Neutron-Neutron Quasifree Scattering*

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The reaction D(n, $2n$)p has been measured at $E_{\rm inc}=14.1$ MeV, $\theta_{n(3)}=\theta_{n(4)}=30°$, $\varphi=180°$, and the results are compared with the predictions of two separable-potential models. Neutron-proton and proton-proton quasifree scattering from nucleon + deuteron reactions at 14 MeV are also compared with the predictions of the same models. The upper limit of 2 mb/sr^2 is determined for the reaction D(n, $n\gamma$)d.

The purpose of this study is to contribute to the understanding of nucleon-induced deuteron breakup processes and to investigate what can be learned about neutron-neutron effective-range parameters from quasifree scattering (QFS). Experimental data[1-14] indicate that the enhancement associated with the quasifree kinematic conditions is one of the salient features of multiparticle reactions even at $E_{\rm inc}\sim 10$ MeV.[6-9] However, this does not imply that the pole graph represents a dominant contribution, nor that the cross section can be factored, one term being the half-off-the-energy-shell t matrix. The importance of the pole-graph contribution can be tested[15-19] and the results of measurements[11,17-19] of the reactions ^{6}Li(p, $p\alpha$)d and ^{6}Li(α, 2α)d at $E_{\rm inc}\sim$ 50-80 MeV indicate that the spectator model[1] (SM) gives a correct description of the data except for a normalization factor. The spectator model has been seccessfully applied to D(N, $2N$) QFS at $E_{\rm inc}\gtrsim 150$ MeV,[1-3,20] but it fails at $E_{\rm inc}\lesssim 100$ MeV.[4-10] Various simple modifications have been proposed: (i) off-the-energy-shell effects, but they do not seem to be large enough to account for the discrepancy between the data and the theory[10,20,21]; (ii) final-state interaction (FSI) effects, which improve the fit to the data at $E_{\rm inc}\gtrsim 150$ MeV,[2,3,20] but do not explain the 46-MeV data[5]; (iii) modified simple impulse approximation (MSIA),[22] which explains the energy variation of the absolute cross section and the shape of the spectra.[6] These simple models are inadequate at low energies,[23,24] and indeed they do not explain, e.g., the observed ratio D(p, pn)/D(p, $2p$).[6,9,13,14,25]

Neutron-neutron interaction remains a problem of considerable interest.[26] The latest analysis of the reaction D(π^-, nn)γ gives a value of $a_{nn}=-16.6\pm 1.3$ fm.[27] A comparison procedure[28] applied to the reactions D(p, n)$2p$, D(n, p)$2n$, ^{3}He(d, t)$2p$, and ^{3}H(d, ^{3}He)$2n$ gives $a_{nn}=-16.45\pm 1.0$ fm and $r_{nn}=3.1\pm 0.5$ fm. This application has been criticized[10,29,30] and these values are not reliable independent determinations of a_{nn} and r_{nn}.

Neutron-neutron QFS was studied by bombarding a cylindrical 2-in.×2-in. C_6D_6 target with the 14.1-MeV neutron beam defined by associated α particles. Two outgoing neutrons were detected at $\theta_{n(3)}=\theta_{n(4)}=30°$, $\varphi=180°$. The overall angular resolution was ±6°. The main experimental problem is the large background from γ's and from direct and elastically scattered neutrons. The background was reduced by requiring the four detectors (α, target, neutron-right, and neutron-left) to be in coincidence and by kinematically over-determining the process by measuring the time of flight and the scattering angles of the two neutrons and the energy of the recoil proton (E_T).[31] A further reduction in background of 20-25% was achieved by requiring that the neutron energy derived from the scintillator light output be compatible with the energy derived from neutron time of flight. Real and accidental events

