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Polarized Proton Scattering from Polarized ^{3}He

T. V. Daniels[*]
The University of Massachusetts Amherst
E-mail: tvdaniels@physics.umass.edu

Spin-correlation coefficients for p+^{3}He elastic scattering have been measured between 2 and 6 MeV in the TUNL tandem laboratory using a combination of polarized proton beam and a spin-exchange optical pumping polarized ^{3}He target. These data, along with cross-section and beam analyzing power measurements also made at TUNL, were included in a global phase-shift analysis of the sizable dataset of p+^{3}He elastic scattering below 12 MeV. The resulting phase shifts and observables are compared to theoretical calculations using realistic NN potential models, including models derived from chiral perturbation theory.

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[*] Speaker.

1. Introduction

Ab initio calculations of light nuclear systems are based on realistic nucleon-nucleon potential models which have been adjusted to reproduce two-nucleon (NN) scattering and bound-state data accurately [1]. The comparison of such calculations with nucleon-deuteron scattering measurements reveals general agreement for the cross-section and tensor analyzing powers, but significant underprediction of the beam and target analyzing powers [2]. A similar "A$_y$ Puzzle" has been reported for p+^{3}He elastic scattering [3]. All NN models and theoretical methods yield this disagreement, which is not resolved by including the 3N force necessary to reproduce the 3N and 4N binding energies [4].

A wealth of experimental data exists for p+^{3}He elastic scattering below 12 MeV proton energy, with the most recent phase-shift analysis by George and Knutson [5] performed on a database of over 1000 data points. That analysis, however, was unable to constrain a unique set of parameters, and instead obtained two solutions which fit the data equally well. The difference between the two solutions was largest for spin-correlation coefficients below 4 MeV, where no such data exist. With the aim of resolving the phase-shift ambiguity, a polarized ^{3}He target [6] has been used to measure angular distributions of the spin-correlation coefficients A$_{xx}$ and A$_{yy}$ and the target analyzing power A$_{0y}$ at proton energies between 2 and 6 MeV [7]. Those new data, along with those of Fisher *et al.* [3], have been included in a new global phase-shift analysis following that of George and Knutson.

2. Experiment

2.1 Polarized Target

The polarized ^{3}He target was specifically designed for low-energy charged-particle scattering experiments and has been described previously in detail [6]. In contrast to previous targets used for the same purpose [8]-[13] which operated by metastability-exchange optical pumping (MEOP) at a few millibar ^{3}He pressure, the present target used spin-exchange optical pumping (SEOP) with Rb or a mixture of Rb and K. This method has previously been used in polarized ^{3}He targets for electron [14] and gamma-ray [15] scattering experiments, and was selected for this project to take advantage of the greater target thickness made possible by the 8 bar ^{3}He pressure.

The use of thin windows to minimize energy loss of the low-energy charged particle incident and scattered beam in the scattering cell limited the pressure in that region to about 1 bar. Therefore, the optical pumping, driven by a 60W fiber-coupled diode laser system tuned to the 795nm Rb D1 absorption line, took place in a system external to the scattering chamber and polarized ^{3}He was batch-filled into the scattering cell. The scattering cell was a 5.1 cm Pyrex sphere with Kapton-covered openings along the equator for the incident and scattered particles, and was housed in a compact sine-theta coil to provide a uniform 0.7 mT magnetic holding field. An NMR coil pressed against the rear of the cell was used to measure the target polarization, as discussed below.

2.2 Scattering Measurements

Measurements were made at five proton energies below 6 MeV which overlap the energies of both Fisher *et al.* [3] and Alley and Knutson [13]. Polarized and unpolarized beams from the

Triangle Universities Nuclear Laboratory (TUNL) tandem accelerator were directed by an analyzing magnet to a 62 cm diameter scattering chamber. Beam energies were adjusted to offset energy loss in the foils and gas, as modeled with TRIM [17]. The beam and target polarizations were reversed frequently during data-taking. The beam polarization was reversed at either 1 or 10 Hz in the sequence “udduduud”, where “u” means “spin-up" and “d” means “spin-down”. The target polarization was reversed less frequently, since a few seconds were required to reverse the target’s magnetic field. Polarized target data were collected for intervals of 2.5 m in each spin orientation, with NMR measurements of the magnitude of the polarization made immediately before and after the orientation was reversed. The target polarization decayed with a 2-3 h time constant, so this process was stopped when the gas was judged to be too depolarized, generally after about 1 h.

