$E2$ transition in the reaction ^{2}H(γ,n)^{1}H

E. Hadjimichael
Physics Department, Fairfield University, Fairfield, Connecticut 06430

M. L. Rustgi and L. N. Pandey
Department of Physics and Astronomy, State University of New York, Buffalo, New York 14260
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The ratio of the differential cross section for ^{2}H(γ,n)^{1}H at $\theta=45°$, 135°, and 155°, to that at $\theta=90°$ lab angle, is found to furnish a very fine microscope for resolving the strength of the $E2$ multipole transition which reflects the admixture of nonspherical components in the NN system.

INTRODUCTION

For many years, the deuteron has served as a laboratory for testing our ideas on the interaction of nucleons in a bound system. In particular, measurements of deuteron photoreactions have produced a large amount of experimental information that has been subject to detailed theoretical analysis.[1] Perhaps due to its nature and to significant statistical and systematic uncertainties, this information has left unanswered some important questions on the interacting NN system.

One of the crucial aspects of the NN interaction phenomenon is its tensor part which manifests itself in the admixture of nonspherical components, i.e., the D state, in the deuteron wave function, among other things. The phenomenology that reflects the important characteristics of the D state, e.g., the asymptotic S/D ratio,[2] includes the deuteron quadrupole moment[3] and its rms radius and important transition multipoles that enter the cross section and other observables in deuteron reactions, as, for example, the tensor polarization t_{20}.[4]

In recent years, the framework for deriving the NN interaction has been enlarged to include quantum chromodynamics (QCD) inspired elements,[5] such as quark-gluon fundamental interactions, soliton-like hadrons, etc., beyond the traditional boson-exchange picture. It is therefore particularly compelling now to procure and exploit interesting data that can reveal more firmly the dynamics of the NN interaction phenomenon.

It is in this spirit that we have examined again the low-energy ^{2}H(γ,n)^{1}H reaction for possible phenomenology that might help this effort. We are particularly interested in discovering ways to isolate multipole amplitudes that reflect uniquely the role of the admixture of nonspherical components in the NN system, e.g., $E2$ and $M2$ transition amplitudes. To be of any use, these must be measurable experimentally with better accuracy than has been customary in deuteron photodisintegration experiments in the past. Furthermore, the low energy region is of interest because the theoretical analysis is more secure in this regime.

SEPARATION OF MULTIPOLE AMPLITUDES

One has always assumed in the past, and correctly so, that the lower multipoles $M1$ and $E1$, set the scale for the total cross section near threshold, the angular distribution at low energies, and the recoil nucleon polarization at nonforward angles, also at low energies (<20 MeV). Examples of these are shown in Figs. 1–3.

The percent polarization of recoil neutrons vs c.m. angle shown in Fig. 1, at two energies and for two potential models, the Paris potential[6] and the supersoft core (SSC) (Ref. 7) potential includes relativistic order and meson-exchange contributions to the nuclear current.[1] The solid line shows estimates when only the $E1$ and $M1$ multipoles contribute (the $E1$-$M1$ approximation), while the dashed line is the result when $E1$, $M1$, $E2$, and $M2$ multipole transitions are taken into account (the $E2$-$M2$ approximation). It is obvious that for $\theta>80°$, the $E1$,$M1$ multipoles are the only ones that count. Precise data in this region could pin down unequivocally these lower order multipoles.

Similarly, the $E1$-$M1$ approximation and the $E2$-$M2$ approximation to the differential cross section are shown,

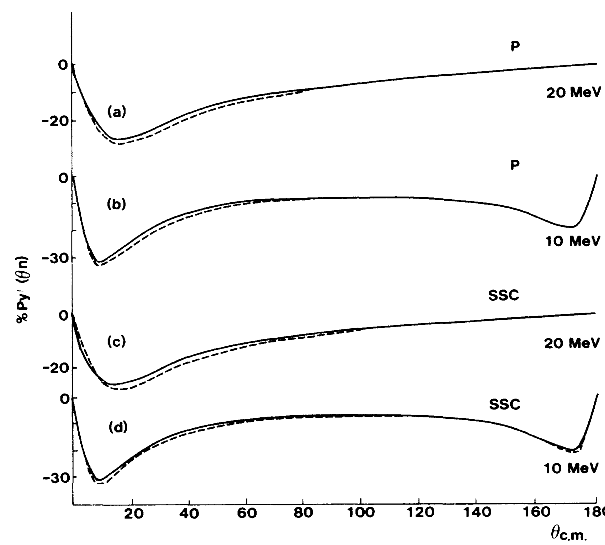

FIG. 1. The percent polarization of recoiling neutrons in ^{2}H(γ,n)^{1}H calculated with the Paris potential (P) and the supersoft core potential (SSC), at 10 and 20 MeV photon energy. The solid line is the result in the $E1$-$M1$ approximation, while the dashed line includes the contribution from higher multipoles.

