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Quasifree Scattering in the ^{3}He($\vec{p}$, 2p)^{2}H and ^{3}He($\vec{p}$, pd)^{1}H Reactions at 64.9 MeV

Shigeru KAKIGI*, Kiyoji FUKUNAGA**,
Akira OKIHANA† and Tuguhisa SEKIOKA††

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The ^{3}He($\vec{p}$, 2p)^{2}H and ^{3}He($\vec{p}$, pd)^{1}H reactions at 64.9 MeV were investigated in the quasifree scattering region. The cross sections and the analyzing powers were measured at several coincidence angle pairs. They were compared with the calculation in the plane-wave impulse approximation and a modified one taking account of double scattering effect.

KEY WORDS: ($\vec{p}$, 2p), ($\vec{p}$, pd) Reactions/ Quasifree Scattering/ Few-Nucleon System

1. INTRODUCTION

In recent years, the quasifree scattering (QFS) for few-nucleon systems have been studied. The QFS cross sections are calculated in the plane-wave impulse approximation (PWIA) on the spectator model usually used for the QFS process. Shapes of the energy spectra are well reproduced by the PWIA calculation but absolute values of the PWIA cross sections are larger than experimental values. The latter fact can be ascribed to multiple-scattering (MS) effects, which are measured with a MS factor[1)].

For the ^{3}He($\vec{p}$, 2p)^{2}H reaction, the ratio of the cross section measured to that calculated in the PWIA has been well reproduced by the MS calculation taking account of the single and double scatterings[2,3)]. In the present study, the MS effect in the QFS region is investigated for the ^{3}He($\vec{p}$, 2p)^{2}H reaction in the kinematical condition other than that for the previous one and for the ^{3}He($\vec{p}$, pd)^{1}H reaction in which the deuteron is the scattering partner in the QFS process, not the spectator as in the ($\vec{p}$, 2p) QFS reaction.

2. EXPERIMENTAL PROCEDURE

A 64.5 MeV polarized proton beam was obtained from the AVF cyclotron of the Research Center for Nuclear Physics (RCNP) of Osaka University. The ion source was tuned to provide the maximum polarization of the beam. The polarization axis was adjusted perpendicular to the reaction plane. The spin direction of the beam was periodically changed. The beam polarization was monitored with a polarimeter set at the upper stream from a scattering chamber. The polarimeter was composed of a polyethylene target and two NaI(Tl) scintillation detectors

* 柿木　茂 : Institute for Chemical Research, Kyoto University, Uji, Kyoto 611.
** 福永清二 : Yamagata University, Yamagata 990.
† 沖花　彰 : Kyoto University of Education, Kyoto 612.
†† 関岡嗣久 : Himeji Institute of Technology, Himeji 671-22.

placed symmetrically at 47.5° with respect to the beam direction. The analyzing power for the $p+{}^{12}C$ elastic scattering at 64.5 MeV was 0.975 ± 0.009[4]. The beam polarization was stable within a range from 0.85 to 0.86 during the experiment. The beam spot was about 2 mm in diameter at the center of the scattering chamber and the beam current was about 150 nA. A 13 cm diameter gas chamber with 10 μm Havar windows containing ^{3}He gas (isotopic purity 99.98%) was set at the center of the scattering chamber. The gas pressure, monitored with a gage, was 3 atm at room temperature.

Charged particles from reaction on the target were detected with four $\Delta E-E$ counter telescopes. Two of them (A and B) placed 10° apart were set on one side of the beam and two others (C and D) placed 10° apart on the other side of the beam. Each counter telescope consisted of a totally depleted Si surface barrier ΔE detector and a 25.4 mm thick NaI(Tl) scintillation E detector. The thicknesses of the ΔE detectors were 200 μm for the telescopes A