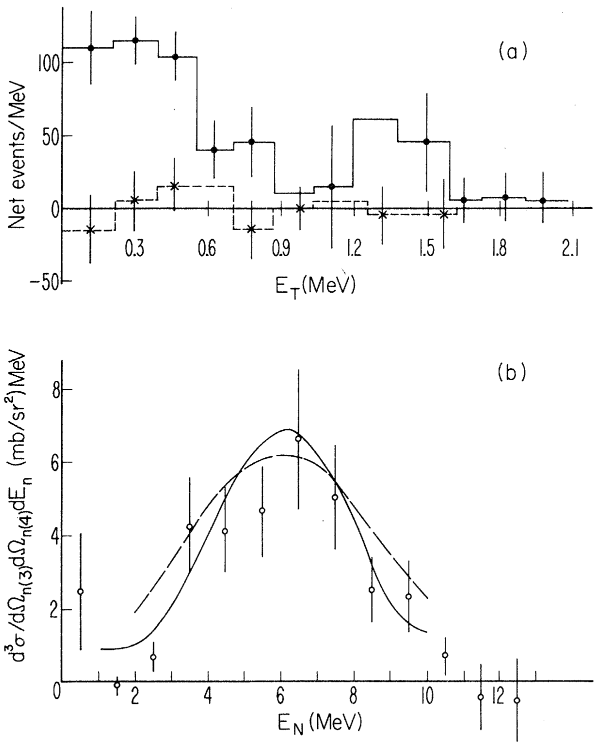

FIG. 1. (a) The measured target energy spectrum incorporating the fourfold coincidence requirement (α, target, neutron-right, and neutron-left detectors). Accidental events are subtracted. C_6D_6, solid histogram; C_6H_6, dashed histogram. Representative statistical errors are shown. (b) Neutron-neutron correlation spectrum projected on neutron energy axis. Solid curve is the prediction of the YYY model calculated for 14.4 MeV. Dashed curve is the SM with normalization factor $N = 0.236$. Error bars are absolute uncertainties. The effect of energy and angular resolution is not folded in.

were accumulated simultaneously. A C_6H_6 cylindrical 2-in.×2-in. target was also used to investigate the background. The lowest energy measured in the target counter was 40 keV, while the lowest kinematically allowed E_T are 180 keV (30°), 50 keV (35°), and 30 keV (36°). $D(n, 2n)p$ events appear on a kinematical locus in the three-dimensional space $E_{n(3)}$-$E_{n(4)}$-E_T.

The measured target detector energy spectra incorporating the fourfold coincidence requirement are shown in Fig. 1(a). The number of events after subtracting accidental events is consistent with zero for the C_6D_6 target for E_T outside the kinematical locus and for the C_6H_6 target for all E_T, corroborating the reliability of the experimental arrangement. The following counting rates were typical: α and target detector, 4×10^5 counts/sec; neutron detectors, 3×10^3 counts/sec; and D(n, $2n$) events, 1 count/hr. The

