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Measurement of Neutron-Deuteron Polarization at 35 MeV*

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The neutron polarization asymmetry in neutron-deuteron scattering has been measured from 44.5° to 160° (c.m.) neutron angle. The results display quantitatively the same structure as proton-deuteron polarization data, but discrepancies appear for angles corresponding to those near the minimum of the differential cross section. In this region the polarization is considerably more negative than in the proton-deuteron case, and both are more negative than current theoretical predictions.

A much better understanding of the theory of elastic scattering of nucleons on deuterium has been gained recently, particularly through calculations of polarization phenomena as well as differential cross sections.[1-8] Experimental data exist for proton polarization in a wide range of energies. For neutrons, sparse data exist up to 22.7 MeV. Although proton polarizations are measured in general with higher accuracy, neutron polarizations are more directly computable. The present work contributes polarization data for neutrons on deuterons at higher energy, 35 MeV. For angles near 120°, corresponding to those near the minimum of the differential cross section, we find that the *nd* values of polarization $P(\theta)$ are considerably more negative than those for *pd*. They are also more negative, as are the *pd* values, than current theoretical predictions.

It has been suggested[9,6] that the nucleon-deuteron polarization $P(\theta)$, rather than the cross section, may be a more sensitive testing ground for the structure of the scattering matrix. For example, the shape of $P(\theta)$ versus θ appears to change quite rapidly with energy.[6] However, the calculations with tensor forces are difficult and require a large number of coupled integral equations.

Phenomenological and semiphenomenological calculations[10-12] of $P(\theta)$ up to 40 MeV have been quite successful. Recently, several calculations of $P(\theta)$ starting from the coupled integral equations have been made. Krauss and Kowalski[6] used the unitary first-order-approximation procedure of Sloan[13] and assumed a simple separable Yamaguchi potential which included S-wave singlet and S- and D-wave triplet nucleon-nucleon partial-wave states, but not P waves. Pieper[3] then included S, P, and D waves in the two-potential formalism to calculate $P(\theta)$. Agreement with experiment is very good at low energies, $\lesssim 14$ MeV, and qualitatively good up to 40 MeV. At 14 MeV Doleschall[4] has also performed a calculation including P waves which is in good agreement with the experimental $P(\theta)$ distribution. It seems clear that eventually more exact dynamics and more realistic two-nucleon potentials will be used to produce reliable calculations at higher energy.

We have chosen 35 MeV for the *nd* neutron polarization measurements so as to be able to compare with the *pd* proton polarization measurements at 35 MeV.[14] A preliminary report[15] which contained early data has been given elsewhere.

Our experimental layout is shown schematically in Fig. 1 for the case where a scintillating target, neutron detectors, and a CAMAC data acquisition system were used. The 35-MeV neutron beam, of polarization $P_1 = 0.31 \pm 0.03$,[16] is

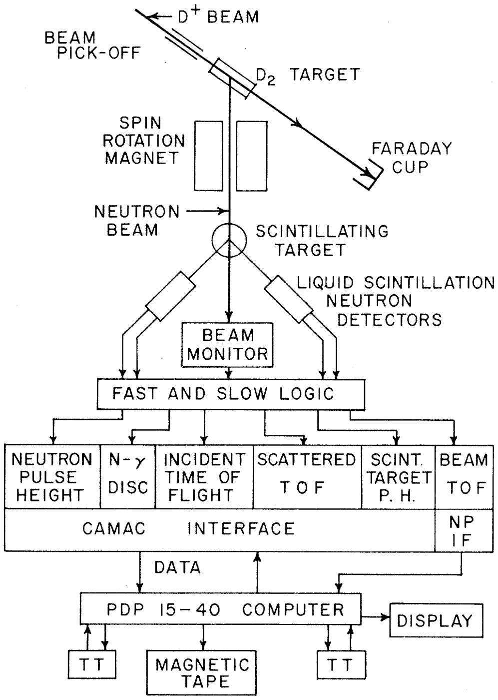

FIG. 1. Experimental setup used for the case of events detected with a scintillating target and neutron detectors. See the text for details.