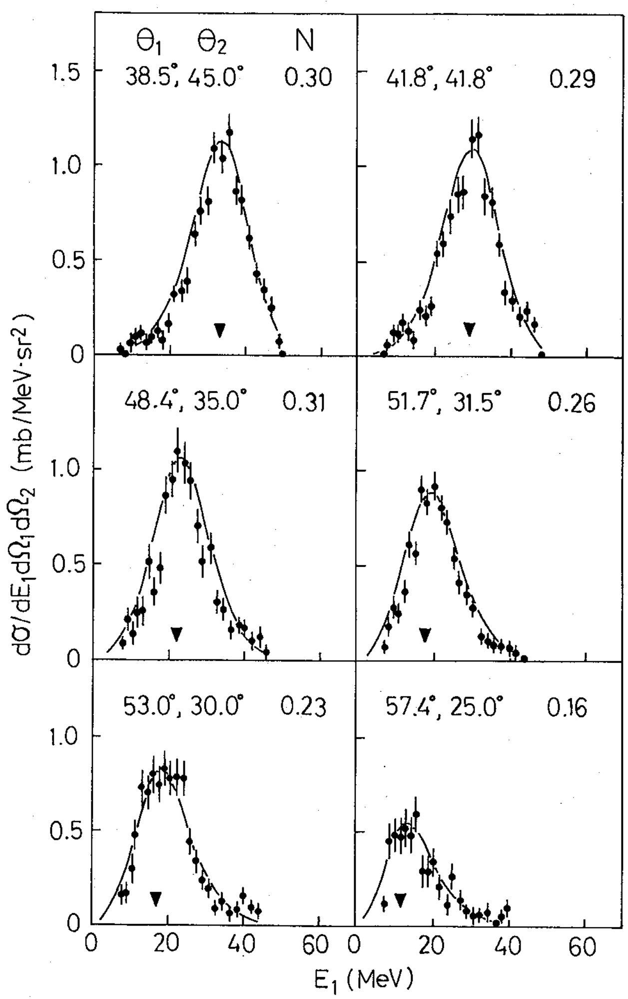

Fig. 1. Coincidence energy spectra for the ${}^3\mathrm{He}(\vec{p}, 2p){}^2\mathrm{H}$ reaction at 64.9 MeV. Solid lines represent the PWIA values multiplied by factors N.

and C, and 150 μm and 100 μm for the telescopes B and D, respectively.

Double slit systems made of 10 mm thick lead were used to define the target volume and solid angles of the detectors. For each coincidence pair, one slit system (for the detector A or B) defined the target volume, which was contained in the umbra of the other (for the detector C or D), its front slit serving only as a buffer. For coincidence measurements, one of the detector pairs (A–C, A–D, B–C and B–D) was choosen with taking into account the energy of detected particles and the thickness of the ΔE counter. Coincidence angle pairs are shown in Tables I and II.

Signals from the counter telescopes were analyzed through a fast-slow coincidence circuit. Signals (ΔE, E, timing, coincidence pair and beam spin direction) were stored on a magnetic tape through the RCNP RAW DATA PROCESSOR-PDP11 system. Data were analyzed off-line with the FACOM M-380Q system at the Institute for Chemical Research of Kyoto University.

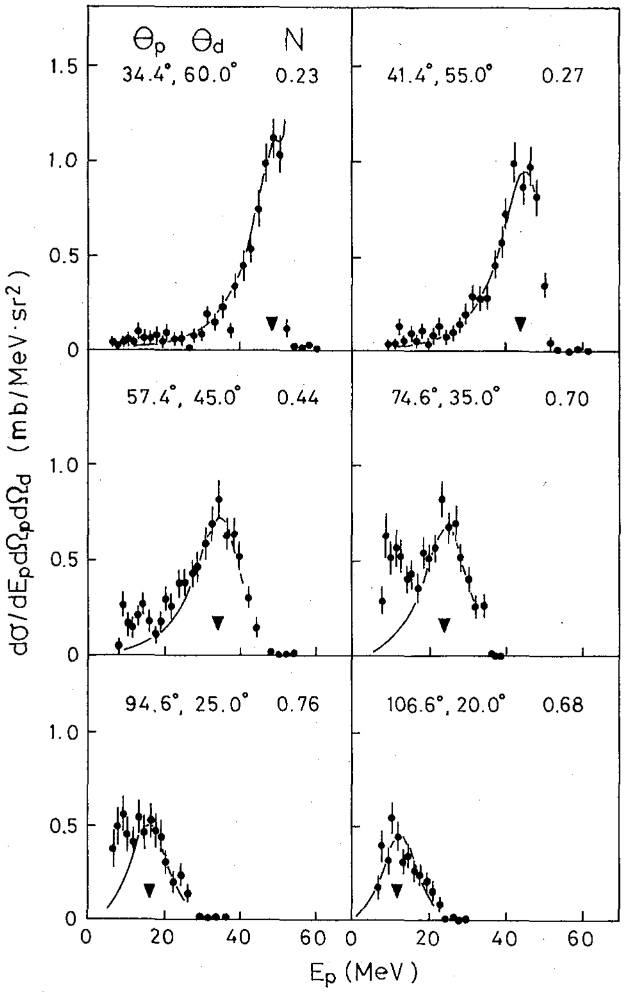

Fig. 2. Coincidence energy spectra for the $^3He(\vec{p}, pd)^1H$ reaction at 64.9 MeV. Solid lines represent the PWIA values multiplied by factors N.