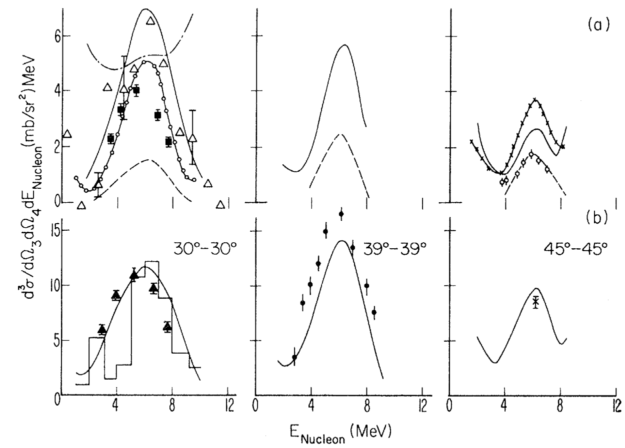

FIG. 2. (a) D(n,$2n$)p and D(p,$2p$)n; (b) D(n,np)n and D(p,pn)p. The solid curves are prediction of the YY model for $E_{\rm inc} = 14.4$ MeV, $\theta_3 = \theta_4 = 30°$, 39°, and 45°, respectively ($\varphi = 180°$), compared with experimental data: dots, 14-MeV (p,pn), Ref. 25; open triangles, present data; crosses, 15-MeV (p,pn), Ref. 13; open circles, 14-MeV 43°-43°, Ref. 6; squares, 13-MeV (p,$2p$), Ref. 8; solid triangles, 12-MeV (p,pn), Ref. 9; histogram, 14.4-MeV (n,np), Ref. 33. Only several representative data points are shown. Data of Ref. 33 were averaged over a 1-MeV interval. Dash-dotted curve shows first and second terms of multiple-scattering series normalized by 0.33. Open-circle curve shows first and second term in the unitarized model. Crosses show YYY model for 43°-43°. Dashed curves are MSIA for $R = 10.55$ fm.

cross section for the reaction D(n, $2n$)p was determined relative to the n-p and n-d elastic-scattering cross sections, which in principle allows this measurement to be made with an uncertainty of ±5%. The accuracy of this experiment is ±15% due mainly to statistics.[32] Figure 1(b) shows the neutron-neutron correlation spectrum.

Present experimental results as well as available data on D(n, np)n,[33] D(p, $2p$)n,[6,8] and D(p, pn)p[9,25] at $E_{\rm inc}\sim 14$ MeV are compared in Fig. 1(b) and Fig. 2 with the predictions of (i) the SM,[1] (ii) the MSIA[22] using $R = 10.55$ fm which was found to fit 14-MeV 43°-43° data,[6] and (iii) two models[34] based on the Faddeev equation using a spin-dependent, S-wave, separable Yamaguchi potential: first, the YY model[35,36] which assumes $a_{nn} = -23.78$ fm and $r_{nn} = 2.67$ fm, and second, the YYY model[35,36] which uses $a_{nn} = -16.0$ fm and $r_{nn} = 2.50$ fm.

The following conclusions can be drawn: (1) SM does not fit the data. (2) MSIA does not explain the angular variation. (3) YY and YYY models give a very good fit to the D(n, $2n$)p and D(n, np)n data, but the agreement with considerably more accurate D(p, $2p$)n and D(p, pn)p data is not as good. It is not clear how much the inclusion of a Coulomb force would affect the results. (4) For the angles studied in this work the cross sections derived from the two separable models differ by 0.1-3%. The values of $\sigma_{nn}(E_{nn}\sim 3\text{ MeV})$ for the two sets of effective-range parameters differ less than 5%. (5) Both separable-potential models explain the $(n, 2n)/(n, np)$ ratio[23] and the gross features of the angular dependence. (6) The multiple-scattering series does not converge at low energies[24] as can be seen by comparing the exact calculation with the results from the truncated multiple-scattering series. The first order (SM) gives too large a cross section and the second order [first plus second terms: dash-dotted curve in Fig. 2(a)] does not even show the QFS peak. (7) The unitarized model[24] of the multiple-scattering series gives much better results (open-circle curve in Fig. 2, 30°-30°).

The results of this study together with the analysis of FSI[35-38] in neutron-induced deuteron breakup and the analysis of nucleon-deuteron elastic scattering demonstrates that the separable model gives, in general, adequate description of the data and could be applied to extract unknown interaction parameters. Since the experimental value of a_{nn} is ~ -16 fm,[27] the agreement between the YYY model and the present data can be interpreted as evidence favoring $r_{nn} = 2.5$ fm. The same conclusion can be reached if one uses the spectator model (though the preceding discussion shows it to be invalid at these energies), assumes the final energy prescription (though off-the-energy-shell effects could be relatively large, and this prescription could be wrong[21]), and hopes that some inadequacies are canceled by use of comparison with D$(p, 2p)n$ data.[6-8] This procedure yields $\theta_{nn}(E_{nn}\sim 3\text{ MeV}) = 1350 \pm 250$ mb from which, when using the latest a_{nn},[27] one extracts $r_{nn} = 2.4 \pm 1.6$ fm.

