^{3}He(e,d)e′p isochromats and angular distribution measurements

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An angular distribution and isochromats for the reaction ^{3}He(e,d)e′p were measured to determine the importance of $E2$ strength near the peak of the ^{3}He(γ,d)p cross section. The angular distribution was analyzed using both a complete and approximate virtual photon spectrum. The isochromats were compared to a plane wave model prediction and least squares fitted to determine the relative amounts of $E1$ and $E2$ strength.

[NUCLEAR REACTIONS Measured $\sigma(\theta_d, E_d, E_0)$ obtained $\sigma(E_d, E_0)$, $\sigma^{E1}(\gamma, d)$, and $\sigma^{E2}(\gamma, d)$.]

I. INTRODUCTION

One of the perplexing and interesting problems in the two body disintegration of ^{3}He is the recent conclusion from a polarized proton capture experiment[1] that near the peak of the cross section ($E_\gamma \approx 12$ MeV) the $E2$ contribution is approximately 12%. While a subsequent remeasurement with a gas cell target resulted in a lower estimate of the $E2$ strength,[2] this experiment nevertheless lent credence to earlier unpolarized photodisintegration studies that gave essentially the same result; namely, if the angular distributions are analyzed under the assumption that only $E1$ and $E2$ transitions are important for low photon energies, $E2$ contributions are significant.

Since plane wave calculations and a Faddeev calculation for the two body breakup of ^{3}He give the result that for near the peak of the cross section less than 2% of the total cross section is $E2$,[3] these experimental results are somewhat surprising, and provide a conundrum for theorists.

However, the best calculations to date have not included the tensor potential in the continuum and the ground state[4]; hence there does seem to be a possibility that appreciable $E2$ strength is yet to be discovered in a proper calculation of this channel. As further motivation for this calculation we performed another experiment which was designed to (a) check the angular distribution at 15 MeV to verify that the measurements of Ref. 1 and earlier work are correct and (b) make use of the fact that the "richness" of the $E2$ virtual photon spectrum relative to the number of $E1$ virtual photons (see Fig. 1) allows one to measure isochromats which are very sensitive to any $E2$ strength.

II. EXPERIMENT

The magnetic spectrometer facility at the University of Saskatchewan Linear Accelerator Laboratory was used to measure deuterons at a fixed excitation energy in ^{3}He as a function of angle and incident electron energy. The experimental equipment is described elsewhere[5]; thus only the salient details are given here.

The momentum analyzed electron beam from the accelerator was incident on a gaseous ^{3}He target pressurized to 1.0 atm. The target was a right circular cylinder, 2.54 cm in radius, 3.50 cm high, and oriented with its axis of rotation perpendicular to the electron beam and to the path of the detected deuterons. The target wall was made of 6.4 μm Havar. The beam current was monitored by a SLAC type of nonintercepting ferrite, whose response is linear and reproducible to ±2%.

Deuterons were detected in a spectrometer containing surface barrier silicon detectors mounted in the focal plane of a 30 cm, 127° double focusing magnet. The signals from the detectors were digitized by 11 bit analog-to-digital converters and read through CAMAC by a PDP 11-55 computer. The deuterons were easily distinguished from all other mass groups that can be emitted by ^{3}He. A typical spectrum is shown in Fig. 2.

To measure isochromats the spectrometer was set at a fixed magnetic field and angle and the incident beam energy was varied up to ~100 MeV. For the angular distribution measurement the spectrometer angle was changed in

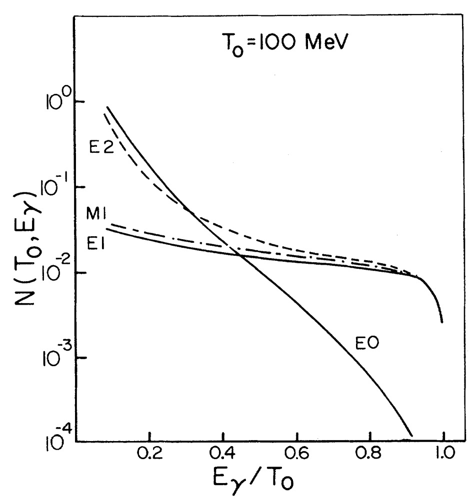

FIG. 1. Plane wave virtual photon spectra for various multipoles.

steps of $\approx 10°$. To keep the excitation energy in ^{3}He fixed, the magnetic field was also changed, taking into account the kinematic energy shift from forward to backward angles.

