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Measurements of analyzing power for $^{2}H(\vec{n},n)^{2}H$ scattering at 14.1 MeV and comparisons to $^{2}H(\vec{p},p)^{2}H$

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Data for the analyzing power $A_y(\theta)$ for the elastic scattering of neutrons from deuterons have been measured at 14.1 MeV for the range from 30° to 153° (c.m.) to accuracies between ±0.003 and ±0.006. The results are compared to previous n-d data at 14 MeV and are in significant disagreement with the most recent measurement. The present data are in excellent agreement with a Faddeev calculation by Doleschall. The data are also very similar to p-d scattering data at 14.1 MeV, although systematic deviations are observed at forward angles and near the maximum of $A_y(\theta)$ at 130°. Recent calculations indicate that Coulomb effects can explain most of these differences, although some features will require further investigation.

[NUCLEAR REACTIONS $^{2}H(\vec{n},n)^{2}H$, $E=14.1$ MeV; measured $A_y(\theta)$, compared to $^{2}H(\vec{p},p)^{2}H$, compared to Faddeev calculations.]

The nucleon-deuteron system is the simplest case in which subtle effects such as many-body forces or charge-symmetry breaking can be studied. Exact Faddeev calculations can be made for low-energy n-d scattering, but the conclusions obtained so far from the analysis of such data have been limited by the small magnitude of $A_y(\theta)$ and the low accuracy of n-d data. Further, although data of high accuracy exist for p-d scattering, exact calculations cannot be performed for this system because of the Coulomb interaction. Approximate p-d Faddeev-type calculations can be tested by comparing the differences between accurate n-d and p-d measurements to the corresponding differences between the calculated values. These comparisons may eventually provide the first evidence for nuclear charge-symmetry breaking or three-body forces. Because such differences are expected to be small, the data sets must have high accuracies. We have recently reported[1] data for the n-d analyzing power at 10 MeV with the accuracy needed to test the exact n-d Faddeev calculations and the approximate Faddeev-type p-d calculations. The present paper extends such tests to 14 MeV, an energy long favored for both experiments and calculations.

As shown in Fig. 1, the accuracy of the previous n-d $A_y(\theta)$ data[2–4] at 14 MeV is insufficient to provide a stringent test of the theoretical calculations. Here the solid line through the n-d data is a curve obtained by Brock *et al.*[4] by fitting the product $\sigma(\theta)A_y(\theta)$ with associated Legendre polynomials. The dotted line represents a similar fit for the accurate p-d data of Duder *et al.*[5] at 14.1 MeV. The differences between the forward-angle $A_y(\theta)$ data are not surprising; they appear also in $\sigma(\theta)$ comparisons and are almost entirely due to the long-range part of the Coulomb interaction. However, the difference at the maximum of $A_y(\theta)$, which is near the minimum of the differential cross section $\sigma(\theta)$, is much larger than that observed in the $A_y(\theta)$ comparison of p-d data to the more accurate n-d data at 12 MeV reported[6] in 1978 or in our comparison[1] at 10 MeV. This large difference is also inconsistent with recent calculations by Zankel and Hale,[7] who approximately included the Coulomb effects in the p-d calculation.

To test three-nucleon calculations, as well as to definitively resolve the inconsistencies in the differences between the p-d and n-d results, it was necessary to obtain n-d $A_y(\theta)$ data of considerably higher accuracy than any previously measured at 14 MeV. At the Triangle Universities Nuclear Laboratory (TUNL), the intensity of our polarized neutron beam and the techniques described briefly in Ref. 1 permit us to obtain such data. The polarized neutron beam is produced via the polarization transfer reaction $^{2}H(\vec{d},\vec{n})^{3}He$ at 0°. In the present work the neutron beam energy was 14.1 MeV with a total spread of 250 keV. The left-right asymmetry of the neutrons scattered elastically from a small deuterated scintillator is determined by means of two detectors located

