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Test of proton-induced ^{2}H breakup: Investigation for the special kinematic condition of collinearity

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The breakup of ^{2}H induced by 156 MeV protons has been studied in the $(p,2p)$ and the (p,pn) reactions in the kinematically complete measurement with the unique kinematic condition: The three nucleons are collinear in the center of mass system of three nucleons in the final state. Also we performed experiments having neighboring kinematic conditions. The $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ spectrum gives a peak in the region far from the final-state interaction and the true quasifree interaction regions. In this region of interest $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ is calculated by a model derived from the fixed-scattering-center approximation proposed by L'Huillier and Ballot with Benoist-Gueutal. The model gives a smooth minimum, while the experimental peak is very sharp and sensitive to θ_3. The fixed-scattering-center approximation explains the present experimental $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ spectrum in the entire region fairly well except at this peak. Because of this, we consider this peak difficult to explain by the fixed-scattering-center approximation to the Faddeev equation solution. This peak is similar to that observed by Lambert *et al.* at 23 MeV.

[NUCLEAR REACTIONS ^{2}H$(p,2p)$, ^{2}H(p,pn), $E=156$ MeV. Measured $\sigma(\theta_1, \theta_2, E_1)$ with three final-state nucleons collinear.]

I. INTRODUCTION

In the last 15 years, the breakup of ^{2}H by nucleons has been measured under various kinematic conditions, and the recent development of theoretical treatments[1] of the three-nucleon problems by Ebenhöh-type methods seems to fit qualitatively the available data (except for polarization data) obtained with kinematically complete experiments in an interval of about 20 to 50 MeV, using separable S-wave potentials in the phase-space regions called "the quasifree scattering regions (QFS)" and those called "the final-state interaction regions (FSI)" for nucleon-nucleon scattering. But for other energy regions, this method does not agree as well with the data,[2] and recently obtained precise experimental information[3] shows that the standard calculations are inadequate at all energies except the 20–50 MeV region.

Although very few data[4] exist at energies greater than 100 MeV, it has been shown that the theory, introduced by Aaron *et al.* and modified by Wallace[5] for energies higher than 100 MeV by always using a separable S-wave potential, could not explain quantitatively the experimental results for the ^{2}H$(p,2p)n$ reaction at 156 MeV in the FSI peak if one takes into account all terms of the multiple scattering series. One does get a fairly good fit if one takes into account terms only up to the second order.[6(b)] For several years, L'Huillier and Ballot have studied with Benoist-Gueutal the sensitivity of the proton-induced ^{2}H breakup reaction in the region of a few hundred MeV to two-nucleon off-shell t matrix elements in the multiple scattering expansion, by using various realistic potentials.[6(a)] They succeeded in getting a fairly good fit in the QFS and FSI regions if they kept terms up to the second order but they could not distinguish any off-shell effect either in the QFS region or in the FSI one.[6(a)] Recently, they have attempted to estimate the error due to the truncation of the Faddeev series by terminating at second order. In order to do this, they have introduced a model called "the fixed-scattering-center approximation (FSA)" used in elastic nucleon-nucleon scattering.[7] In this model the relative motion of the two target nucleons during the collision time is neglected. The comparison of our experimental cross sections $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ with the FSA cross sections in first order and up to second order, and of the integral solutions, showed that the effect of the multiple scattering calculated up to higher than second order is not negligible. The integral solution reproduces the experimental $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ fairly well, quantitatively, even in the FSI region.[6(a),7,8(a)]

We are interested in making a kinematically complete experiment by extending our method, which consists of detection of the ^{2}H breakup induced by protons of 156 MeV with particular kinematic conditions over a region far from the FSI and the true QFS regions. Recently, Lambert *et al.*[9] have presented the experimental results of an investigation of an unique kinematic condition for the ^{2}H breakup induced by protons of 23 MeV through $(p,2p)$ reaction. In this unique condition, the spectator nucleon (a neutron) is at rest in the entire center of mass system in the final state: In other words the three nucleons are collinear in the final state. We are interested in this investigation for the following reasons:

(1) The phase-space region in question is far from the FSI region and the true QFS region, so that such an investigation is in our field of interest.