In both cases the measured cross section is given by

$$\frac{d^2\sigma}{d\Omega\, dE_d}=\frac{Y(\theta,E_d)}{\Delta\Omega\Delta E_d n_t(\theta)}\ , \tag{1}$$

where $Y(\theta,E_d)$ is the number of deuterons detected per incident electron, $\Delta\Omega$ is the spectrometer solid angle, $n_t(\theta)$ is the number of target nuclei per cm^2, and ΔE_d has been corrected to correspond to the appropriate energy bite at the center of the target.

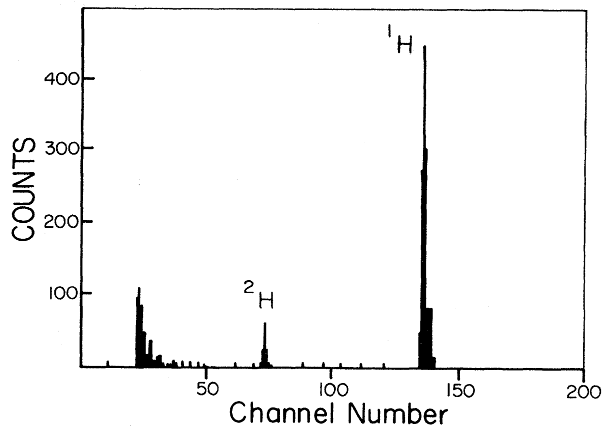

FIG. 2. A typical pulse height spectrum. The deuteron peak defines the two-body breakup of ^{3}He.

A. Angular distribution data

The angular distributions were analyzed by using a complete virtual photon spectrum (VPS) theory calculated in plane wave approximation that contains the multipoles $E0$, $E1$, $E2$, and $M1$.[6] The electrodisintegration data were fitted to the form

$$\frac{d\sigma}{d\Omega}=\mathscr{C}_0^e\left[1+\sum_{l=1}^{4} C_l^e P_l(\cos\theta)\right]\ , \tag{2}$$

where

$$\frac{d\sigma}{d\Omega}=\frac{Y(\theta,E_d)}{\Delta\Omega n_t(\theta)\Delta E_\gamma/E_\gamma} \tag{3}$$

and E_γ is calculated assuming photonlike kinematics. The C_l^e's are then transformed to the corresponding photodisintegration coefficients C_l^γ's by

$$\mathscr{C}_0^\gamma=\frac{\pi}{\alpha}\mathscr{C}_0^e\left[\frac{1}{1+R_E{}^2\ln\lambda}\right]\left\{1-2R_E\frac{C_2^e}{B}+\frac{C_4^e}{A}\left[\tfrac{5}{6}R_E\left[\frac{C-D}{B}\right]-(\tfrac{5}{6}R_E-\tfrac{14}{9}R_k{}^2)\right]\right\},$$
$$C_1^\gamma=\frac{\pi}{\alpha}\frac{C_1^e}{E}\ ,$$
$$C_2^\gamma=\frac{\pi}{\alpha}\frac{1}{B}\left[C_2^e-\frac{5}{12}\left[\frac{C-D}{A}\right]C_4^e\right]\ ,$$
$$C_3^\gamma=\frac{\pi}{\alpha}\frac{C_3^e}{E}\ ,$$
$$C_4^\gamma=\frac{\pi}{\alpha}\frac{C_4^e}{A}\ , \tag{4}$$

where

$$A=(1+R_E{}^2)\ln\lambda+R_K{}^2(1+\tfrac{5}{3}R_E-\tfrac{25}{12}R_E{}^2)\ ,$$
$$B=(1+R_E{}^2)\ln\lambda-2R_E-\tfrac{3}{2}R_E{}^2\ ,$$
$$C=R_K{}^2(\tfrac{1}{6}-\tfrac{5}{3}R_E+\tfrac{3}{2}R_E{}^2)\ ,$$
$$D=2R_E+\tfrac{3}{2}R_E{}^2\ ,$$
$$E=(1+R_E{}^2)\ln\lambda+R_K(-1+\tfrac{1}{2}R_E+\tfrac{11}{6}R_E{}^2)\ ,$$

with

$$R_E=\frac{E_0-E_\gamma}{E_0}\ ,\quad R_K=\frac{E_0-E_\gamma}{E_\gamma}\ ,\quad \text{and } \lambda=\frac{2E_0(E_0-E_\gamma)}{m_0E_\gamma}\ .$$