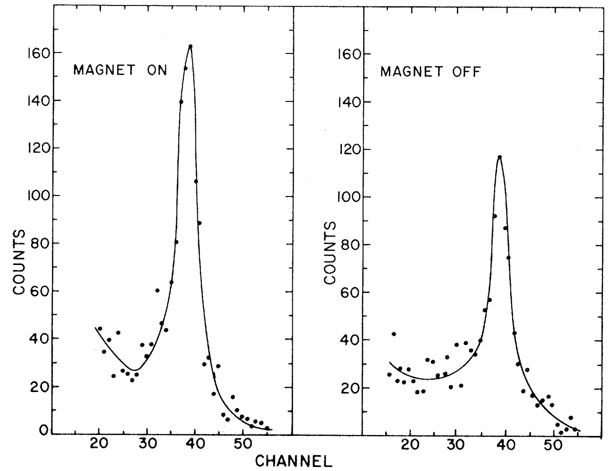

FIG. 2. Recoil-deuteron pulse-height spectra in the scintillating target, after appropriate restrictions on other parameters, for the case of the right neutron detector at 90° (120° c.m.) with the spin-precession magnet on and off.

produced by the reaction $d+d\rightarrow n+{}^3\mathrm{He}$ at 24.0° lab as distinct from the angle of 29.6° used earlier.[17] The horizontal field of the magnet is used to rotate the neutron beam polarization through 180° so that polarization asymmetries can be measured by a given fixed detector.

The scintillating target (ST) contained NE218 liquid scintillator, mainly deuterated heptane $[(C_7D_{16})_n]$. For early ST runs NE102 plastic scintillators were used as neutron detectors, which did not allow pulse-shape (neutron-γ) discrimination. Later, when CAMAC became available, NE213 liquid scintillators were used so that neutron-γ discrimination could be incorporated. This added feature greatly reduced the background present at the two largest angles (104° and 120° c.m.) at which ST data were taken. In addition to the pulse-shape parameter, indicated by "N-γ" in Fig. 1, each CAMAC event was characterized by neutron pulse height, incident time of flight (from the beam pickoff to the ST), scattered-neutron time of flight, and ST pulse height. For the early data taken without CAMAC, only the latter two parameters were recorded, with analog cuts being placed on the incident time of flight to select the high-Q neutrons and on neutron-detector pulse height for detector efficiency determinations.

For the backward c.m. angles, recoil deuterons from a thin (36 mg/cm^2) target of deuterated polyethylene $[(CD_2)_n]$ were detected in two-element (ΔE-E) plastic-scintillator telescopes which allowed identification of the recoil deuterons in the presence of protons. One or two telescopes were placed on each side of the beam. A helium bag was used to reduce background deuterons, particularly those from ^{14}N. The beam monitor was used to allow background runs with a carbon target to be normalized to the corresponding foreground runs with the $(CD_2)_n$ target.

For the ST technique there were true backgrounds due to breakup protons which produced an event continuum under the recoil-deuteron peak. Proton pulse heights due to n-p final-state interactions were calculated to be only 50 to 60% of recoil-deuteron pulse heights at the same neutron angles. So it was assumed that the continuum background underneath the recoil-deuteron peak was smooth and phase space–like. This background, which appeared to have only a small asymmetry, amounted to a correction ranging from 5 to 22%. The remaining backgrounds, which were random, ranged from 5 to 21%. They were in general smaller for the CAMAC data than for the early two-parameter data which were taken without the benefit of n-γ discrimination. Figure 2 shows the ST recoil-deuteron pulse-height spectra in coincidence with the right de-

TABLE I. The *nd* polarization at 35 MeV.

Lab angle (deg)	Particle detected	C.m. angle (deg)	Polarization
30	*n*	44.5	+0.083 ±0.027
45	*n*	65.7	+0.005 ±0.026
60	*n*	85.7	−0.189 ±0.048
75	*n*	103.9	−0.380 ±0.056
90,30	*n*, *d*	120.0	−0.505 ±0.066
25	*d*	130.0	−0.187 ±0.120
20	*d*	140.0	+0.219 ±0.115
15	*d*	150.0	+0.207 ±0.030
10	*d*	160.0	+0.103 ±0.032

tector with magnet on and off for the (worst) case of 90° lab (120° c.m.). These spectra are obtained after cuts on incident time-of-flight n-γ discrimination, and neutron pulse height, and after random subtraction.

For the case of the large c.m. angles where deuterons were detected with ΔE-E telescopes, the true backgrounds ranged from 17% up to 38% at the largest lab angle (≃120° c.m.). Random events in this case were only a few percent of true events.