Two-dimensional energy spectra were obtained after particle identification and subtraction of random coincidence events.

3. RESULTS AND DISCUSSION

In two-dimensional coincidence spectra, yields were localized along kinematical loci of the three-body processes. The yields were projected on the proton energy axis. Figs. 1 and 2 show energy spectra of protons from the ^{3}He($\vec{p}$, 2p)^{2}H and ^{3}He($\vec{p}$, pd)^{1}H reactions, respectively, plotted with solid circles. Error bars include only statistical uncertainty. Peaks are observed at the energies, indicated by arrows, corresponding to zero of the unobserved particle energy in the laboratory system. Thus the peaks can be attributed to the QFS process with the unobserved particle as a spectator.

The measured cross sections were compaired with the PWIA calculations based on the spectator model. A three-body reaction a+A→1+2+3 is considered, where the particle a is the projectile and the particle A the target nucleus assumed to consist of particles b and c bounded, A=(bc). The PWIA differential cross section is given as

Table I. Cross sections and analyzing powers for the QFS process in the ^{3}He($\vec{p}$, 2p)^{2}H reaction at 64.9 MeV.

θ_1 (deg)	θ_2	$d\sigma/dE_1d\Omega_1d\Omega_2$ (mb/Mev sr^2)	A_y
25.0	57.4	0.51±0.05	−0.013±0.079
30.0	53.0	0.77±0.09	−0.051±0.050
31.6	51.5	0.84±0.05	+0.047±0.032
33.9	49.4	0.90±0.09	
35.0	48.4	0.99±0.06	−0.021±0.046
38.5	45.0	1.09±0.07	−0.026±0.033
41.8	41.8	1.11±0.06	−0.002±0.038

Table II. Cross sections and analyzing powers for the QFS process in the ^{3}He($\vec{p}$, pd)^{1}H reaction at 64.9 MeV.

θ_p (deg)	θ_d	$d\sigma/dE_pd\Omega_pd\Omega_d$ (mb/Mev sr^2)	A_y
29.7	62.2	1.38±0.12	+0.085±0.058
34.1	59.6	1.15±0.08	−0.063±0.049
35.0	58.4		−0.025±0.045
41.4	55.0	0.94±0.08	−0.010±0.053
45.0	51.4		−0.070±0.054
57.4	45.0	0.62±0.07	−0.277±0.061
60.0	44.4	0.66±0.06	−0.309±0.052
74.6	35.0	0.59±0.06	−0.385±0.061
94.6	25.0	0.40±0.05	−0.395±0.060
106.6	20.0	0.34±0.05	−0.220±0.076

$$(d\sigma/d\Omega_1 d\Omega_2 dE_1)_{PWIA} = K \times S \times (d\sigma/d\Omega)_{12} \times |\Phi(p_3)|^2, \qquad (1)$$

where K is the kinetic factor given by

$$K = [M_{12}{}^2 p_1 p_2{}^2 E_3/(p_a E_b)]/[p_2(E_2+E_3) - E_2(\mathbf{p}_2+\mathbf{p}_3)\mathbf{p}_2/p_2],$$

with

$$E_b = (p_3{}^2 + m_b{}^2)^{1/2}$$

and S is the spectroscopic factor, $S=1/2$ for ^{3}He target. $(d\sigma/d\Omega)_{12}$ is the half-off energy shell differential cross section for the 1+2 scattering in the (12) center of mass system. These were replaced approximately by the on-shell values in the post collision prescription, which were obtained from the data for pp scattering[5] and for pd scattering[6,7,8,9] through interpolation. $|\Phi(p)|^2$ is the momentum density, given by

$$|\Phi(p)|^2 = [\alpha\beta(\alpha+\beta)^3]/[\pi(\alpha^2+p^2)(\beta^2+p^2)]^2.$$