Alternatively one can divide Eq. (3) by the dominant multipole spectrum in order to obtain the effective photodisintegration cross section. Here we used the spectrum

$$N^{E1}(E_0,E_\gamma)=\frac{\alpha}{\pi}\{R_E{}^2+[(1+R_E{}^2)\lambda-2R_E-\tfrac{3}{2}R_E{}^2]\sin^2\theta\}/\sin^2\theta\ . \tag{5}$$

TABLE I. Angular distribution coefficients at $E_\gamma \sim 15$ MeV. We have refitted previous work to the form given by Eq. (2).

Experiment	E_γ (MeV)	$\mathscr{C}_0$ $\left[\frac{\mu b}{sr}\right]$	C_1^γ	C_2^γ	C_3^γ	C_4^γ
Fetisov *et al.* (Ref. 9)	12–16	72±6	0.46±0.11	−0.67±0.17	−0.41±0.19	−0.13±0.23
Belt *et al.* (Ref. 8)	15.3	0.81±0.01[c]	−0.33±0.01	−0.89±0.01	0.29±0.02	−0.08±0.01
Matthews *et al.* (Ref. 10)	16	47±1	−0.45±0.02	−0.87±0.04	0.36±0.04	−0.08±0.05
This work	14.75	76±1[a]	−0.26±0.02	−0.92±0.03	0.18±0.03	−0.01±0.04
		78±1[b]	−0.29±0.02	−0.92±0.03	0.24±0.03	−0.02±0.04

[a]Coefficients determined using equation set 4.
[b]Coefficients determined by using the approximate virtual photon spectrum given by Eq. (5).
[c]Note that these data were given as capture results. Detailed balance was not applied in the fitting procedure that we used.

In this case the data are least squares fitted to Eq. (2) except that the coefficients now correspond directly to the C_l^γ's. These coefficients are compared to earlier photodisintegration data at $E_\gamma \approx 15$ MeV in Table I, and within the errors the agreement is reasonably good. In Fig. 3 both analyses are shown; the complete VPS method is given by the shaded error band.

If we assume that only $E1$ and $E2$ transitions contribute, the amount of $E2$ strength indicated by our angular distribution can be determined from the direct terms

$$\frac{\sigma(E2)}{\sigma(E1)} = \left[\frac{7C_4^\gamma}{12C_2^\gamma + 5C_4^\gamma}\right] \tag{6}$$

or from the asymmetry in the cross section, i.e., the interference term

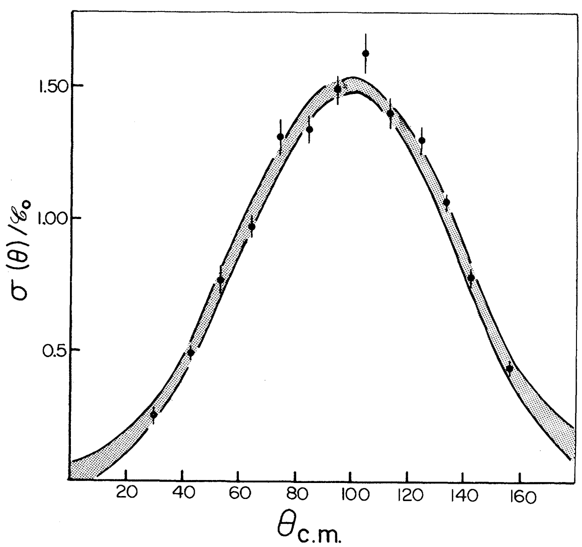

FIG. 3. Angular distribution of deuterons at 14.75 MeV. The shaded region is the error band that comes from the complete VPS analysis. The solid circles and error bars are the results when the approximate VPS is used [Eq. (5)].

