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SCATTERING OF PROTONS AND PIONS

FROM POLARIZED ^3He

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INTRODUCTION

The subject of this paper involves, directly or implicitly, spin-spin interactions at the atomic, nuclear, and subnuclear levels. The production of polarized ^3He targets by the optical pumping spin exchange method (see Chupp *et al.*¹) proceeds first by absorption of a circularly polarized photon by an alkali atom (Rubidium). A constant flux of photons from a laser is required to compensate for alkali spin destruction, either in alkali-alkali collisions or, as will be shown below, in three-body collisions leading to the formation of alkali- ^3He molecules. The collisional transfer of alkali polarization to ^3He involves the Fermi contact hyperfine interaction between the angular momentum of the alkali atom and the ^3He nuclear spin.

At the nucleonic level the main component of the ^3He wave function² consists of a spatially symmetric S state, with the two protons in a spin singlet state, and with the neutron carrying the ^3He spin. However, the spin-dependent nucleon-nucleon interaction introduces small components into the ^3He wave function which can be calculated by the Faddeev method. The results depend on whether, in addition to two-body forces between nucleon pairs, three-body forces, or meson degrees of freedom and nucleon substructure, or relativistic effects are included in the calculations. Consistency tests of the A=3 wave function are provided by experimental binding energies, charge radii, magnetic moments, electric and magnetic form factors. The ^3He wave function has recently been investigated in a novel way by nucleon knockout reactions from polarized ^3He (see Rahav *et al.*³). A comparison of target-related spin observables in a nucleon knockout experiment with those for NN scattering can provide information on spin-momentum correlations of nucleons in the polarized target nucleus. The power of the method depends critically on the importance of rescattering corrections which are difficult to calculate.

The question to what extent polarized ^3He is equivalent to a polarized neutron is of interest for investigations of the subnucleonic structure of the neutron. Quasielastic scattering of longitudinally polarized electrons from polarized ^3He is sensitive to interference terms between longitudinal and transverse scattering (see Blankleider and Woloshyn⁴) and shows promise^{5,6} for measurements of the electric form factor of the neutron at large momentum transfers. The non-vanishing electric form factor and an expected^{7,8} non-zero quark contribution to the neutron spin are manifestations of quark spin-spin interactions which arise in a QCD description of nucleon structure.

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In the following sections we report progress made recently at TRIUMF to improve the density and volume of polarized ^3He targets. Quantitative estimates of the laser power required for Rb optical pumping at various Rb densities, ^3He pressures and target cell geometries will be given. First nuclear physics results obtained with the TRIUMF target will then be presented. Spin observables in proton-induced nucleon knockout reactions are shown to be sensitive probes of the nucleonic spin structure of ^3He . Experimental results on spin observables and asymmetries in elastic scattering of protons and pions from polarized ^3He determine previously unexplored spin-dependent amplitudes.

THE TRIUMF POLARIZED ^3He TARGET

The polarized ^3He target setup used in the experiments is shown schematically in Fig. 1. A full description of the technical details can be found in a recent paper by Larson *et al.*⁹ We discuss here some of the new features which differ from earlier work¹. The $5S_{1/2} \rightarrow 5P_{1/2}$ D1 transition in Rb is optically pumped by circularly polarized photons from a frequency tuneable Ti:Sapphire laser pumped by all visible lines from an Argon ion laser. With two such systems 8-9 Watts of power at 795 nm is obtained. The expanded, parallel light beam illuminates the target from below. The target glass cell is inside an oven to select the desired Rb density (typically $4 \times 10^{14} \text{ cm}^{-3}$ at 453 K). The target cell contains about 120 Torr of N_2 for collisional quenching of fluorescent Rb light, and ^3He . A cryogenic setup using cold helium gas has allowed us to produce cells at relative ^3He densities p from 3 to 12 ($p = 1$ corresponds to 760 Torr at 273 K).

Transmission measurements with continuous, linearly (σ_z) or circularly polarized (σ_x) light of wavelengths between 790-800 nm were carried out⁹ to determine the laser power required for optical pumping of a certain Rb density, [Rb]. The Rb D1 lineshapes are strongly asymmetric and exhibit shifts and broadening approximately linear in the ^3He pressure. In contrast to σ_z light which has a typical range of $82 \text{ p} \mu\text{m}$ at $[\text{Rb}] = 4 \times 10^{14} \text{ cm}^{-3}$, σ_x light has a much longer range in polarized Rb since it can only be absorbed by the depleted

Fig. 1. Schematic layout of the polarized ^3He target system used at TRIUMF.

magnetic substate. The transmission scans with circularly polarized light determine the spin destruction rate per Rb atom, Γ_{SD} , and an approximately 40 μm thick unpolarized Rb layer at the glass boundary.