(2) It must be more credible with $E_p = 156$ MeV than with $E_p = 23$ MeV if an effect similar to that presented by Lambert *et al.* for this unique kinematic condition is observed. Because Haftel, Peterson, and Wallace examined the experimental cross sections $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ for the $^2H(p, 2p)n$ reaction obtained in the 14–60 MeV region by comparing them with those calculated by the code of Ebenhöe using various separable potentials and they demonstrated that the sensitivity of the calculation to on-the-energy-shell and off-the-energy-shell interactions is very small ($\leq 5\%$) in the QFS regions. However, in regions far from the QFS, particularly in the FSI peak regions, the off-the-energy-shell effect is very large ($\geq 50\%$). This discrepancy must increase with the incident proton energy.[10] (This tendency has also been suggested by L'Huiller.[6(a)])

(3) We can perhaps examine experimentally, in the future, some meson-exchange mechanism in nucleon-nucleon interaction by this three-nucleon collinear kinematic condition in the nucleon-nucleon interaction. Therefore, we have performed a similar experiment with a 156 MeV proton beam. We have detected simultaneously the $^2H(p, 2p)n$ and $^2H(p, pn)p$ reactions. The preliminary analysis of the experimental results has already been presented.[8,11(b)]

II. KINEMATIC CONDITIONS

In the present experiment, we chose the symmetric kinematics by using the three angle pairs: $\theta_1 = -\theta_2 = 58.3°$, $59.8°$, and $56.8°$, respectively. The first pair includes the unique kinematic condition: Three nucleons are collinear in the final state (the spectator nucleon is at rest in the center of mass system for the entire system). The other two pairs are $\pm 1.5°$ away from the first one. In Table I, the kinematic factors in the neighborhood of these particular conditions are presented and the kinematic presentation is shown in Fig. 1. The kinematic energy in the entire center of mass system of the third nucleon is designated as $\overline{E}_{3\,\text{c.m.}}$.

As is shown in Table I, with $\theta_1 = -\theta_2 = 58.3°$, we can investigate the region where three nucleons are almost collinear ($\overline{E}_{3\,\text{c.m.}} = 0.002$ MeV at $E_1 = 68.0$ MeV) but it is not as easy for $\theta_1 = -\theta_2 = 59.8°$ ($\overline{E}_{3\,\text{c.m.}} = 0.227$ MeV for $E_1 = 66$ MeV) and for $\theta_1 = -\theta_2 = 56.8°$ ($\overline{E}_{3\,\text{c.m.}} = 0.292$ MeV for $E_1 = 71$ MeV).

If an effect similar to that observed by Lambert *et al.* must exist in general, we might detect a similar effect for $\theta_1 = -\theta_2 = 58.3°$ but it might not be so clear for the other two angle pairs.

III. EXPERIMENTAL PROCEDURE

The 156 MeV proton beam extracted in a stochastic manner from the Orsay synchrocyclotron was used. The experimental layout is the same as that used for the investigation of the proton-induced ^{3}He breakup[8,11(a)] except for the target which was liquid ^{2}H similar to that used in the ^{2}H breakup experiment.[4]

TABLE I. The kinematic factors in the neighborhood of the unique condition.