$$\frac{\sigma(E2)}{\sigma(E1)} \geq 20 \left[\frac{C_3^\gamma}{12C_2^\gamma + 5C_4^\gamma}\right]^2 . \tag{7}$$

These equations follow from transforming the coefficients of a multipole expansion

$$\sigma(\theta) = b \sin^2\theta + c \sin^2\theta \cos\theta + d \sin^2\theta \cos^2\theta ,$$

where the direct terms b and d arise from $E1$ and $E2$ transitions and c is due to their interference. Our data yield values of $E2$ strength consistent with the most recent theory[7] that addresses this question of $E2$ strength when we use either the direct or asymmetry term in the angular distribution. Other experiments, however (Refs. 8–10) give answers consistently higher than theoretical predictions when the $E2$ cross section is estimated with the direct term. These results are shown in Table II.

B. Isochromat data

The isochromat data were obtained by using

$$\sigma_{e,d}(E_0) = \sum_l \int_{thr}^{E_0} \sigma_{\gamma,d}^{El}(E_\gamma) N^{(El)}(E_0, E_\gamma, Z) \frac{dE_\gamma}{E_\gamma} ,$$

where $\sigma_{e,d}(E_0)$ is related to the measured cross section Eq. (1) by

TABLE II. Estimates of % $E2$ strength from the angular distribution data using Eqs. (6) and (7). Recall that the theoretical estimate is $\lesssim 0.02$.

Experiment	Direct term [Eq. (6)]	Asymmetry term [Eq. (7)]
Fetisov *et al.*	11 ±2	4.5±4.8
Belt *et al.*	5.1±0.6	1.4±0.2
Matthews *et al.*	5.2±3.2	2.2±0.5
This work	0.6±2.5[a]	0.5±0.2
	1.3±2.5[b]	0.9±0.2

[a]Coefficients determined using equation set 4.
[b]Coefficients determined by using the approximate virtual photon spectrum given by Eq. (5).

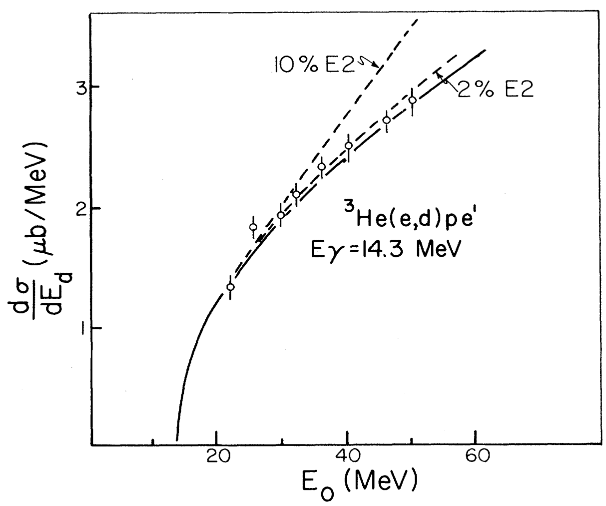

FIG. 4. Isochromat at $E_\gamma = 14.3$ MeV. These data were taken to complement the angular distribution measured at approximately the same energy. The solid line corresponds to a pure $E1$ calculation using an Irving-Gunn ground state wave function. The other curves, as indicated, correspond to the assumption that 2% and 10% of the total cross section is due to $E2$ transitions.

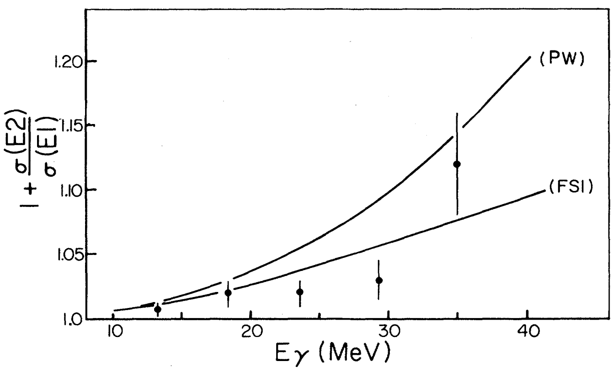

FIG. 5. Estimate of $E2$ strength as a function of E_γ from the isochromat analysis. The curves correspond to employing $E1$ and $E2$ photo cross sections calculated when final state interactions between the deuteron and the proton are taken into account (FSI) and when they are ignored and a plane wave is used (PW).