respectively, by the short-dash line and the solid line in Figs. 2(a) and (b), for outgoing protons [Fig. 2(a)] and outgoing neutrons [Fig. 2(b)]. The data points are from Ref. 8. Results with different potential models are very similar, and so we show only those with the SSC model. Relativistic order, and meson-exchange effects are included in the $E1$ and $M1$ amplitudes. It is clear that once again, the contribution from the $E2$ and $M2$ amplitudes is not differentiated by the experimental data from the $E1$-$M1$ approximation results for the angular distribution. This situation is even more extreme in the case of the total cross section shown for two potential models in Fig. 3, along with some recent experimental points.[9] The two approximations in this case give results that are indistinguishable from each other on the graph. In conclusion, it appears that the $E2$ and $M2$ amplitudes have no measurable impact on the polarization of recoiling nucleons, the angular distribution, and the total cross section in the low energy region, and they cannot therefore be isolated by means of these observables in this theoretically favorable region.

We do believe, however, that in spite of appearances, there is a way to isolate and have a closer look at the $E2$ amplitude. This can be done by means of the ratio of the differential cross section for ^{2}H(γ,n)^{1}H at forward and backward angles to that at 90°. The experimental measurements of these ratios, some of which have already been performed at Argonne National Laboratory,[10] have the advantage of reduced systematic errors. From the point of view of the phenomenological analysis, they magnify and project out the effect from the $E2$ transition to an extent that a determination of this amplitude is now feasible, assuming that we have secure knowledge of the $E1$ and $M1$ amplitudes.

The contribution to the differential cross section from the $E2$ transition shifts the entire angular distribution curve to a lower or higher angular range, with the $\theta=90°$ point as a pivot, as shown in Figs. 2(a) and (b). The ratio of the cross section at forward and backward angles (shifted), to that at $\theta=90°$ (unshifted), provides an excellent microscope which resolves the contribution of the $E2$ transition from those of the lower multipoles. The Argonne measurements[10] for $\sigma(45°_L)/\sigma(90°_L)$, $\sigma(135°_L)/\sigma(90°_L)$, and $\sigma(155°_L)/\sigma(90°_L)$, where the subscript L indicates laboratory angles, are shown in Figs. 4(a)–(c).

Theoretical estimates of these cross section ratios with the SSC potential and the Paris potential are shown by the second and third lines, respectively, in the $E2$-$M2$ approximation, and by the first line in the $E1$-$M1$ approximation,

