NEW PHYSICS IN *p-d* ELASTIC SCATTERING AT LOW ENERGIES*

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We have performed a number of high precision measurements of cross sections and polarisation observables in p-d scattering from $E_p = 245$ keV to the breakup threshold. We observed very good agreement between experiment and calculations for the cross sections and tensor analysing powers while a discrepancy for vector analysing power persists and increases with decreasing beam energy. We demonstrated that current three nucleon forces cannot account for this puzzling observation and suggest that the origin of the discrepancy is either due to the inadequacies of NN potential models or, more likely, to the existence of a new type of three body force. We also confirmed for the first time the existence of a theoretically predicted pole in the doublet S-wave effective range function.

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1. Introduction

The study of the three nucleon system at low energies provides a stringent test of our understanding of nuclear dynamics, the nucleon-nucleon (NN) and three-nucleon ($3N$) interactions. A comparison of cross sections

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and polarisation observables with state-of-the-art calculations allows us to test the theoretical p-d scattering wave functions and provides insight into underlying NN potentials.

In recent years there have been a number of measurements and calculations of nucleon-deuteron (N-d) scattering below the break-up threshold. The data for p-d scattering until recently could not be meaningfully compared with calculations because of difficulties in treating the Coulomb interaction in the framework of Faddeev equations. Only with the development of hyper-spherical harmonic method by the Pisa group [1] are such comparisons possible. Good agreement between the data and calculations using modern NN potentials was observed for cross section and tensor analysing powers [2], but significant differences were found in the vector analysing power A_y for N-d scattering and iT_{11} for d-p scattering [3].

In this work we present further experimental data at very low energies and discuss possible explanations for this discrepancy known as the "A_y puzzle" [3,4]. We also discuss the experimental confirmation of the existence of a pole in the doublet S-wave effective range function for p-d scattering resulting from the recent phase-shift analysis of low energy data [5].

2. Experiments

The measurements described here were carried out at the Triangle Universities Nuclear Laboratory. The polarised and unpolarised proton and deuteron beams were produced by an atomic beam polarised ion source [6] and accelerated using one of two different systems depending on the beam energy. For beam energies below 680 keV, we used the low-energy beam facility consisting of a mini-tandem accelerator [7] in combination with the 107-cm diameter high-voltage scattering chamber [8]. The energy calibration of the accelerator system has been established to $\pm$ 1 keV using resonances in ^{19}F$(p,\alpha\gamma)$ and ^{27}Al(p,γ) reactions. The experiments at beam energies above 680 keV were performed using an FN tandem accelerator and a 62-cm diameter scattering chamber.

The use of thin targets is very important in low-energy experiments for minimising energy loss and straggling effects. The targets were hydrogenated or deuterated diamond-like carbon foils fabricated by a plasma-assisted chemical vapour deposition technique [9]. The targets consisted of approximately 0.3 to 1.0×10^{18} and 0.6 to 2.0×10^{18} hydrogen or deuterium and carbon atoms/cm^2, respectively, with thinner targets used at lower energies. Energy losses in these targets were below 5 keV.

Since the analysing powers of interest are very small (of the order of 10^{-2} to 10^{-3}) special care is required to reduce the systematic errors in the measurements. The beam polarisation was determined using three different polarimeters located behind either scattering chamber. The $^3\mathrm{He}(\vec{d},p)^4\mathrm{He}$ reaction was used on-line for deuteron tensor polarimetry [10] due to its large cross section and large and well known tensor analysing powers. The data were taken using three spin states with tensor polarisations of $p_{ZZ} \approx \pm 0.7$ and $p_Z = 0$. Proton polarisation was determined with a polarimeter using the $^6\mathrm{Li}(\vec{p},{}^3\mathrm{He})^4\mathrm{He}$ reaction [11], which has a superior figure of merit for proton energies from 200 to 800 keV. Two spin states were used with polarisations of $p_Z \approx \pm 0.7$. In iT_{11} measurements, the vector polarisation of the deuteron beam was determined on-line via the $^{12}\mathrm{C}(\vec{d},p)$ reaction [12] with measured vector polarisation of $p_Z \approx \pm 0.55$.

The spin states were cycled at the source approximately once every second in order to minimise the effects of slow changes in the beam position, target thickness or amplifier gain. Tests for false asymmetries were carried out by measuring $^{197}\mathrm{Au}(\vec{d},d)$ scattering at $\theta_{\mathrm{lab}} = 40°$ under identical conditions as the *p-d* measurements. For example, for $E_d = 1.3$ MeV all of the analysing powers for $^{197}\mathrm{Au}(\vec{d},d)$ are expected to be $< 10^{-4}$. The results of these tests were consistent with zero on the level of 5×10^{-4}, the statistical uncertainty of the measurement.