$$\sigma_{e,d}(E_0) = \int_0^{E_{d_{max}}} \frac{d^2\sigma}{d\Omega\, dE_d} d\Omega\, dE_d \ .$$

Hence the isochromats

$$\frac{d\sigma}{dE_d} = \sigma^{E1}_{\gamma,d}(E_\gamma)\frac{N^{E1}}{E_\gamma} + \sigma^{E2}_{\gamma,d}(E_\gamma)\frac{N^{E2}}{E_\gamma} \quad (8)$$

can be formed by carrying out the angular integration. This was accomplished by including in our angular distributions the earlier ^{3}He(e,d)e',p work of Kundu.[11] We undid his virtual photon analysis and determined the resulting electrodisintegration angular distributions at fixed excitation energies in ^{3}He. The energy dependence of these angular distributions was found by least squares fitting to a polynomial in E_γ. This angular integration was experimentally verified to be independent of incident energy for the range of incident energies used in this experiment. Kundu's data were only used in the analysis to avoid unnecessary extrapolation when performing the angular integration. His electrodisintegration cross sections were checked at a number of energies and angles and found to be consistent with our newer data.

These isochromats were analyzed two ways. First $\sigma^{E1}_{\gamma,d}(E_\gamma)$ was calculated using an Irving-Gunn ^{3}He ground state wave function, with a Hulthen deuteron and plane wave final state. We calculated 0%, 2%, and 10% $E2$ contribution to the total cross section in order to compare to the experimental values of $d\sigma/dE_d$ in Eq. (8). Plane wave virtual photon spectra were used in this calculation. These results are shown in Fig. 4, and as can be seen, the 14 MeV isochromat for $E < 50$ MeV requires that the total cross section contains less than 2% $E2$, in order to agree with the data. Note that we have not included monopole transitions in spite of the fact that $N^{E0} \approx N^{E2}$, as seen from Fig. 1. This was done for two reasons: First, we are primarily interested in departures (whether $E2$ or $E0$ is immaterial) from an $E1$ analysis in the isochromats, and second, over the energy region we are investigating $\sigma(E2) > \sigma(E0)$.

We have also extended these isochromat measurements to higher incident energies and additional excitation energies in ^{3}He. These data were treated differently inasmuch as rather than comparing to a plane-wave model, the measured cross sections $d\sigma/dE_d$ were least squares fitted and the free parameters $\sigma^{E1}_{\gamma,d}(E_\gamma)$ and $\sigma^{E2}_{\gamma,d}(E_\gamma)$ in Eq. (8) were determined from the fit. Here we used the distorted wave VPS calculations of Onley and Wright[12] and made a correction for finite size effects.[13] The quantity

$$1 + \sigma^{E2}_{\gamma,d}(E_\gamma)/\sigma^{E1}_{\gamma,d}(E_\gamma)$$

is shown in Fig. 5. These data give the result that $E2$ transitions contribute less than 2% for $E_\gamma < 25$ MeV but start to become important as E_γ increases. Because of the limitation on the maximum deuteron energy that we are presently able to detect, we cannot distinguish between the theoretical predictions of $\sigma^{E2}(E_\gamma)/\sigma^{E1}(E_\gamma)$ for the cases where a plane wave is assumed and the final state interactions between the outgoing nucleons are taken into account.[3]

III. CONCLUSION

We have shown that at energies near the peak of the ^{3}He(γ,d) cross section the theoretical predictions for the amount of $E2$ strength in this channel are in agreement with the present data. The angular distribution data and the isochromat data near 15 MeV give consistent results, namely the amount of $E2$ strength is less than 2% of the total cross section, which in turn is consistent with theoretical predictions for the amount of $E2$ at $E_\gamma \sim 15$ MeV. It would be very useful to extend these measurements to higher excitation energies in order to completely map out the $E2$ strength in ^{3}He.

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