\mathbf{k}\cdot\mathbf{x}_i}\mathbf{k}\cdot\sigma_i\mathbf{x}\nabla_i \; . \tag{2}$$

With regard to the MEC contributions to the $E2$ amplitude, we focus on the dominant two-nucleon processes of π-meson range. These include the one which in pseudoscalar (ps) meson-nucleon theory incorporates a $N\bar{N}$ vertex as shown in Fig. 2(a). In pseudovector (pv) theory, this process is equivalent to a "seagull" diagram as shown in Fig. 2(b). We have obtained results using both couplings. In addition, the process in Fig. 2(c), with a nucleon resonance N^* in intermediate states, is included in the current considerations.

In ps theory, the contribution to the nuclear charge density from the process in Fig. 2(a) is evaluated to be

$$\begin{aligned}\rho_{\pi NN}(\mathbf{k},\mathbf{r}) = -\frac{i}{2M}f_{\pi NN}^2[&F_M^s\tau_1\cdot\tau_2(\sigma_1\cdot\mathbf{k}\sigma_2\cdot\hat{\mathbf{r}}e^{i\mathbf{k}\cdot(r/2)}-\sigma_2\cdot\mathbf{k}\sigma_1\cdot\hat{\mathbf{r}}e^{-i\mathbf{k}\cdot(r/2)})\\ &+F_M^v(\tau_{2z}\sigma_1\cdot\mathbf{k}\sigma_2\cdot\hat{\mathbf{r}}e^{ik\cdot(r/2)}-\tau_{1z}\sigma_2\cdot\mathbf{k}\sigma_1\cdot\hat{\mathbf{r}}e^{-ik\cdot(r/2)})]\Phi(x_\pi)\; .\end{aligned} \tag{3}$$

The π-N coupling is $f_{\pi NN}^2=0.08$, and

$$\Phi(x_\pi) = \left[1+\frac{1}{x_\pi}\right]\left[\frac{e^{-x_\pi}}{x_\pi}\right] ,$$

$F_M^s=(1+\kappa_s)=0.88$, and $F_m^v=(1+\kappa_v)=4.70$; also $x_\pi=\mu_\pi r$, $\mathbf{r}=\mathbf{r}_1-\mathbf{r}_2$, and μ_π is the pion mass in fm^{-1}.

Finally, the contribution to the charge density from the N^* process in Fig. 2(c) is evaluated in the manner described in Ref. 7, i.e., by making use of the pion photoproduction amplitude based on dispersion-theoretical methods.[8] When only local terms of lowest order in $1/M$ are kept, where M is the nucleon mass, the result is

$$\begin{aligned}&\rho_{N^*}(\mathbf{k},\mathbf{r}) = -(\tfrac{2}{3})ih_2(0)\mu_\pi^2(1+\kappa_v)[\tau_{2z}\sigma_1\cdot\mathbf{k}\sigma_2\cdot\hat{\mathbf{r}}e^{ik\cdot(r/2)}-\tau_{1z}\sigma_2\cdot\mathbf{k}\sigma_1\cdot\hat{\mathbf{r}}e^{-ik\cdot(r/2)}]\Phi(x_\pi)\; ,\\ &h_2(0)=\frac{0.0658}{\mu_\pi^3}\; .\end{aligned} \tag{4}$$

The MEC charge density, Eq. (3), has been used to augment the $E1$ amplitude in several calculations of deuteron photodisintegration.[1,9,10] The item of central interest for our purposes is the contribution from Eqs. (2)–(4) to the quadrupole operator in the long-wavelength limit

$$Q_{ij} = \frac{i}{2}\frac{\partial}{\partial k_i}\frac{\partial}{\partial k_j}\rho(k)|_{k\to 0}\; , \tag{5}$$

as well as to the electric dipole operator.

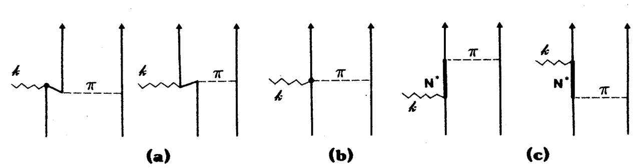

FIG. 2. Meson-exchange processes whose contributions to the ^{2}H charge density were taken into account in this work (see the text). The wiggly line is a photon of momentum $\mathbf{k}$.

By incorporating Eqs. (2)–(4) into the electric multipole operators, we calculate enhanced amplitudes and obtain results for the cross-section ratios, shown by line 4 in Fig. 1. The difference between lines 3 and 4 is dominated by the spin-orbit term, Eq. (2). We note only a small change in the agreement with experimental data. Unfortunately, the microscopic processes in Fig. 2 do not yield the energy dependence in the coefficients c, d, and e necessary to produce the excellent agreement given by the phenomenological results, line 5. Results obtained with MEC charge densities found with the pv πNN coupling are quantitatively very similar to those with the ps coupling shown in Fig. 1, and hence they are not displayed separately.

Our analysis in Ref. 1 remains valid, however, and so we maintain the position that there is much to be learned about the quadrupole transition amplitude from the cross-section ratios shown in Fig. 1. We reiterate the need for an experimental check of the Argonne data as we pursue theoretical efforts to understand the nuclear microscopic phenomena that give rise to these experimental observations.

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