Thus

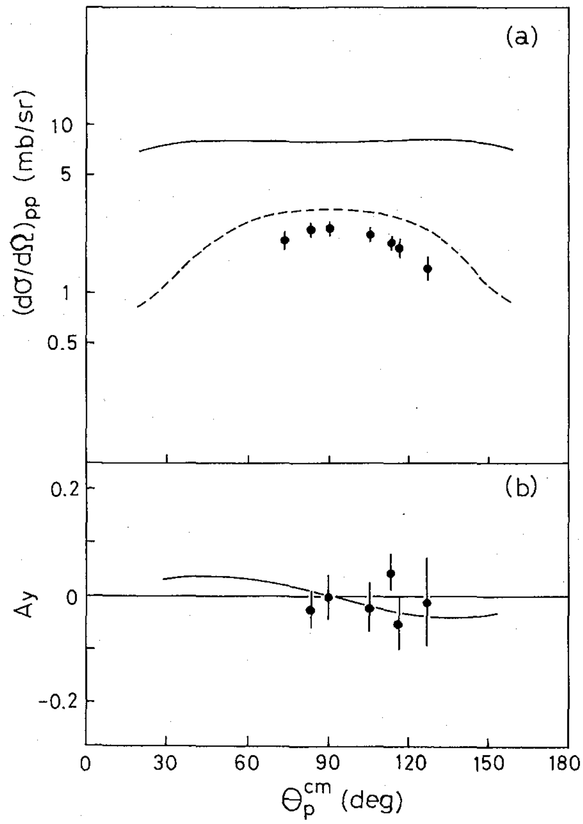

Fig. 3 Two-body pp cross sections deduced from observed QFS cross sections using the PWIA formula (a) and pp-QFS analyzing powers (b) for the $^3He(\vec{p}, 2p)^2H$ reaction at 64.9 MeV. Solid lines represent the pp elastic scattering cross section and analyzing power, and dashed line the elastic cross section multiplied by the MS factor.

$$|\Phi(0)|^2=[(\alpha+\beta)/(\alpha\beta)]^3/\pi^2.$$

The parameters (α, β) in fm^{-1} are (0.4201, 1.202) for $^3He(pd)$[10]. Thus $|\Phi(0)|^2=0.437\times10^{-6}$ MeV^{-3}. In Figs. 1 and 2, solid lines represent the PWIA cross sections multiplied by factors N shown in the figures. Shapes of the energy spectra are well reproduced by the PWIA calculation but $N<1$, the absolute values being not reproduced.

Next the differential cross sections at the QFS points ($T_3=0$) were obtained and listed in Tables I and II for the $^3He(\vec{p}, 2p)^2H$ and $^3He(\vec{p}, pd)^1H$ reactions, respectively. Two-body scattering cross sections $(d\sigma/d\Omega)_{12}$ were deduced from the QFS ones using eq. (1) and are shown in the upper parts of Figs. 3 and 4 with solid circles as a function of the angle θ_1^{cm} in the (12) center of mass system. The relative kinetic energy T_{1-2} is constant of 26.6 MeV for the $(p, 2p)$ reaction and 37.5 MeV for the (p, pd) reaction. The deduced cross sections are compared with

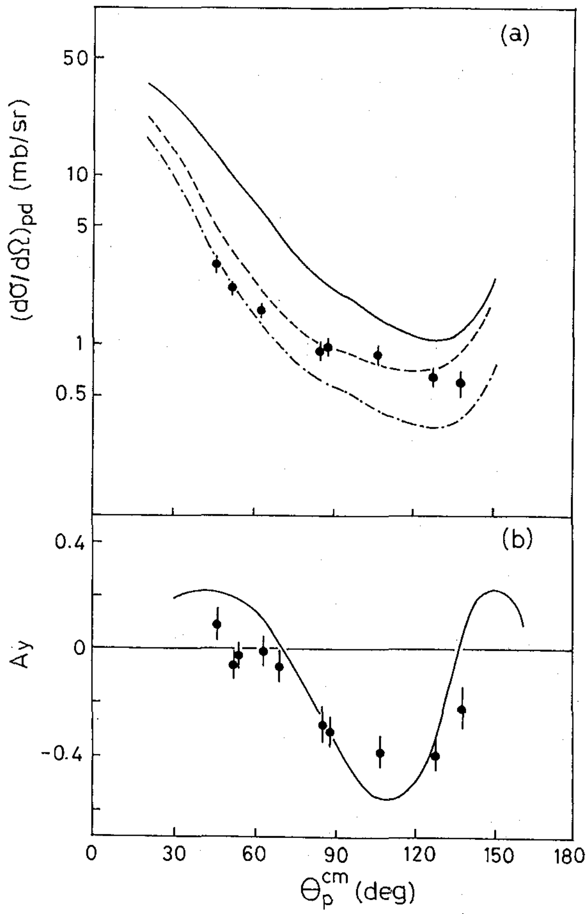

Fig. 4. Two-body pd cross sections deduced from observed QFS cross sections using the PWIA formula (a) and pd-QFS analyzing powers (b) for the $^3He(\vec{p}, pd)^1H$ reaction at 64.9 MeV. Solid lines represent the pd elastic scattering cross section and analyzing power, and dashed and dash-dotted lines the elastic cross section multiplied by the MS factors for the pd singlet and quartet states, respectively.

the elastic scattering ones, represented with solid lines in the figures. The absolute values diminish in the QFS process.