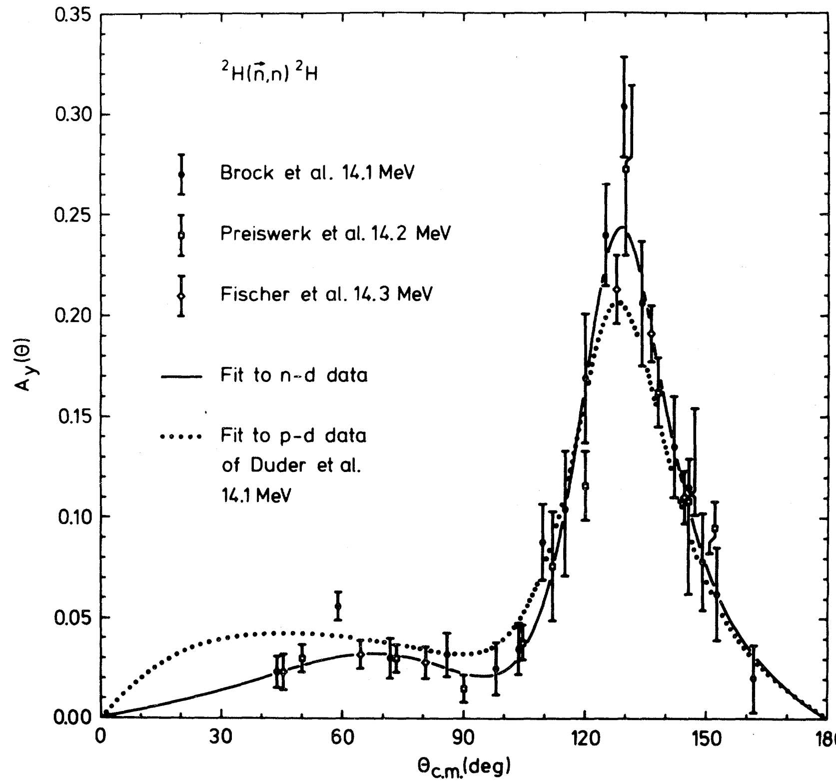

FIG. 1. Neutron-deuteron analyzing power data around 14 MeV as of a year ago and fit to proton-deuteron data.

symmetrically to the left and right of the neutron beam. The statistical uncertainties of our data ranged from ± 0.002 to ± 0.005. The data were corrected for finite geometry and multiple scattering within the deuterated scintillator using Monte Carlo techniques. These corrections are small, so their uncertainties are correspondingly very small. The worst case for multiple scattering effects is near $\theta_{c.m.} = 130°$, where the overall uncertainty for the reported data is ± 0.0065.

Our results are presented in Fig. 2 along with the high-accuracy p-d data of Duder *et al.*[5] at the same energy. The solid curve through the n-d data is based on fitting the product $\sigma(\theta)A_y(\theta)$ with associated Legendre polynomials, using a combined set[8] of measurements for the n-d cross section $\sigma(\theta)$. The dotted curve through the p-d data is the same as that shown in Fig. 1. The uncertainty of our data around 130° is a factor of 3 to 4 smaller than the uncertainty quoted by Fischer *et al.*[3] and Brock *et al.*[4] The data reported by Brock *et al.* and Preiswerk *et al.*[2] are not supported by our measurements, but there is excellent agreement with the data of Fischer *et al.*

In Fig. 3 we compare our present results with a 14.1 MeV Faddeev calculation performed by Doleschall and reported by Duder *et al.*[5] in 1979. This calculation, which used a separable nonlocal nucleon-nucleon T matrix, is in excellent agreement with our data. Such was not the case for our previous report[1] at 10 MeV, where Doleschall used a modified nucleon-nucleon T matrix.[9] A Faddeev calculation by Benayoun *et al.*[10] at 14.1 MeV, which is based on a realistic local nucleon-nucleon potential, underestimates the magnitude of $A_y(\theta)$ near 130°, although the lower values we report here reduce the earlier discrepancy considerably.

As shown by the curves in Fig. 2, the most sensitive regions for testing p-d approximations are at the forward angles and at the maximum of $A_y(\theta)$, around $\theta_{c.m.} = 130°$. Zankel and Hale[7] have calculated approximately the p-d analyzing power at 14.95 MeV, starting from the n-d Faddeev results obtained by Fayard *et al.*[11] According to their results, the difference between the n-d and p-d predictions at forward angles is mainly due to the long-range part of the Coulomb interaction. The difference near 130° is due to the interference between the strong interaction and the Coulomb interaction inside the range of the strong interaction. The size of their calculated difference near 130° is in excellent agreement with that found in the present work and is also consistent with our previous measurements[1,6] at 10 and 12 MeV. However, the calculated p-d curve is shifted slightly to larger scattering angles than that for n-d, an effect which is not observed experimentally. Previously, we