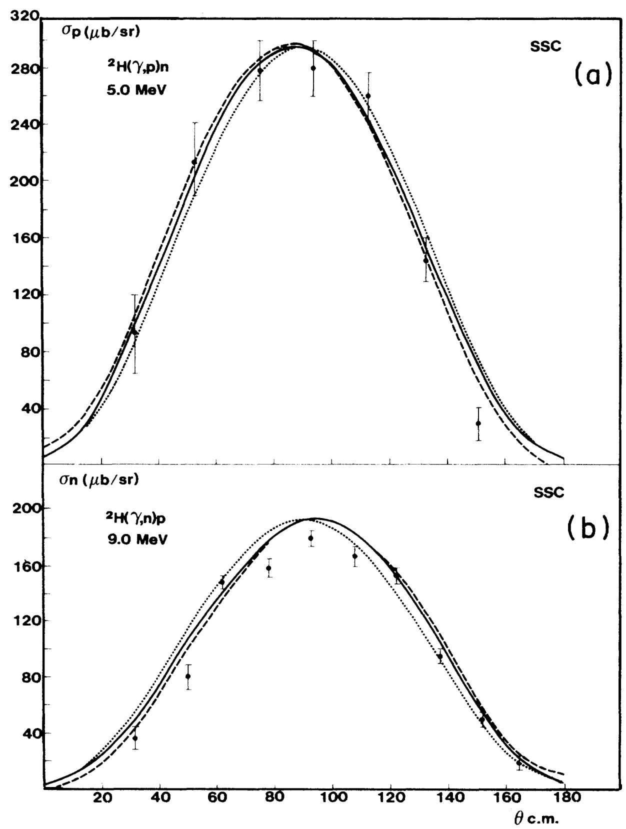

FIG. 2. The differential cross section for (a) outgoing protons at 5.0 MeV and (b) outgoing neutrons at 9.0 MeV. The short-dash line is the result in the $E1$-$M1$ approximation and the solid line includes contributions from the $E2$,$M2$ transitions as well. The long-dash line shows the result found with the modified coefficients c, d, and e.

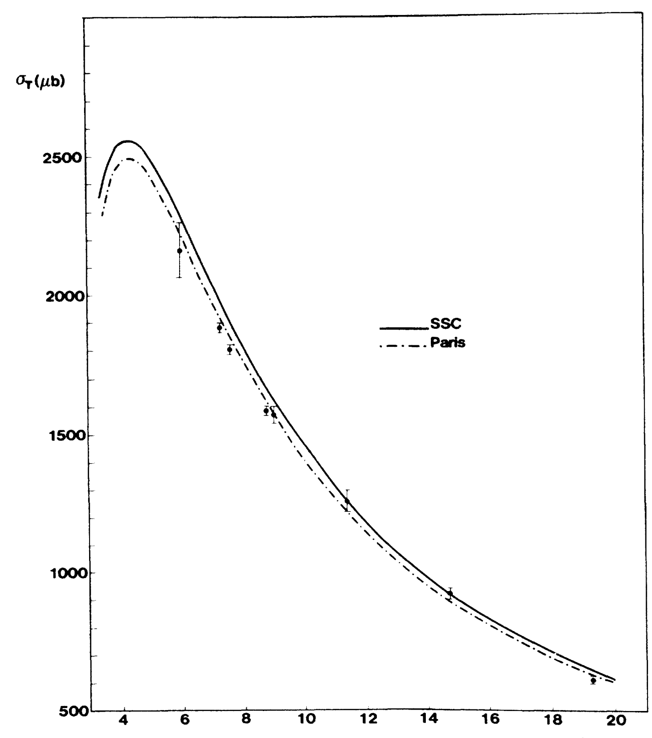

FIG. 3. The total cross section for ^{2}H(γ,n)^{1}H as a function of photon energy for two potential models in the $E1$-$M1$ approximation. The result that includes the contributions from the $E2$,$M2$ amplitudes found either with the unmodified coefficients c, d, and e or with the modified ones cannot be distinguished from the curves in this figure.

mation. Two observations are immediately in order. First, in contrast to the situation shown in Figs. 2 and 3, the difference between the $E2$-$M2$ and $E1$-$M1$ approximation results in Figs. 4(a)–(c) is very large on a scale defined by the indicated uncertainty in the data; second, the best theoretical estimate represented by the second and third lines (in the $E2$-$M2$ approximation) is in considerable disagreement with the experimental data at low energies, independent of potential model. Obviously, these cross section ratios are a much more sensitive gauge of the theoretical basis of the photodisintegration calculation. If the data are correct, we are led to believe that the strength of the $E2$ transition multipole in the traditional impulse approximation is inadequate.

Recall that the expansion of the differential cross section in the $E2$-$M2$ approximation, in terms of Legendre polynomials in the c.m. system, takes the form

$$\sigma(\theta)=a+b\sin^2\theta-c\cos\theta-d\sin^2\theta\cos\theta+e\cos^2\theta\sin^2\theta \quad (1)$$

for outgoing neutrons (for protons, reverse the sign of the c and d coefficients). The total cross section in this approximation is

$$\sigma_T=4\pi(a+\tfrac{2}{3}b+\tfrac{2}{15}e)\ . \quad (2)$$

Table I shows the contributions to the coefficients a, b, c, d, and e from the various transition multipoles and their interferences.

The only place that the $E2$ transition has a significant impact is in the c and d coefficients and, to a lesser degree, in the e coefficient. The $M2$ amplitude does not contribute to e and seems to be generally not important.

