Comments and Addenda

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Quasifree *p-p* Scattering in the Reaction ^{2}H(*p*, 2*p*)*n* from 21.5 to 56.4 MeV

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Quasifree *p-p* scattering has been studied in the reaction ^{2}H(*p*, 2*p*)*n* between 21.5 and 56.4 MeV. Results have been fitted with simple impulse-approximation models which reproduce the position and shape of the quasifree peak but give too high an absolute value for the cross section.

Simple impulse-approximation models[1] are very suitable for explaining quasifree (QF) proton-proton scattering at bombarding energies E_0 higher than 150 MeV. At energies lower than 20 MeV these models reproduce the position well,[1-6] and with less accuracy the shape of the QF peak, but the absolute value is too high. In some cases this factor is found to vary with energy.[7] In Ref. 3 it is found to be constant between 6.5 and 13 MeV. Quasifree scattering (QFS) in the breakup of deuterons by protons has already been studied in the intermediate-energy region and a paper[7] reported data collected in three different laboratories. Our results concern the *d*(*p*, 2*p*)*n* reaction and have been obtained from 21.5 to 56.4 MeV using the Grenoble variable-energy cyclotron. Targets were 98% enriched $(CD_2)_n$ foils of 2 and 4 mg/cm^2 depending on the incident energy. For the chosen set of angles ($\theta_1 = -\theta_2 = 43°$) the momentum transferred to the spectator neutron approaches zero. The two protons are detected in coincidence by two telescopes each composed of a 100-μm ΔE surface-barrier Si detector and a thick (4 to 7 mm) Li-drifted E detector. Each event is characterized by five parameters: the energies E_1 and E_2 of the two protons detected at times t_1 and t_2; the energy losses ΔE_1 and ΔE_2 in the ΔE counters; and the time interval $\Delta t = t_1 - t_2$. These parameters are stored on magnetic tapes driven by a PDP-9 on-line computer. Particle identification is made by computer analysis of the recorded events. The time parameter Δt permits a subtraction of background counts (corresponding to random coincidences between particles scattered into two different beam pulses) from the total counts to give the true coincident spectra. The energy E_1 is then plotted versus E_2 and projections are made over the axis E_1. In Fig. 1 is given the triple-differential cross section $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ versus E_1 for $E_0 = 21.5$ and 40 MeV. The quoted errors are statistical only. Absolute normalization uses the ^{2}H(*p*, *p*)^{2}H elastic scattering

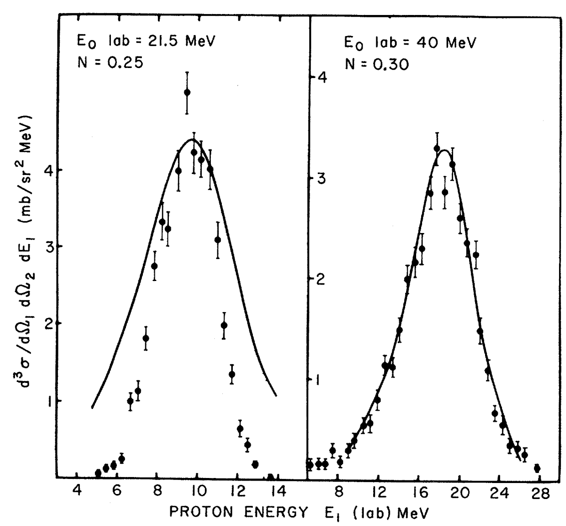

FIG. 1. Differential cross section $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ versus E_1 at $E_0 = 21.5$ MeV (left) and 40 MeV (right). The solid curve is a fit using the KWC model. N is a normalization factor.

TABLE I. Differential cross section $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ at the maximum height of the QFS peak. The indicated error includes statistical and systematic uncertainties.

Laboratory incident energy (MeV)	Detection angles (deg)	Cross section at the QFS peak (mb/MeV sr^2)	Normalization factor
21.5	42.5-42.5	4.28 ±0.43	0.25
25	43-43	3.5 ±0.52	0.23
30	43-43	4.3 ±0.43	0.32
35	43-43	3.4 ±0.51	0.28
40	43-43	3.3 ±0.50	0.30
41.5	43-43	4.49 ±0.45	0.41
49.4	42.5-42.5	3.96 ±0.40	0.41
56.4	42.5-42.5	4.39 ±0.44	0.51

data; uncertainty on the absolute cross section is of the order of ±10%. The experimental results are displayed in Table I.

The experimental results have been fitted with the Kuckes-Wilson-Cooper (KWC) model[1,6] which relates the QFS cross section to the p-p scattering cross section by

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_1} = |\phi(p_3)|^2 \left(\frac{d\sigma}{d\Omega}\right)^{p-p}_{\text{free}} \times P,$$

where $\phi(p_3)$ is the Hulthén wave function of the deuteron, P is a phase space factor, and $(d\sigma/d\Omega)^{p-p}_{\text{free}}$ is the free elastic p-p cross section. For this latter value we have taken the free p-p cross section[8] at $\theta_{\text{c.m.}}=90°$ for the energy available in the exit channel. One observes that the peak position and shape are fairly well reproduced at 40 MeV, but there is a tendency for the calculated shape to become wider than the experimental one at low energy. The absolute magnitude is characterized by a normalization factor N which is the ratio of the calculated to the experimental cross section. This factor varies from 0.25 at 21.5 MeV to 0.51 at 56.4 MeV. So the experimental absolute cross section is never reproduced by the above simple model below 60 MeV.