The strong increase of Γ_{SD} versus ${}^3\text{He}$ pressure (see Fig. 2) was unexpected and implies that Rb spin is lost not only by Rb-Rb collisions (constant contribution to Γ_{SD}) but also in 3-body collisions of Rb and two ${}^3\text{He}$ atoms (quadratic contribution). The 3-body collisions may lead to the formation of Rb- ${}^3\text{He}$ molecules, with the third partner required to carry away the molecular binding energy. It is our conjecture that Rb spin is lost by the spin-rotation interaction between the Rb atomic spin and the rotational angular momentum of the molecule. The molecules are expected to have a short lifetime because of the high binary collision rate ($\approx 2 \times 10^{10}$ Hz), however a sizeable spin rotation angle may still accumulate stochastically between absorption of subsequent photons. The strong increase of Γ_{SD} versus p makes it unfavorable to optically pump Rb at high ${}^3\text{He}$ pressures. The lower limit for the laser power required on resonance to obtain 96% Rb polarization, at $[\text{Rb}] = 4 \times 10^{14} \text{ cm}^{-3}$, and for various cell geometries and ${}^3\text{He}$ pressures, is shown in Fig. 3.

Fig. 2. Dependence of the Rb spin destruction rate on the ${}^3\text{He}$ pressure. The solid curve represents a fit to the total measured spin destruction rate, the dotted line is the assumed constant Rb-Rb contribution, the dashed line is the spin destruction calculated for Rb- ${}^3\text{He}$ spin exchange.

Fig. 3. Calculations of the laser power required to obtain 96% average Rb polarization in cells of various thicknesses. The curves represent an empirical fit.

The rate of Rb- ${}^3\text{He}$ spin exchange was determined from the decay of ${}^3\text{He}$ polarization at various Rb densities following laser irradiation for at least 12 hours. At $[\text{Rb}] = 4 \times 10^{14} \text{ cm}^{-3}$ we find a rate of $(10.6 \text{ hr})^{-1}$ independent of ${}^3\text{He}$ pressure. This corresponds to a velocity-averaged spin-exchange cross section, $\langle \sigma_{SEV} \rangle = (6.1 \pm 0.2) \times 10^{-20} \text{ cm}^2 \text{ s}^{-1}$.

Two different target sizes have been used. For achromatic proton beams typical cell volumes are 17 cm^3 , the inner cell diameter of 1.7 cm is sufficient to avoid beam interactions with the side walls. For pion-induced reactions cell diameters are as large as 2.5 cm (35 cm^3 volume) although this does not prevent a small fraction of the pion beam from striking the cell walls. During proton experiments tracking wire chambers are used to separate events from the gas volume from those originating in the $\approx 1 \text{ mm}$ thick glass end windows. For pion experiments full vertex reconstruction is necessary using tracking wire chambers for both incoming beam and scattered particles.

DETERMINATIONS OF THE ${}^3\text{He}$ TARGET POLARIZATION

The bulk ${}^3\text{He}$ polarization is analysed and reversed using the nuclear magnetic resonance (NMR) technique of adiabatic fast passage (AFP) at a frequency of 100 kHz. Our NMR setup is similar to the one described by Chupp *et al.*¹ Absolute normalization factors were obtained by comparing the ${}^3\text{He}$ AFP NMR signals with proton AFP NMR signals from water-filled cells of the same dimension. Since at 293 K the proton polarization in water is 8.2×10^{-9} the ${}^3\text{He}$ signal is larger by a factor of $(P({}^3\text{He})/3.71 \times 10^4)$. Thus for measurements of the absolute target polarization the NMR system has to be linear over six orders of magnitude. Furthermore, the temperature dependence of the impedance of the pickup coil circuit has to be accurately known between 293 K and 460 K.