$\theta_1 = -\theta_2$	E_1 (MeV)	E_2 (MeV)	E_3 (MeV)	θ_3	E_{12} (MeV)	E_{13} (MeV)	E_{23} (MeV)	$\overline{E}_{3\,\text{c.m.}}$ (MeV)
59.8°	68.00	63.94	21.64	−2.79	99.34	27.34	22.69	0.282
	67.00	65.00	21.57	−1.38	99.43	26.13	23.84	0.241
	66.00	66.02	21.55	0.07	99.45	24.93	25.02	0.227[a]
	65.00	67.00	21.57	1.37	99.43	23.84	26.13	0.241
	64.00	67.94	21.63	2.70	99.37	22.76	27.27	0.279
58.3°	70.00	66.48	17.09	−2.63	99.73	26.82	22.84	0.039
	69.00	67.53	17.04	−1.10	99.77	25.64	23.97	0.008
	68.00	68.54	17.03	0.41	99.78	24.50	25.11	0.002[a]
	67.00	69.51	17.06	1.88	99.75	23.39	26.24	0.020
	66.00	70.45	17.12	3.33	99.70	22.33	27.36	0.059
56.8°	73.00	67.28	13.29	−4.73	99.24	28.28	21.88	0.370
	72.00	68.36	13.21	−3.01	99.31	27.08	23.01	0.319
	71.00	69.40	13.17	−1.32	99.35	25.92	24.13	0.292[a]
	70.00	70.41	13.16	0.35	99.36	24.79	25.25	0.295
	69.00	71.39	13.18	1.98	99.34	23.69	26.37	0.300

[a]The most favorable conditions in the given θ_1-θ_2 pairs for the three-nucleon collinearity in the finite state.

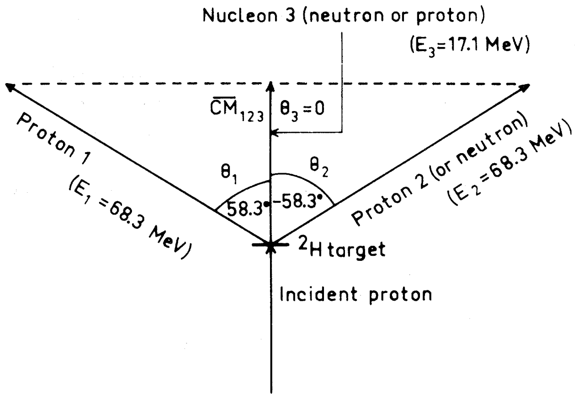

FIG. 1. The designation of the kinematic parameters and the numerical values for the ^{2}H(p, 2p)n or ^{2}H(p, pn)p reactions in an unique condition $\theta_1 = -\theta_2 = 58.3°$, $\bar{E}_{3c.m.} = 0$ for $E_0 = 156$ MeV.

The details of geometric conditions and characteristics of the detectors were presented in Refs. 11 and 4: $\Delta\Omega_1 = 7.06\times 10^{-4}$ sr ($\Delta\theta_1 = 1.7°$) and $\Delta\Omega_2 = 5.48\times 10^{-4}$ sr ($\Delta\theta_2 = 1.5°$). The identification of particles and the energy measurement in the first detecting direction ($\theta = \theta_1$) were done by the first $\Delta E - E$ telescope introduced in the reaction chamber up to 60 cm away from its center. This telescope is composed of a ring plastic counter placed behind a collimator, a 300 μm Si-surface-barrier counter, and a NaI crystal detector (diam = 51 mm and 76 mm thick having a window of 0.2 mm thick Be). The value of the energy loss in the Si detector ΔE_{Si} is 300 KeV/MeV for $E_1 = 20$ MeV, 50 KeV/MeV for $E_1 = 40$ MeV, 14 KeV/MeV for $E_1 \geq 60$ MeV, and the energy resolution in the first telescope ΔE_1 is ~0.23 MeV at $E_1 = 20$ MeV, ~0.75 MeV for $E_1 = 40$ MeV, and ~0.90 MeV for $E_1 \geq 50$ MeV for protons. The detection of the second proton (or neutron) at θ_2 was done by the second telescope composed of a small plastic scintillation counter placed outside the reaction chamber, S_T (1 mm thick), a large plastic scintillation counter S_2 (diam = 18.5 cm and 2 mm thick), and a large liquid scintillation counter, NE213. This NE213 counter with diam = 17.5 cm and length = 25.4 cm has a stainless-steel window (of 175 μm). It was placed at 662 cm from the center of the reaction chamber. For the detection of charged particles, S_T is coupled in coincidence with S_2 and NE213, while for the detection of neutrons, S_T is not coupled and S_2 is coupled with NE213 in anticoincidence. The E_2 resolution is about 2.0 and 3.0 MeV for protons of 30 and 60 MeV, respectively. The difference of the times of flight $T_1 - T_2$ has also been measured for determination of neutron energy in the (p, pn) reaction. The T_{12} for neutrons corresponding to the reaction for which $E_1 = 60$ and 30 MeV, respectively, are 59.2 and 45.9 ns and the resolution of T_{12} is about 4 ns (eight channels) for $T_{12} = 59.2$ and 45.9 ns. These ΔT_{12} correspond to $\Delta E_1 \lesssim 7$ MeV and $\lesssim 5$ MeV for $E_1 = 60$ and 30 MeV, respectively. The (p, 2p) and (p, pn) reactions have been measured simultaneously. The four parameters E_1, ΔE_{Si}, E_2, and T_{12} and the second telescope charge-identification signal for each event have been recorded on line using a Hewlett Packard 2116B computer. The electronic block diagram used was similar to that of Ref. 4 except for the S_T detector and the computer. The total number of incident protons for the series of $\theta_1 = 58.3°$ was 4.35×10^{14}, and 8.7×10^{13} for the series of $\theta_1 = 56.8°$ and 59.8°. In order to minimize accidental coincidences, a very weak beam current (1 to 2 nA) was maintained. Consequently, we took a great deal of machine time.