In Fig. 2 is given the differential cross section $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ at the maximum height of the QFS peak versus the incident energy E_0. These results are in good agreement with those given in Ref. 7. The solid curve represents KWC calculations of the type described above. The dotted line is the result of a calculation of the inhomogeneous term of the Faddeev equation where the antisymmetrization and the spin-isospin dependence have been taken into account.[9] Rescattering and higher-order terms are neglected. The two calculations

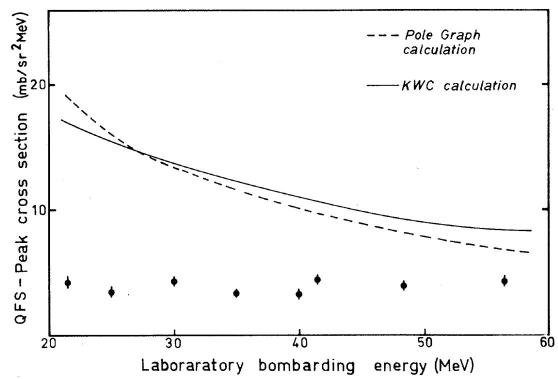

FIG. 2. Differential cross section $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ at the maximum height of the QFS peak versus the incident energy E_0.

give about the same results above 20 MeV. One sees that the simple impulse approximation gives the shape of the spectra, but the absolute value disagrees by a factor approaching unity as the incident energy increases. Despite the careful choice of the detection geometry which should enhance the QFS mechanism, this shows that higher-order terms are not negligible at the energy considered. This agrees with exact calculations[10] of the three-body breakup performed with an unrealistic separable nucleon-nucleon interaction.

Another phenomenological approach consists of the introduction of a cutoff radius r_c in the deuteron wave function.[7] This modified simple impulse approximation agrees well with experiments except below 14 MeV. In this approach the incident proton is supposed to interact only once with one particle of the deuteron where the two nucleons forming the target are at a distance larger than a critical distance r_c. This last free parameter alone permits one to fit both the absolute value and the shape of the QF peak.

There is another approach based on graph series or Faddeev equations which attempts to explain the discrepancy by rescattering effects without introducing any new parameters. This method has been applied with success to the nucleon-deuteron system in the elastic scattering case.[10] The same type of calculation applied to the QFS would be very interesting and is being performed at Grenoble.[11]

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^{68}Zn(d, ^{6}Li)^{64}Ni Reaction at 27.2 MeV

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The differential cross section for the reaction ^{68}Zn(d,^{6}Li)^{64}Ni at 27.2 MeV, leading to the lowest 0^+ and 2^+ states was measured. The angular distributions show a diffraction pattern and forward peaking characteristic of a direct process. A distorted-wave Born-approximation (DWBA) calculation, in the zero-range approximation, with states represented by radial wave functions with $N=5$ and $N=4$ nodes for $L=0$ and $L=2$, respectively, was performed. The form factors correspond to the wave function of an α particle moving in a Woods-Saxon potential. From the optical-model analysis the relative strength of the 0^+ and 2^+ states can be determined within 20% error. In addition, a DWBA calculation including structure factors obtained on the basis of the pairing-plus-quadrupole model, with a coherent sum over the center-of-mass radial quantum number N, was used. The predicted ratio $\sigma(2^+)/\sigma(0^+)$ is 0.8 of the experimental value, with no significant difference in the shape of the angular distributions in both analyses.

A number of papers[1-3] have emphasized the direct character of the (d,^{6}Li) reaction in light nuclei. In order to investigate whether this is also the case in the medium-mass region, and whether the cross sections are large enough to be useful as a tool in nuclear-structure studies, we measured the differential cross sections for the reaction ^{68}Zn(d,^{6}Li)^{64}Ni at 27.2 MeV.

A self-supporting foil of enriched ^{68}Zn (98.5%) was bombarded with the 27.2-MeV deuteron beam of the Buenos Aires Synchrocyclotron, with an energy spread of 300 keV. An over-all energy resolution of 450 keV full width at half maximum was obtained.

The experimental setup included two independent detection systems operating simultaneously. One of them consisted of a conventional ΔE-E telescope of solid-state detectors which allowed the passage of the light particles.

The other one was a single detector thick enough (100 μm) to stop only the most energetic lithium ions. The detectors, placed in symmetrical positions off the azimuthal plane, allowed for a continuous cross-check of the data for the same angle. The results are plotted in Fig. 1.

The angular distributions for the 0^+(g.s.) and 2^+ (1.34 MeV) of ^{64}Ni show the diffraction structure and forward peaking characteristic of a direct-reaction mechanism. There is an indication of the surface localization of the reaction in the rather large decrease of the cross section at larger angles.

The solid lines in Fig. 1 correspond to a DWBA calculation carried out with the code DWUCK in the zero-range approximation. The form factors we used correspond simply to the wave function of an α particle moving in a Woods-Saxon potential of radius, diffuseness, and depth (around 200 MeV) such as to bind, at the appropriate energy, the states represented by a radial wave function[4] with

TABLE I

	V (MeV)	r_{0R} (fm)	a_R (fm)	W_D [a] (MeV)	r_{0W} (fm)	a_W (fm)	r_{0C} (fm)
Deuteron [b]	71.9	0.96	0.99	56	1.35	0.75	1.25
Lithium	300	1.50	0.65	40	1.50	0.65	2.50

[a] Woods-Saxon derivative.
[b] From Ref. 4.