Though this measurement was not designed to obtain neutron-deutron bremsstrahlung cross sections, as a by-product one can determine the upper limit $d^2\sigma(\theta_n = 30°, \theta_\gamma = 30°)/d\Omega_n d\Omega_\gamma = 2$ mb/sr^2.

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Reaction $\pi^+p\to\eta^0\Delta^{++}$: A Test of A_2 Regge-Pole Exchange*

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New results are presented on the reaction $\pi^+p\to\eta^0\Delta^{++}$ between 1.2 and 2.67 GeV/c. The data above 2 GeV/c, when combined with some existing data, give evidence for a dip in the t distribution near $t=-1.5$ (GeV/c).^{2} This dip, and other features of the data, are adequately described by an A_2 Regge-pole model. The effective A_2 trajectory is calculated and found to disagree with that obtained from the reaction $\pi^-p\to\eta^0n$.

We have performed a measurement of the total and differential cross sections and the Δ^{++}-decay angular distributions for the reaction

$$\pi^+p\to\eta^0\Delta^{++} \qquad (1)$$

at incident momenta between 1.3 and 3.0 GeV/c. At the higher energies this reaction is expected to proceed by the exchange of only the A_2 trajectory in the t channel, and hence provides a check of the properties of A_2 exchange deduced from the reaction

$$\pi^-p\to\eta^0n. \qquad (2)$$

In addition, these new data, when combined with some existing data, allow us to explore a higher $|t|$ region than previously possible in either Reaction (1) or (2). We observe a dip near $t=-1.5$ (GeV/c)^2 that, in terms of standard nonsense wrong-signature zero (NWSZ) Regge models, would correspond to the A_2 trajectory passing through -1 (GeV/c)^2.

The new measurements are based on several Bevatron exposures of the Lawrence Radiation Laboratory 25-in. hydrogen bubble chamber to π^+ of momenta 1.28, 1.39, 1.55, 1.62, 1.75, 1.85, 2.3, and 2.67 GeV/c. We include in the analysis published data between 3 and 4 GeV/c[1] (henceforth referred to as 3.5 GeV/c) and data at 3.7 GeV/c.[2] In total, some 95 000 four-prong events were measured on the flying-spot digitizer (FSD) and on the on-line Franckensteins (COBWEB) and constrained to the one-constraint (1C) hypothesis

$$\pi^+p\to\pi^+p\pi^+\pi^-\pi^0. \qquad (3)$$

Extensive use was made of the automatic ionization measurements available from the FSD in order to discriminate between conflicting hypotheses. In Fig. 1 we show the $\pi^+\pi^-\pi^0$ and the π^+p mass distributions from hypothesis (3) at 2.67 GeV/c to illustrate the relatively small potential backgrounds.

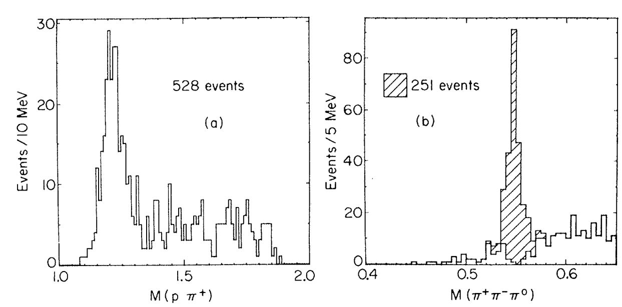

FIG. 1. Invariant-mass distributions for the reaction $\pi^+p\to\pi^+p\pi^+\pi^-\pi^0$ at 2.67 GeV/c. (a) $p\pi^+$ combinations recoiling off an η^0. (b) $\pi^+\pi^-\pi^0$ combinations recoiling off a Δ^{++}. The shaded area indicates the events selected as η^0's by the 2C fit.