IV. EXPERIMENTAL DATA TREATMENT, EXPERIMENTAL RESULTS, AND COMPARISON WITH THEORETICAL CALCULATION

The bi-parametric $E_1 - \Delta E_{\mathrm{Si}}$, E_1-E_2, and E_1-T_{12} events from the Hewlett Packard recorded tape were analyzed by a UNIVAC 1100 computer. The experimental differential cross sections $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ for the ^{2}H(p, 2p)n and ^{2}H(p, pn)p have been obtained after the ordinary corrections and

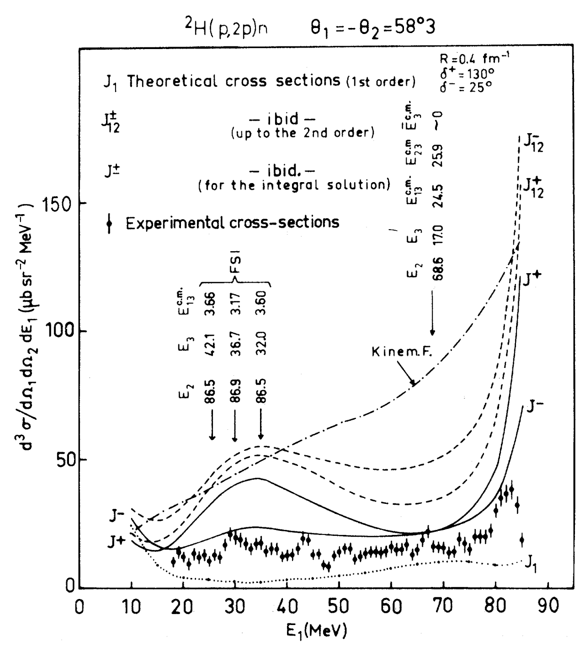

FIG. 2. The $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ cross sections for the ^{2}H(p, 2p)n reaction with the angles $\theta_1 = -\theta_2 = 58.3°$. The meanings of theoretical curves J_1, $J_{12}^{\pm}$, and $J^{\pm}$ are explained in the text.

the efficiency correction for neutron counting of the second detector NE213. Our experimental $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ values for the $(p, 2p)$ reaction with $\theta_1 = -\theta_2 = 58.3°$ are presented in Fig. 2. In this spectrum three peaks are observed: $E_1 \sim 30$, 43, and 68 MeV. The peak near $E_1 = 80$ MeV is due to the phase-space factor and the kinematic limitation. The peak near $E_1 = 30$ MeV is the FSI-type peak because $E_{13\,\mathrm{c.m.}} = 3.17$ MeV at this energy and it is the minimum value of this series. The peak near $E_1 = 43$ MeV might be the p-^{1}H elastic scattering tail [the counts due to ^{1}H impurity are below 1/100 of ^{2}H at the ^{2}H$(p, 2p)n$ QFS peak, but the cross section of p - ^{1}H being ~3.8 mb/sr at $E_1 \sim 43$ MeV ($\theta_1 = 58.3°$), the tail might not be negligible].