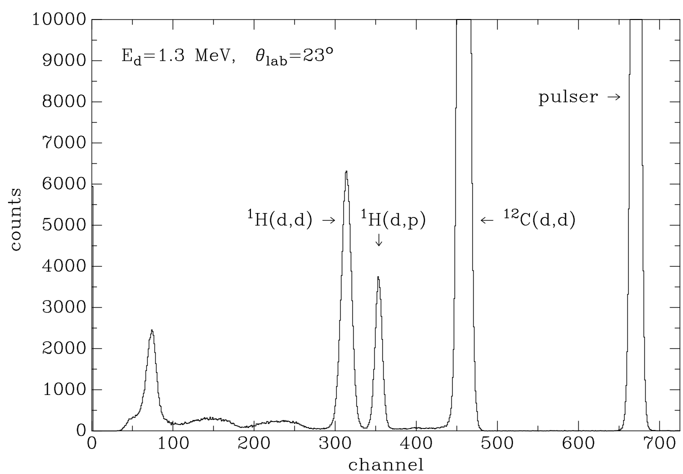

Fig. 1. Typical spectrum of $^1\mathrm{H}(\vec{d},d)$ scattering at $E_{\mathrm{c.m.}} = 432$ keV.

Scattered deuterons and protons were detected with two sets of three silicon surface barrier detectors located between 15 and 25 cm from the target and placed symmetrically on each side of the beam. A typical spectrum is shown in Fig 1. At certain angles thin mylar foils were placed in front of the detectors to stop heavy nuclei recoiling from the target or to separate the deuterons from $^1\mathrm{H}(\vec{d},d)$ scattering from protons produced in the $^{12}\mathrm{C}(\vec{d},p_1)$ reaction. Dead time corrections, which were kept below 5%, were

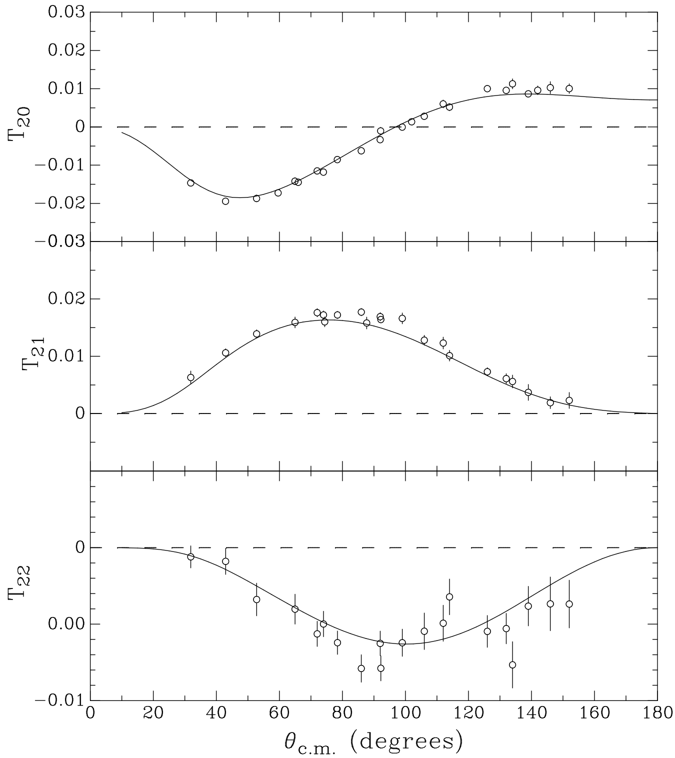

Fig. 2. Tensor analysing powers for ${}^1\mathrm{H}(\vec{d},d)$ scattering at $E_{\mathrm{c.m.}} = 432$ keV. The solid line is a theoretical prediction using the AV18+UR force model.

determined by sending pulses to the detector preamplifiers. The analysing powers were determined from the counts in the observed peaks after correction for background and dead time. The angular distributions of three tensor analysing powers obtained at $E_d = 1.3$ MeV ($E_{\mathrm{cm}} = 432$ keV) are shown in Fig 2.

For the measurements of vector analysing powers scattered protons and deuterons were detected in coincidence using two pairs of symmetric detectors located on either side of the incident beam. The detector angles were set to observe either particle in the more forward detector in coincidence with the corresponding particle in the more backward detector on the opposite side of the beam. The time resolution of the coincident peak was about 10 ns. It should be noted that the coincident technique is essential for measuring small analysing powers since it allows elimination of carbon-induced events and allows p-d events to be counted at the high rate necessary to obtain adequate statistics.

3. Discussion of results

The experimental results are compared to the calculations utilising the Pair-Correlated Hyperspherical Harmonic (PHH) basis [1] to construct scattering wave functions and the Kohn variational principle to determine the scattering matrix elements. The calculations have been done using the Argonne AV18 potential [13] with and without the $3N$ interaction of Urbana (UR) [14] and scattering waves with orbital angular momentum up to $L = 4$ have been taken into consideration.