We have recently tested the AFP NMR method by observing the reaction ${}^3\text{He}(\bar{p}, \pi^+) {}^4\text{He}$ which samples the ${}^3\text{He}$ polarization only in the beam interaction region. For reactions of the spin type $\frac{1}{2} + \frac{1}{2} \rightarrow 0 + 0$ parity conservation in the strong interaction implies the equalities to $A = A_{ho} = \mp A_{on}$ and $A_{nn} = \mp 1$, where the first and second subscripts refer to beam polarization p_b and target polarization $p_t = P({}^3\text{He})$, respectively. The lower sign applies if

Fig. 4. Beam-related asymmetry R for the ${}^3\text{He}(p, \pi^+) {}^4\text{He}$ reaction versus the target polarization determined by AFP NMR.

there is a parity change in the reaction. At a proton energy of 416 MeV and a laboratory scattering angle of 28° we have observed a clean π^+ peak from the reaction and measured the beam-related analyzing power, $A = 0.474 \pm 0.018$, using an unpolarized target. Unknown target polarizations can then be determined by a single measurement of the beam-related yield asymmetry $R = (u-d)/(u+d)$ via

$$p_t = \frac{2R - p_s A + p_d R A}{p_s - 2r A - p_d R}$$

where $p_s = p_s^u - p_s^d$ and $p_d = p_d^u + p_d^d$. The values of the beam-related asymmetries, R , measured during pump-up of the target are plotted in Fig. 4 at the values of the target polarization p_t measured simultaneously by AFP NMR. The results for p_t from the reaction method are found to be in good agreement with AFP NMR. The reaction method is more direct and less susceptible to systematic errors than the NMR method. The largest ^3He polarizations observed during bench tests were 79% and 72% for cells at $p=7$ and $p=9$, respectively. Typical values during experiments are in the range from 0.45 to 0.70.

NUCLEON KNOCKOUT FROM POLARIZED ^3He

We have carried out (p,2p) and (p,pn) two-arm coincidence experiments at incident proton energies of 290 MeV³ and, very recently, at 220 MeV¹¹. Only results from the 290 MeV experiment will be reported here. Directions and momenta of both the scattered proton and the knock-on nucleons were determined. The leading proton was detected in a magnetic spectrometer (MRS), whereas the knock-on protons or neutrons were identified by two separate two-scintillator telescope arrays. The momentum of the knock-on nucleon was inferred from the nucleon time-of-flight.

If one assumes plane waves for all particles (PWIA) the reaction can be described as follows: the incident polarized proton (four-momentum $[k_0, \vec{k}]$, spin s , mass M) scatters off a bound nucleon ($[E(p), \vec{p}]$, S , M) in the polarized target ($[M_A, 0]$, p_A , M_A). Detection of the scattered proton ($[E(k'), \vec{k}']$, s_1 , M) determines the energy transfer $\omega = E(k) - E(k')$ and momentum transfer $\vec{q} = \vec{k}_0 - \vec{k}'_0$ to the ejected nucleon ($[E(p'), \vec{p}']$, s_2 , M). Four-momentum conservation yields for the residual ($A-1$) system ($[E(P_{A-1}), \vec{P}_{A-1}] = [\omega + M_A - E(p'), \vec{q} - \vec{p}']$). In the PWIA the recoil momentum $\vec{P}_{A-1}$ is a direct measure of $\vec{p}$, the initial momentum of the struck nucleon.

The kinematics were chosen to emphasize low momenta of the struck nucleon. The invariant missing energy, $E_m = E^2(P_{A-1}) - \vec{P}_{A-1}^2 + M - M_A$, is then confined to a narrow region corresponding to either a deuteron [$\ln(p, 2p)$] or a slightly unbound two-nucleon pair. Since the time-of-flight resolution was insufficient to separate d and pn residual final states we have summed over missing masses in the time-of-flight spectra for each ω bin measured by the MRS. The comparison with the PWIA was then made using the closure approximation by replacing $E(P_{A-1})$ by $\{(\vec{P}_{A-1})^2 + \vec{M}_{A-1}^2\}^{1/2}$, where $\vec{M}_{A-1}$ was fixed at twice the nucleon mass. The spin dependent cross section can then be written^{3,4}

$$\frac{d\sigma(s, S_A)}{d\Omega_{k'} d\Omega_{p'} d\omega} = \int \frac{M^4 \cdot k' \cdot p^2 \cdot dp'}{(2\pi)^2 \cdot |\vec{k}| \cdot E \cdot E(p')} \times \delta(E(k) + M_A - E(k') - E(p') - \{\vec{P}_{A-1}^2 + \vec{M}_{A-1}^2\}^{1/2}) \times \sum_{s_1', s_2'} M_{NN}^{\dagger}(p, S') \cdot M_{NN}(p, S) \cdot D^{SS'}(p).$$