Scattered particles emerging from the target were detected by four pairs of Si detectors which could be rotated to the desired angle. Available angles were restricted by the windows in the sine-theta coil’s mu-metal shield to 20° increments between 30 and 150°. The shield could be moved axially so that “intermediate” angles offset by 10° were also available. The detectors were collimated to restrict the range of visible scattering angles to be 1.5°. Beam current on target was measured by a electrostatically suppressed Faraday cup located about 0.5 m behind the target cell. The observables were extracted from peak yields in left and right detectors using an extension of the geometrical mean method [18] for analyzing powers to include polarized beam and target. An instrumental asymmetry stemming from small-angle steering of the beam and scattered particles by the target magnetic holding field was measured with unpolarized beam and target and subtracted from the polarized target asymmetries used to measure A_{0y}.

2.3 Beam Polarimetry

Proton beam leaving an atomic beam polarized ion source [19] passed through a calibrated Wien filter at the ion source to orient the spin quantization axis of the beam in the desired direction at the scattering chambers. The magnitude of the beam polarization was measured periodically using p+^{4}He elastic scattering in either the target cell or in a separate cell in a polarimeter chamber installed upstream of the target chamber. Published phase shifts [20] were used to calculate the analyzing powers for the energies at the center of the cell.

For more than half of the spin-correlation data, however, the beam polarization was unstable, so that periodic monitoring did not necessarily determine the average polarization. Therefore, the beam polarization for all A_{yy} measurements was determined by normalizing our relative A_{y0} measurements to published values [16, 13]. The procedure was extended to about one-third of the A_{xx} measurements by “tipping” the spin 20° out of the plane with the Wien filter and applying the above analysis to the y-component. The remaining A_{xx} measurements with stable beam polarization relied on polarimeter measurements as described above.

2.4 Target Polarimetry

As discussed in detail by Katabuchi *et al.* [6], the target polarization was monitored using pulsed NMR. These relative NMR data for each target cell were calibrated against separate ^{4}He + ^{3}He A_y measurements. This calibration method was motivated by the prediction of Plattner and Bacher [21] of an A_y = -1 extremum near 15.33 MeV ^{3}He lab energy and 47° ^{3}He lab scattering

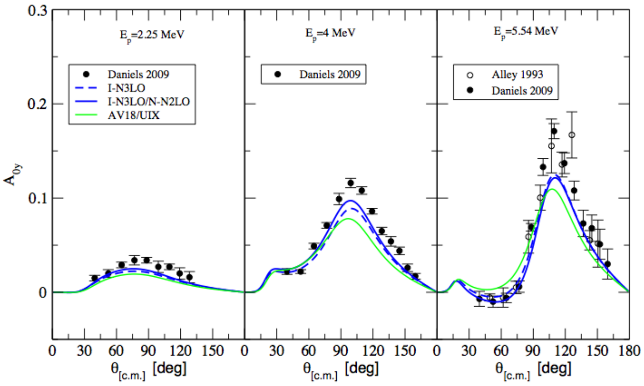

Figure 1: Measurements (Daniels *et al.* [7] and Alley and Knutson [13]) of A_{0y} at three proton beam energies, compared with theoretical calculations [27] using different NN and 3N potential models as described in the text. Plots taken from Ref. [27].