We have subtracted the mean accidental counts and all background counts registered 48 ns before or after of the number of events in each point of the E_1-T_{12} map, but it is not quite possible to eliminate a trace of the background. At $E_1 = 68$ MeV the energy E_3 being minimum ($E_3 = 17$ MeV) in this region, there should also exist the QFS-type peak but it must be a very broad one as is hereafter shown in the theoretical curve J_1. Consequently, if the peak at $E_1 = 68$ MeV is sharp, it could be due to the collinearity effect as observed by Lambert *et al.* L'Huillier has calculated the cross sections $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ for ^{2}H$(p, 2p)n$ with our kinematic conditions by using the FSA approximation.[6(a),7] [L'Huillier used J values divided by kinematic factors in her articles, Ref. 6(a), but here, they include kinematic factors. The meaning of the parameters indicated in Fig. 4 are explained in Ref. 6(a).]: $R = 0.4$ fm, $\delta^+ = 130°$ and $\delta^- = 25°$.] She has calculated the $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ using the first order terms (J_1), up to the second order terms ($J_{12}^{\pm}$) [where the signs + and − depend on the phase shift satisfying the imposed conditions as explained in Ref. 6(a)], and the integral solution ($J^{\pm}$). These values and the kinematic factor have also been presented in Fig. 2. In order to make the results independent of the kinematic factors, we divide the $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ by the kinematic factors and present the results in Fig. 3(a) in comparison with the corresponding theoretical values ($\dot{J}$). The calculation has been done approximately, without the search of true optimum values for the parameters used. Again the peaks at $E_1 \approx 30$, 43, and 68 MeV are visible. The comparison of the experimental spectrum with the theoretical ones indicates the following:

(1) The first order term calculation J_1 does not fit the experimental spectrum; the calculation up to the second order terms $J_{12}^{\pm}$ gives approximately the form of the experimental spectrum, but the absolute values of $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ are too large; the integral solution calculation J^- gives a fairly good fit for the absolute values of $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ and the J^+ represents a good shape of the spectrum as observed in the other kinematic conditions.[6(a),8]

(2) At $E_1 = 68$ MeV, the theoretical curves $J^{\pm}$ coincide with each other and both curves possess a smoothly varying minimum. This fact might suggest that the sharp experimental peak at this point