The "momentum distribution"

$$D^{SS'}(p) = \sum_{(A-1)\text{final states}} g_{A-1,A}^{\dagger}(p, S') \cdot g_{A-1,A}(p, S) \quad (1)$$

depends only on the target wave function, with the quantity $g_{A-1,A}(p, S)$ the probability amplitude for finding a nucleon in a plane wave state of momentum p and spin S with the

rest of the nucleus in a state S_{A-1} and invariant mass $\vec{M}_{A-1}$. The sum over final states includes all final state quantum numbers not otherwise indicated. The invariant nucleon-nucleon (NN) amplitude $M_{NN}(p, S)$ was constructed from the SM86 phase shift solution¹². For the spin dependent momentum distribution the Afnan and Birrell¹³ wave function was used as discussed in Ref. 4.

The experiment had to satisfy several, sometimes conflicting, requirements. The NN amplitudes had to be well known and large for both pp and pn scattering. This implied beam and target polarization normal to the scattering plane, and incident proton energies of 300 MeV or less. The angle for the leading proton ($\theta_1 = 27.5^\circ$) had to be large enough to allow vertex reconstruction to the target, yet sufficiently small to retain a tolerably large NN cross section. The angles for the scintillator arrays ($\theta_2 = 58^\circ$ and 71°) and the ω range of the MRS (50–120 MeV) had to encompass overlapping nucleon momenta ranging from 0–110 MeV/c for the 58° array, to 70–160 MeV/c for the 71° array.

For beam and target polarized normal to the scattering plane, the spin-dependent yield can be written as

$$\sigma = \sigma_o (1 + A_{no} p_b + A_{on} p_t + A_{nn} p_b p_t) \quad (2)$$

where the subscripts (bt) in A_{no} , A_{on} and A_{nn} refer to the direction of the projectile and target

Fig. 5. Differential cross section (top) and beam-related analyzing power A_{no} (bottom) for the $^3\text{He}(\bar{p}, 2p)$ proton knockout reaction at 290 MeV and PWIA predictions. The filled circles and solid lines refer to recoil protons detected in the 58° array, the open squares and dotted lines to those in the 71° array.

polarization and p_b and p_t are the known polarizations of beam and target, respectively. The results from a least-squares fit of four (p,2p) yield combinations for opposite beam and target polarizations are shown in Figs. 5 and 6 together with PWIA calculations. Corrections for energy loss, spectrometer acceptance, random coincidences, and (negligible) background from N_2 in the target have been applied. The differential cross sections and beam-related analyzing powers A_{no} in Fig. 5 are shown separately for the 58° and the 71° arrays used to detect the recoil protons. The same normalization factor was used for both the 58° and the 71° data. These data, together with previously obtained absolute spectral functions from $(e,e'p)^{14}$ and (p,2p) reactions¹⁵ and spin correlation parameters A_{nn} for the $pd \rightarrow ppn$ reaction¹⁶ would seem to support the validity of the PWIA and the smallness of rescattering corrections provided $q < 160$ MeV/c.

The spin correlation parameter A_{nn} shown in Fig. 6 is three times more sensitive to proton spin-momentum correlations than A_{no} , and is less susceptible to instrumental effects arising from the infrequent reversal of the target spin (several hours). The (p,2p) A_{nn} results differ strongly from those for pp scattering ($A_{nn}(pp) \sim 0.82$) and reflect the spin-momentum correlation of protons in ${}^3\text{He}$. At $q = 0$ about 14% of the protons have their spin antiparallel to the ${}^3\text{He}$ spin, whereas for protons with $q \sim 90$ MeV/c the momentum distributions $D_{SS'}(p)$ are spin independent. This is in good agreement with the PWIA calculations which, furthermore, show that the spin-momentum correlation effects are predominantly caused by the weak mixed-symmetry S' states. Our measurement provides evidence that the S' states contribute about 1.5% to the ${}^3\text{He}$ wave function in agreement with Faddeev calculations, e.g. those of Afnan and Birrell¹³.