The experimental results are given in Table I and plotted in Fig. 3. The errors shown do not include the scale error (≃10%) from the uncertainty in the beam polarization. At 104° c.m. both CAMAC and two-parameter data were obtained and the results are essentially in agreement. Smaller-angle results are derived from the two-parameter data. At 120° c.m., both CAMAC ST and recoil-deuteron data were recorded. The results are not in agreement: The former gives 0.67 ± 0.10 and the latter 0.34 ± 0.10 for $P(120^\circ)$, where the uncertainties arise from counting statistics. The final polarizations quoted in the table are unweighted averages.

Consideration of possible systematic errors leads one to favor the clearer CAMAC point at 120° (see Fig. 2). For this angle the recoil-deuteron detection technique is at its limit: Energy resolution of the low-energy deuterons reaching the plastic E detector is poor, and backgrounds are large, ≃38%, and rising steeply towards lower energy. Thus, systematic errors may be appreciably larger than for the corresponding CAMAC datum point.

The difference between the *pd* and *nd* polarizations shown in Fig. 3 appears to be real. Near 23 MeV,[18-22] differences have also been noted over a similar angular range.

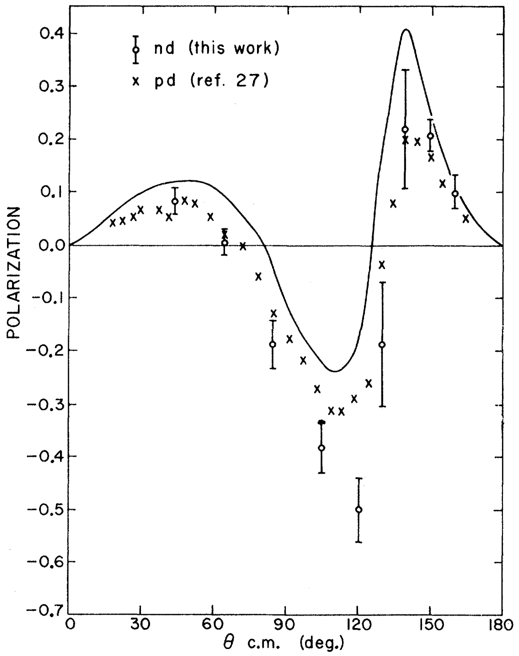

FIG. 3. The *nd* and *pd* polarization data for $P(\theta)$ plotted against c.m. angle θ for 35 MeV incident neutron energy. Solid curve, 40-MeV calculation of Pieper from Ref. 3.

The recent theoretical calculations of $P(\theta)$ at 40 MeV,[3] while having roughly the correct shape and qualitative agreement with experiment, underestimate the magnitude of the *pd* polarization near 120° for that energy (see Fig. 3). Presumably such calculations would make predictions of $P(\theta)$ which would considerably underestimate the present 35-MeV *nd* measurements in that angular range.

The prediction of correct *pd* and *nd* polarizations and the explanation of the apparent *pd*-*nd* polarization differences provide most interesting challenges for future three-nucleon calculations.

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Nuclear Excitation Energy in Muon Capture

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Sum-rule techniques are used to evaluate total μ-capture rates. They turn out to be strongly dependent on the mean nuclear excitation energy, whose behavior along the nuclear table is discussed.

As is well known, total μ-capture rates $\Lambda_{\mu c}$ can be roughly thought of as proportional to $Z_{\mathrm{eff}}^4 = RZ^4$, where Z is the number of protons and R a factor describing the overlap of muon and nuclear wave functions. However, as can be seen in Fig. 1, a plot of $Z_{\mathrm{eff}}^4/\Lambda_{\mu c}$ exhibits a wide variation over the nuclear table. This effect has been attributed by Primakoff[1] to nuclear correlations. Anyway, results obtained by this method are critically dependent on the value assumed for a parameter δ_a, measuring nuclear correlations, which enters the rate in addition to an average neutrino momentum $\langle \nu_a \rangle$. The value of δ_a is obtained by a "best fit," about which individual nuclei may of course fluctuate. Later attempts along this line have failed to improve the situation substantially.[2]

The aim of this work is to show that the general features of the process can be explained by the variation along the nuclear table of the average momentum of the emitted neutrino, on which total capture rates are strongly dependent. The corresponding value of the excitation energy in daughter nuclei is in agreement with the hypoth-