This fact can be attributed to the multiple scattering effect. The transition operator U is approximated as

$$U = t_{12} - t_{23} G_0 t_{12} - t_{13} G_0 t_{12},$$

where t_{ij} is the two-body transition operator through the ij pair interaction and G_0 is the free space propagator. The first term corresponds to the transition in the impulse approximation (IA) and the second and third terms contribute to the multiple scattering effect, as a correction to the IA term. The interaction between the projectile proton and the deuteron in ^{3}He contributes to the correction term in the (p, 2p) QFS process and however it plays the leading part in the (p, pd) QFS process. A separable form is assumed for the two-body transition matrix and its parameters (α, β) in fm^{-1} are (−0.1112, 1.20), (0.420, 1.20) and (0.094, 1.20) for the pp singlet, pd doublet and pd quartet states, respectively[2]. The MS factor is calculated and the PWIA cross sections were multiplied by $|\eta|^2$,

$$(d\sigma/d\Omega)_{\mathrm{MS}} = (d\sigma/\mathrm{d}\Omega)_{\mathrm{free}} \times |\eta|^2,$$

shown in Fig. 3 with dashed line and in Fig. 4 with dashed and dash-dotted lines for the pd-QFS in the doublet and quartet states, respectively.

The lower parts of Figs. 3 and 4 show the QFS analyzing powers by solid circles. Also are shown with solid lines those for the corresponding elastic scatterings, obtained from the data for pp[5] and pd[7,8,11,12] scatterings through interpolation. As seen from the figures, the QFS analyzing powers are similar those for the corresponding elastic scatterings.

In conclusion, the double scattering effect can be considered as a correction to the single scattering calculation of the cross section for the QFS region. The calculation including the double scattering well reproduces the experimental cross sections. The result is the same as that for the ^{3}He(p, 2p)^{2}H reaction obtained in different geometries. For the analyzing power, on the other hand, the double scattering seems to be an effect of higher order because the observed values do not differ so much from those for the elastic scattering.

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REFERENCES

(1) K. Fukunaga, S. Kakigi, T. Ohsawa and A. Okihana, *J. Phys. Soc. Jpn.*, **52**, 69 (1983).

(2) S. Kakigi, K. Fukunaga, T. Ohsawa, A. Okihana, T. Sekioka, H. Nakamura-Yokota, S. Tanaka and S. Kato, *Nucl. Phys.*, **A473**, 31 (1987).

(3) S. Kakigi, K. Fukunaga, A. Okihana and T. Sekioka, *Bull. Inst. Chem. Res., Kyoto Univ.*, **68**, 103 (1990).

(4) S. Kato, K. Okada, M. Kondo, A. Shimizu, K. Hosono, T. Saito, N. Matsuoka, S. Nagamachi, K. Nisimura, N. Tamura, K. Imai, K. Egawa, M. Nakamura, T. Noro, H. Shimizu, K. Ogino and Y. Kadota, *Nucl. Inst. and Meth.*, **169**, 589 (1980).

(5) R. Wilson, The Nucleon-Nucleon Interaction (Interscience Publisher, New York, 1963) p. 177.

(6) T.A. Cahill, J. Greenwood, H. Willmes and D.J. Shadoan, *Phys. Rev.*, **C4**, 1499 (1971).

(7) N. Bunker, J.M. Cameron, R.F. Carlson, J. Reginald Richardson, P. Tomas, W.T.H. van Oers and J.W. Verba, *Nucl. Phys.*, **A113**, 461 (1968).

(8) H. Shimizu, K. Imai, N. Tamura, K. Nisimura, K. Hatanaka, T. Saito, Y. Koike and Y. Taguchi, *Nucl. Phys.*, **A382**, 242 (1982).

(9) K. Hatanaka, N. Matsuoka, H. Sakai, T. Saito, K. Hosono, Y. Koike, M. Kondo, K. Imai, H. Shimizu,

T. Ichihara, K. Nisimura and A. Okihana, *Nucl. Phys.*, **A426**, 77 (1984).
(10) I. Slaus, R.G. Allas, L.A. Beach, R.O. Bondelid, E.L. Petersen, J.M. Lambert, P.A. Treado and R.A. Moyle, *Nucl. Phys.*, **A286**, 67 (1977).
(11) N.S.P. King, J.L. Romero, J. Ullmann, H.E. Conzett, R.M. Larimer and R. Roy, *Phys. Lett.*, **69B**, 151(1977).
(12) J.C. Faivre, D. Garreta, J. Jungerman, A. Papineau, J. Sura and A. Tarrats, *Nucl. Phys.*, **A127**, 169 (1969).