We find that calculations utilising realistic NN potentials are in excellent agreement for cross sections (not shown) and tensor analysing powers T_{20}, T_{21} and T_{22}, at $E_{\rm cm} = 432$ keV as seen in Fig 1; however they under predict A_y and iT_{11} by as much as 40% at the lowest energies. The measured energy dependence of iT_{11} at $\theta_{\rm cm} = 89°$ is shown in Fig 3. This discrepancy dubbed the "A_y puzzle" has been observed previously in n-d scattering at energies of a few MeV and it decreases with increasing energy and vanishes at about 30 MeV. It is by far the largest discrepancy observed between the 'exact' calculations and the experimental data and remains one of the most interesting and puzzling problems of few-body physics.

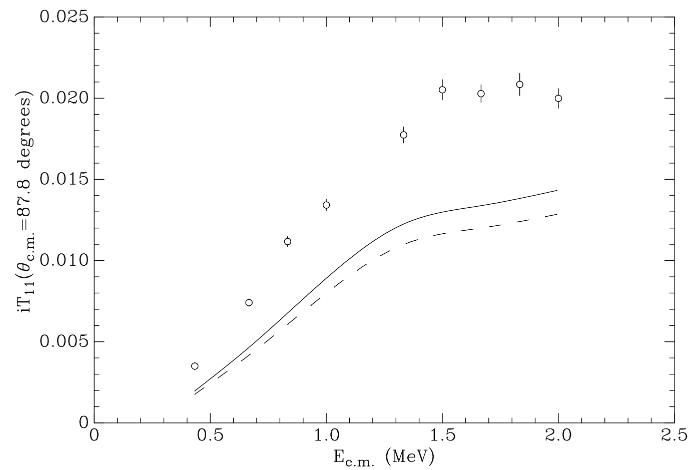

Fig. 3. Energy dependence of vector analysing powers. The solid (dashed) line is a theoretical prediction using the AV18 force model with (without) UR 3NF interaction.

Ref. [15] summarises extensive efforts to improve the agreement with the N-d data by modifying the underlying NN potentials. The values of N-d ^4P_J phase shifts which play the major role in obtaining the correct A_y values are closely correlated with respective ^3P_J phase shifts in NN scattering. Sensitivity studies demonstrated that A_y in N-d scattering is determined by a complicated interplay between the ^3P_J NN interactions. The interest in the investigation of P-wave NN interactions stems from the fact that A_y in N-d scattering is about an order of magnitude larger than in NN scattering at the same energy. It is therefore much easier to study the sensitivity to the P-wave NN interaction in N-d rather than NN scattering. A serious problem arises here because to obtain agreement with the N-d data requires an NN interaction which generates phase shifts which are in disagreement with NN phase shifts obtained from global analyses and modern NN potential models. Authors of Ref. [15] concluded that the low energy ^3P_J phase shifts are questionable and present NN potential models may have built in incorrect P-wave interactions.

In work described in detail in Ref. [3] we investigated the role of another likely cause of the A_y discrepancy, namely the $3N$ interactions. We found that the effect of including modern Urbana $3N$ potential has a very small effect on A_y and iT_{11}. The calculations shown in Fig 3 use the AV18 potential (dashed line) and AV18+UR potential (solid line). Although there is slight improvement when $3NF$ is taken into account, the large discrepancy remains. The reason is that the presently available $3N$ forces, including in addition to the Urbana potential also Brazil [17] and Tucson-Melbourne [18] models are based on two-pion exchange and their strengths are adjusted to reproduce the $3N$ binding energies. For these forces to influence significantly low-energy p-d scattering requires the three nucleons to be close together. In our energy regime the probability of finding three nucleons in close proximity is very small and is further reduced by Coulomb and centrifugal barriers. Inclusion of other processes involving heavier mesons such as π-ρ or ρ-ρ exchanges and occurring at yet shorter ranges is expected to give still smaller corrections. These results lead us to the conclusion that a new type of long-range $3N$ force, perhaps including a spin-orbit interaction may be needed to explain the A_y puzzle.

Encouraged by the abundance of new high quality p-d scattering data at low energies, we have performed (see Ref. [5]) an energy-dependent phase-shift analysis of p-d elastic scattering below the deuteron break-up threshold. We considered more than 1000 data points between $E_{\rm c.m.} = 0.163$ and 2.0 MeV including our own measurements of cross sections at $E_p = 245$ and 316 keV, which are not discussed here. Our motivation was to investigate the apparent discrepancy between theoretical and phenomenological determinations of the proton-deuteron S-wave scattering lengths. Since the spin doublet S-wave channel dominates the ^{3}He ground state, one may expect that the binding energy of ^{3}He and the ^{2}S$_{1/2}$ scattering length calculated with a given potential are strongly correlated and indeed such a correlation exists in the form of so-called 'Phillips lines'. Calculations yield the doublet scattering length $^2a_0$ very near zero while various phenomenological fits have given values varying from 1.3 to 4.0 fm (see Huttel *et al.* Ref. [19] and Ref. [5] for a summary of the previous experimental data and calculations). It was suggested that this discrepancy may be the result of a singularity in the doublet S-wave effective range function near the two-body threshold, analogous to that observed for n-d scattering [16].