Our first task is to discover what modifications might be effected in the coefficients a, b, c, d, and e which will produce good agreement with the data in Fig. 4 without destroying the agreement with the data in Figs. 2 and 3. For this purpose, a least square fit of the Argonne data was carried out at each photon energy, followed by linear and nonlinear regression searches to produce models of the coefficients as a function of photon energy. The result of these searches, though not entirely exhaustive, is that only changes in the coefficients which receive a dominant contribution from the $E2$ transition amplitude i.e., c, d, and e, can accomplish the above-stated task, while tampering with the values of, say, a and b as given by the traditional theory, produces unacceptable results for the differential and total cross section. Hence we find numerical support for our assumption that it is the strength of the $E2$ transition that must be adjusted to yield agreement with the data for the cross section ratios. On the basis of the strength of $E1$, we expect that modifications in $E2$

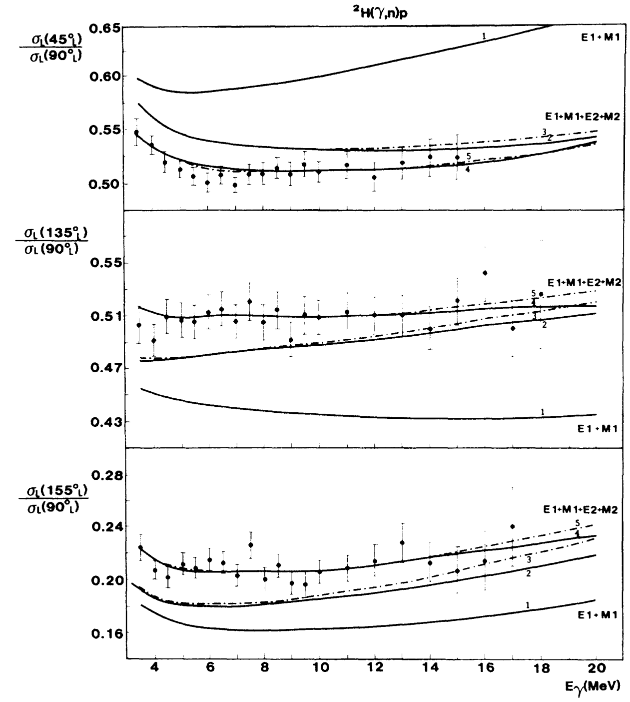

FIG. 4. The ratio of the lab cross section at 45°, 135°, and 155° lab angles to that at 90°, measured at Argonne (Ref. 10), versus photon energy. The theoretical curves are as follows: the first line is the result in the $E1$-$M1$ approximation; the second and third lines, found with the SSC and the Paris model, respectively, include contributions from the $E2$,$M2$ transition amplitudes (unmodified c, d, and e coefficients); the fourth and fifth lines are the final results with modified coefficients c, d, and e (listed in Table II for the Paris potential) for the SSC and the Paris potential, respectively.

will have a far more significant impact through the $E1$-$E2$ interference term, i.e., through coefficients c and d, rather than through the $E2$-$E2$ terms. Indeed, we were able to achieve good fits to the data by changing c and d only. The final results, however, shown by curves 4 and 5 in Figs. 4(a)–(c) are obtained by allowing all three coefficients c, d, and e to change. The modified and unmodified coefficients evaluated with the Paris potential are shown in Table II as functions of photon energy.

We note substantial differences between the unmodified and the modified coefficients. We achieved by this modification a dramatic improvement in the agreement between theoretical estimates and the data for the laboratory cross section ratios. At the same time, this modification does not change the total cross section—

TABLE I. Contributions from the various multipole transitions to the coefficients a, b, c, d, and e.

a	$E1$-$E1$,[a]	$M1$-$M1$,	$M2$-$M2$,	$E1$-$M2$,	$E2$-$E2$,	$E2$-$M1$
b	$E1$-$E1$,[a]	$M2$-$M2$,	$E1$-$M2$,	$M1$-$M1$,	$E2$-$M1$	
c	$E1$-$E2$,[a]	$E1$-$M1$,	$M1$-$M2$,	$E2$-$M2$		
d	$E1$-$E2$,[a]	$E2$-$M2$,	$M1$-$M2$			
e	$E2$-$E2$					

[a]The dominant contribution to the coefficient; the nondominant contributions are very close to zero.