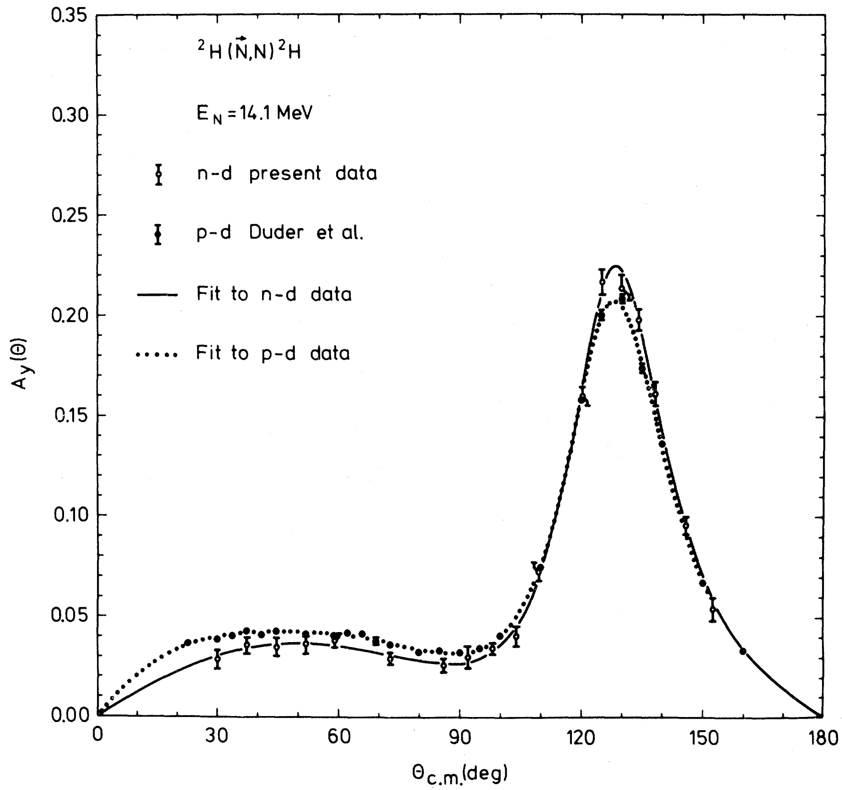

FIG. 2. Present neutron-deuteron analyzing power data compared with proton-deuteron data from Duder *et al.* at 14.1 MeV.

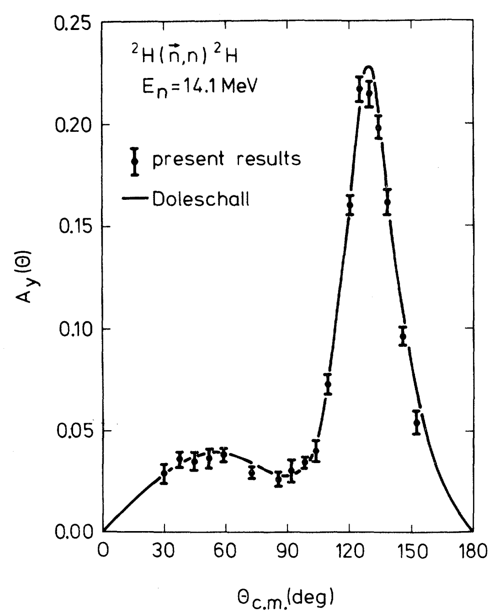

FIG. 3. Neutron-deuteron analyzing power compared to Faddeev calculations performed by Doleschall at 14.1 MeV.

found[1] the same discrepancy at 10 MeV. The differences between the *n-d* and *p-d* predictions result primarily from the inclusion of the asymptotic Coulomb phase shifts in the *p-d* Faddeev-type calculation. The further addition of the short-range Coulomb interference effects changes the magnitude of the calculated $A_y(\theta)$ near 130°, but it causes no change in the angle of the maximum in $A_y(\theta)$. Assuming that the Coulomb effects have been included properly in the calculations, these observations suggest that additional terms need to be added to the nuclear potential.

In summary, our accurate analyzing power data for elastic *n-d* scattering at 14.1 MeV disagree significantly with the recent data of Brock *et al.* Our data support the measurement of Fisher *et al.* at 14.3 MeV and our earlier measurements at 10 and 12 MeV. We are led to the conclusion that the difference between *n-d* and *p-d* analyzing powers in the region of the maximum in $A_y(\theta)$ is much smaller than that indicated by Brock *et al.* The size of this difference as observed in the present work is in good agreement with calculations[7] using a charge-symmetric two-body nuclear interaction. Lastly, the unexplained differences between $A_y(\theta)$ for *n-d* and *p-d* scattering provide a sensitive test of theoretical attempts to include the Coulomb interaction in three-nucleon calculations. Once these calculations can better describe the data for the analyzing powers, similar comparisons can be made for the other observables which have been measured for the *p-d* system. Then, perhaps with even more accurate *n-d* scattering data, the size of the effects due to three-body forces and nuclear charge-symmetry breaking can be determined.

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