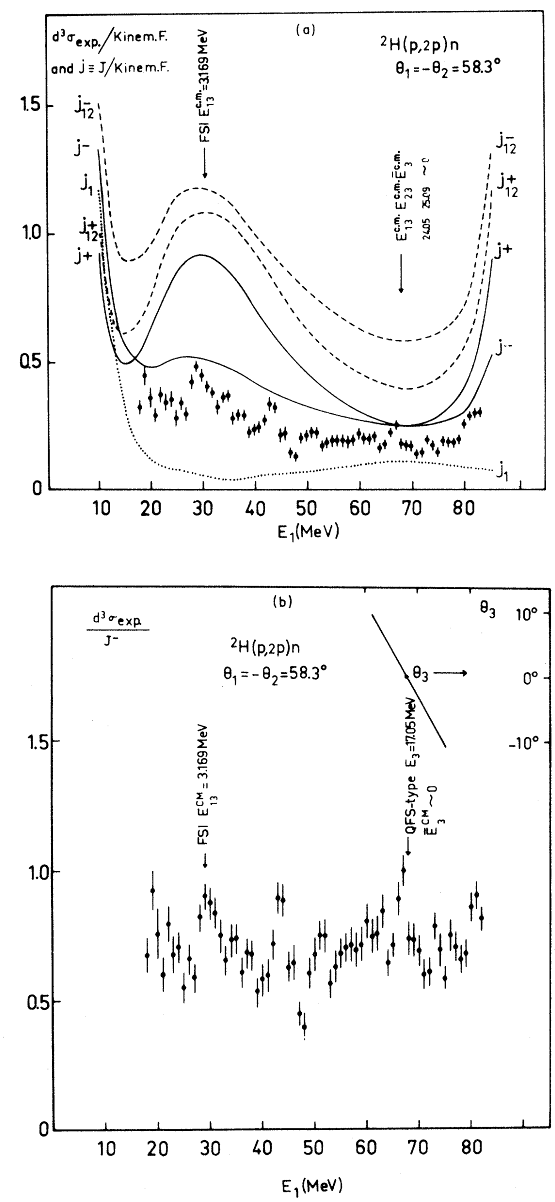

FIG. 3. (a) The values of $(d^3\sigma/d\Omega_2 dE_1)_{\mathrm{exp}}$/kinematic factor, for ^{2}H$(p, 2p)n$ with $\theta_1 = -\theta_2 = 58.3°$ and the theoretical values $J_1 \equiv J$/kinematic factor. (b) $(d^3\sigma/d\Omega_1 d\Omega_2 dE_1)_{\mathrm{exp}}/J^-$ for ^{2}H$(p, 2p)n$ with $\theta_1 = -\theta_2 = 58.3°$. The curve θ_3 presents the θ_3 value corresponding to each kinematic condition presented in Table I.

could not be explained by the nucleon-nucleon interaction calculated in the Faddeev equation, at least by this approximation.

The ratio of the experimental cross sections and the theoretical J^- values are plotted in Fig. 3(b). In this figure, the θ_3 values are also plotted in the neighborhood of the region of interest. The variation of $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ as a function of θ_3 is very large and the width at half maximum of the peak is $\Gamma(E_1) \sim 2.5$ MeV corresponding to $\Gamma(\Delta\theta) \sim 2.5°$. This fact suggests that the peak is very sensitive to θ_3. The analysis of the reaction with $\theta_1 = -\theta_2 = 56.8°$ has also been done, but the statistics is not good; nevertheless, the three peaks similar to those seen in the $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ spectrum for $\theta_1 = -\theta_2 = 58.3°$ are present also in this case but they are displaced on E_1 axis as expected. This fact proves that the measurement is reliable. The peak in question manifests itself at $E_1 \sim 71$ MeV as expected by the calculated kinematics but is much smaller than the 58.3° peak. We expected that the 58.3° peak would disappear because we have taken θ_1 smaller than 58.3° by 1.5°. But our θ_1 slit width, 1.7°, not being sufficiently small relative to the value of Γ of the peak ($\simeq 2.5°$), the tail of the peak of 58.3° appears in the spectrum; the peak at around 44 MeV exists also. This test having been done during our investigation of the proton-induced ^{3}He breakup, the $\Delta\theta_1$ value was not small enough for a test of this kind of investigation. The analysis of the series of $\theta_1 = -\theta_2 = 59.8°$, and the ^{2}H$(p,pn)p$ reaction has also been done, but the statistics were too poor to conclude anything.

V. CONCLUSION

The experimental detection has been done of the ^{2}H$(p,2p)n$ and ^{2}H$(p,pn)p$ reactions induced by 156 MeV protons with the kinematic conditions including the phase-space region where the spectator neutron is at rest in the entire center of mass system. Our purpose was to see if an effect similar to that observed by Lambert *et al.* exists and if the fixed-scattering-center approximation proposed by Benoist-Gueutal *et al.* explains well the experimental cross sections in this region far from the true FSI and the true QFS regions. The first test gives a positive answer: A peak very sensitive for this unique kinematic condition is present at the expected E_1 value. The second test also gives satisfactory results showing that contributions higher than the second order multiple scattering terms are important and sensitive in these regions. The study of these regions suggests that it would be interesting to study more precisely the mechanism of three-nucleon interactions.

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