One of the conclusions of our analysis, resulting mainly from our recent high-precision measurements of cross sections at low energies [9], confirms for the first time the existence of a theoretically predicted [16] pole in the $^2S_{1/2}$ effective range function. We parameterise the $^2S_{1/2}$ effective range function in the form

$$^2K_0(k^2) = [(-1/^2a_0) + r_0k^2 + P_0k^4]/[1-(k/k_0)^2]. \tag{3.1}$$

A fit to the global data set yields a doublet scattering length of $^2a_0 = 0.09 \pm 0.17$ fm and the location of the pole is at ${k_0}^2 = 0.004 \pm 0.004$ fm^{-2}. These results are in very good agreement with theoretical predictions based on calculations using the AV18 potential and is the first experimental observation of this singularity in p-d elastic scattering.

4. Conclusions

In summary, we have performed a number of high precision measurements of cross sections and polarisation observables in p-d scattering from $E_p = 245$ keV to the breakup threshold. Using this data set we confirmed for the first time the existence of a theoretically predicted pole in the doublet S-wave effective range function. We observed very good agreement between experiment and the calculations for tensor analysing powers while a discrepancy for A_y persists and increases with decreasing beam energy. We demonstrated that current three nucleon forces can not account for this puzzling observation. One may therefore conclude that the origin of the discrepancy is either due to the inadequacies of NN potentials or more likely to the existence of a new type of three body force.

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REFERENCES

[1] A. Kievsky, M. Viviani, S. Rosati, *Nucl. Phys.* **A577**, 511 (1994).

[2] A. Kievsky, S. Rosati, W. Tornow, M. Viviani, *Nucl. Phys.* **A607**, 402 (1996).

[3] A. Kievsky, M. Viviani, S. Rosati, C.R. Brune, H.J. Karwowski, E.J. Ludwig, M.H. Wood , *Phys. Lett.* **B406**, 292 (1997).

[4] C.R. Brune, W.H. Geist, H.J. Karwowski, E.J. Ludwig, K.D. Veal, M.H. Wood, A. Kievsky, M. Viviani, S. Rosati, *Phys. Lett.* **B** in press.

[5] T.C. Black, H.J. Karwowski, E.J. Ludwig, A. Kievsky, S. Rosati, M. Viviani, submitted to *Phys. Rev. Lett.*

[6] T.B. Clegg *et al.*, *Nucl. Instr. Meth. Sect.* **A357**, 200 (1995).

[7] T.C. Black, B.E. Hendrix, E.R. Crosson, K.A. Fletcher, H.J. Karwowski, E.J. Ludwig, *Nucl. Instr. Meth. Sect.* **A333**, 239 (1993).

[8] E.J. Ludwig, T.C. Black, C.R. Brune, W.H. Geist, H.J. Karwowski, *Nucl. Instr. Meth. Sect.* **A388**, 37 (1997).

[9] T.C. Black, Ph.D. thesis, University of North Carolina 1994 (unpublished).

[10] S.A. Tonsfeldt *et al.*, in Polarization Phenomena in Nuclear Physics, (Santa Fe, NM 1980), AIP New York 1980.

[11] C.R. Brune, H.J. Karwowski, E.J. Ludwig, *Nucl. Instr. Meth. Sect.* **A389**, 421 (1997).

[12] M.H. Wood *et al.*, TUNL Annual Report **XXXVI**, 125 (1997).

[13] R.B. Wiringa, V.G. Stoks, R. Schiavilla, *Phys. Rev.* **C51**, 38 (1995).

[14] R.B. Wiringa, private communication.

[15] W. Tornow, H. Witala, A. Kievsky, *Phys. Rev.* **C57**, 555 (1998).

[16] C.R. Chen, G.L. Payne, J.L. Friar, B.F. Gibson, *Phys. Rev.* **C44**, 50 (1991).

[17] H.T. Coelho, T.K. Das, M.R. Robilotta, *Phys. Rev.* **C28**, 1812 (1983).

[18] S.A. Coon, W. Gloeckle, *Phys. Rev.* **C23**, 1790 (1981).

[19] E.F. Huttel, W. Arnold, H. Baumgart, H. Berg, G. Clausnitzer, *Nucl. Phys.* **A406**, 435 (1983).