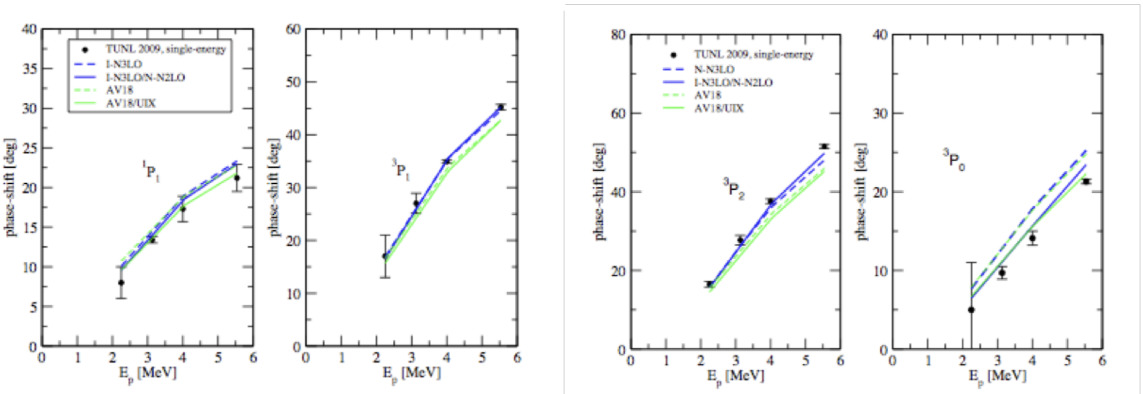

Figure 2: Single-energy experimental P-wave phase-shifts from the global analysis [7] compared with theoretical calculations [27] using different NN and 3N potential models as described in the text. Plots taken from Ref. [27].

angle. Their prediction for its location was only approximate, so *relative* measurements of A_y in ^{4}He+^{3}He elastic scattering as a function of angle and energy near the predicted extremum were made to define the local minimum used for calibration.

3. Phase-Shift Analysis

A phase-shift analysis of the global p+^{3}He elastic scattering database below E_p= 12 MeV was performed following the earlier work of George and Knutson [5], with the addition of about 300 new data points, including the $\frac{d\sigma}{d\Omega}$ and A_{y0} measurements of Fisher *et al.* [3] and the present A_{0y}, A_{yy}, and A_{xx} measurements. These additional data all fell between 1.0 and 5.54 MeV. The search routine was the same as that used in the previous analysis and was provided by George [22].

The program calculated scattering observables as functions of scattering matrix elements, which were in turn parameterized using phase-shifts and mixing parameters according to the Blatt-

Biedenharn convention [23]. The phase-shifts and mixing parameters used were $^1S_0$, $^3S_1$, $^1P_0$, $^3P_2$, $^3P_1$, $^3P_0$, $^1D_2$, $\varepsilon(1^-)$, $\varepsilon(1^+)$, and $\varepsilon(2^-)$, as well as consolidated ^3D_j and ^3F_j triplet phase-shifts. The energy dependence of the phase-shifts and mixing parameters was described by the first three terms in a modified effective-range expansion. These 36 effective range parameters were adjusted to minimize χ^2 with respect to the experimental database using the MINUIT package [24]. As described in Ref. [5], the database was broken into groups of measurements thought to have common normalizations. These 21 normalization factors were analytically adjusted at each step of the parameter search to further minimize χ^2.

The addition of the new data removes the S-wave ambiguity in the previous results [5] without qualitatively modifying the behavior of the other parameters, such as the resonant P-wave behavior associated with excited states of ^{4}Li. The new, low energy data also seem to introduce some tension with previous, higher energy data, as indicated by differences between the present global results and those of Ref. [25] for $^1S_0$ and $^3P_0$.

The global solution had a χ^2-per-datum of about 2 for the data added in this analysis. This could be improved to between 1.3 and 1.5 if points whose individual χ^2 contributions exceeded 10 were rejected. About half of these 13 out of about 300 new points seemed simply to be random outliers, while the others seemed to be associated with systematic problems, including some forward angle A_{0y} points which had been corrected for magnetic steering. In order to gauge the effects of systematic errors, single-energy analyses were performed at energies where new spin-correlation and new or existing cross-section measurements were available. The same method was used for these single-energy fits as for the energy-dependent work, except that the phase-shifts were searched directly, instead of through the effective range parameters.

4. Comparison with Theoretical Calculations

Viviani *et al.* [27] compare these experimental scattering observables and phase shifts with theoretical calculations using the the hyperspherical harmonic technique for several NN + 3N potentials. Examples of the comparsion for A_{0y} and the P-wave phase shifts are shown in Fig. 1 and Fig. 2. The combination of the phenomenological AV18 (NN) and URIX (3N) potentials reproduces most scattering observables, but significantly underpredicts A_{y0} and A_{0y}, which is reflected in the small deviations from the experimental $^3P_2$ and $^3P_1$ phase shifts. The use of 2N [26] and 3N [28] interaction derived from chiral perturbation theory at N3LO and N2LO respectively significantly improves the comparison for those observables and the corresponding phase shifts.

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