TABLE II. Numerical values of the unmodified coefficients a, b, c, d, and e found with the Paris potential, and of the modified coefficients c, d, and e, as functions of photon energy.

	Unmodified					Modified		
E (MeV)	a	b	c	d	e	c	d	e
3.5	12.60	254.40	0.049	18.81	0.35	6.05	34.80	10.20
4.0	9.77	279.93	0.064	24.43	0.53	6.70	37.05	8.80
5.0	6.90	279.98	0.101	30.60	0.83	6.75	40.05	6.65
6.0	5.57	256.69	0.143	32.76	1.04	6.30	41.05	5.25
7.0	4.93	229.37	0.187	32.99	1.18	5.50	39.75	4.25
8.0	4.62	203.64	0.236	32.28	1.27	4.75	37.02	3.45
9.0	4.50	180.87	0.282	31.13	1.33	4.15	34.35	2.75
10.0	4.48	161.17	0.328	29.80	1.37	3.70	32.20	2.25
11.0	4.53	144.21	0.374	28.42	1.38	3.35	30.25	1.80
12.0	4.62	129.60	0.418	27.06	1.39	2.95	28.55	1.55
13.0	4.72	116.99	0.460	25.74	1.39	2.80	27.05	1.40
14.0	4.84	106.04	0.501	24.49	1.39	2.60	25.60	1.22
15.0	4.95	96.49	0.539	23.31	1.38	2.35	24.25	1.19
16.0	5.06	88.12	0.576	22.20	1.36	2.15	22.95	1.10
18.0	5.27	74.22	0.642	20.19	1.33	2.02	20.35	1.10
20.0	5.45	63.24	0.701	18.44	1.28	1.85	18.10	1.18

coefficients c and d do not appear in this latter quantity—and hence no new curve can be drawn on Fig. 3. As for the angular distribution, the new theoretical estimates shown when possible by the long-dash line in Fig. 2 cannot be differentiated by the existing data from those obtained with the unmodified coefficients. Thus the reasonably good agreement with the experimental results for the differential and total cross section is maintained. Assuming that our method for obtaining agreement with data for the cross section ratios is the only one that is physically meaningful, we conclude that these ratios make for a very fine microscope that resolves and renders measurable the strength of the $E2$ transitions in ^{2}H(γ,n)^{1}H. This strength is reflected in the difference between curve 1 and curves 4 or 5 in Figs. 4(a)–(c).

Fine tuning of our results is possible, and the difference between the estimates with the Paris and the SSC potential models indicated in Fig. 4 should not be thought to be significant; a few percent change in the modified c, d, and e coefficients within acceptable limits could change or even eliminate this difference. The significant fact is that the available data for the cross section ratios dictate an energy dependence for the coefficients c, d, and e—the first and last become descending functions of the photon energy—to which the differential and total cross section show no sensitivity at all.

A crucial question to answer is what is the origin of the modification in the $E2$ matrix elements that yields the new coefficients. We recall that the electric quadrupole radial matrix elements in the impulse approximation are typically of the form

$$\int dr\, r^2 \Psi^*_{np}(r) \Psi_d(r) \ , \qquad (3)$$

where Ψ_d represents combinations of the deuteron S- and D-state functions, $U(r)$ and $W(r)$, and Ψ_{np} are final state NN partial waves which, by virtue of angular momentum and parity selection rules, can only be spin-triplet S-, D-, and G-particle waves, i.e., isospin zero states. Noting the r^2 dependence in the integrand in Eq. (3), we conclude that the modifications in c, d, and e coefficients may arise either from modifications in the long range part of the NN wave functions, or from an additional nuclear electromagnetic current involving non-nucleonic degrees of freedom. This latter is as much a reflection of the interaction phenomenon as are the nuclear wave functions. On the basis of a tentative consensus that has emerged recently[2] that the asymptotic strength of the D state, dominated by the one-pion exchange mechanism, is given satisfactorily by such potentials as the Paris and the SSC, and that the fits to low-energy NN scattering phase shifts are adequate, we have first turned our attention to non-nucleonic contributions to the current that may contribute meaningfully to the $E2$ transition. While we are continuing these investigations, however, we hope that through this article we may stimulate experimental interest in repeating and extending the Argonne measurements of differential cross section ratios. We think that confirmation of the Argonne results is necessary to justify continued theoretical effort, and hope that this confirmation will come soon.

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