Whereas the (p,2p) results are in reasonable agreement with the PWIA the (p,pn) results are not (see Fig. 7). The data sample for neutron knockout is only about 6% of that for proton knockout as a consequence of the three times smaller cross sections and of the poor neutron detection efficiencies of 15-20%. Although a few % proton contamination of the neutron sample could explain the observed discrepancy no such misidentified 'neutrons' were observed in elastic PP scattering runs which test the proton veto efficiency over about 30% of the active area of the 58° array. While no instrumental explanation has been found, a failure of the PWIA specific to the (p,pn) reaction seems surprising. In an effort to clarify the (p,pn) situation a new experiment¹¹ has been performed, with an order of magnitude improvement in rate per incident beam particle, with additional veto wire chambers in front of the scintillator array, and at 220 MeV where the sensitivity to neutron spin-momentum correlations

Fig. 6. Spin correlation parameter A_{nn} for the ${}^3\text{He}(p,2p)$ reaction at 290 MeV versus the momentum of the struck proton. The curves represent PWIA calculations referred to in the main text.

Fig. 7. Spin observables for (p,pn) neutron knockout from polarized ${}^3\text{He}$ at 290 MeV. The curves are PWIA predictions.

is a factor of two larger than at 290 MeV. This experiment is presently being analyzed.

ELASTIC PROTON SCATTERING FROM POLARIZED ${}^3\text{He}$

Spin observables A_{no} , A_{nn} and A_{nn} for proton elastic scattering have been measured at incident energies of 200, 290, 400 and 500 MeV. A preliminary summary of these results can be found elsewhere¹⁷. The results for 500 MeV are shown in Fig. 8.

Full four-body calculations of elastic p- ${}^3\text{He}$ scattering at intermediate energies are not available at present. Landau and collaborators¹⁸ have developed a momentum-space optical

Fig. 8. Cross sections (top left), beam and target related analyzing powers A_{no} (top right) and A_{nn} (lower left), and spin correlation parameter A_{nn} (lower right) for ${}^3\text{He}(p,p)$ elastic scattering at 500 MeV. The solid lines represent the parameter-free calculations of ref. 18, the dashed lines are from a preliminary calculation by L. Ray²⁰.

potential using a number of assumptions but without adjustable parameters (solid lines in Fig. 8). The dependence of the observables in the spin $1/2 \times$ spin $1/2$ system on a total of six complex amplitudes is as follows:

$$\begin{aligned}\sigma &= (|a|^2 + |b|^2 + |c|^2 + |d|^2 + |e|^2 + |f|^2)/2 \\ A_{no} &= \text{Re}(a^*e + b^*f)/\sigma \\ A_{on} &= \text{Re}(a^*e - b^*f)/\sigma \\ A_{nn} &= (|a|^2 - |b|^2 - |c|^2 + |d|^2 + |e|^2 - |f|^2)/2\sigma\end{aligned}$$

The importance of the f term in the nuclear amplitude which is parity forbidden in the NN system is evident from the difference between A_{no} and A_{on} in the data of Fig. 8. The theoretical calculations¹⁸ clearly fail to treat the dependence of these observables on the b^*f term correctly. For A_{nn} the calculations bear little resemblance to the data. The small measured values imply that the large amplitudes a , b , e , and f are interfering destructively.

Very recently, preliminary DWBA calculations have been carried out by L. Ray²⁰ who used the relativistic impulse approximation (RIA, see Ref. 21; dashed lines in Fig. 8). Parameters in this calculation were adjusted to reproduce cross sections and analyzing powers. Although this calculation does better it appears that the new spin observables are sensitive to parts of the scattering amplitude not tested by σ and A_y measurements and that these parts are not calculated well enough.

ELASTIC PION SCATTERING FROM POLARIZED ^3He

The elastic scattering of pions from a spin $1/2$ nucleus is described by two complex amplitudes $f(\theta)$ (non-spin-flip) and $g(\theta)$ (spin-flip). The differential cross section

$$\sigma = |f(\theta)|^2 + |g(\theta)|^2$$

corresponds to the incoherent sum of these amplitudes, whereas the asymmetry

$$A_y = 2\text{Im}[f(\theta)g^*(\theta)]/\sigma$$

is determined by the interference of the two amplitudes and is thus more sensitive to the weak spin-flip amplitude. Several momentum-space optical potentials have been constructed which imply substantial asymmetries near the cross section minima^{22,23}.

The first asymmetries in elastic pion scattering from polarized ^3He were obtained recently at TRIUMF's M11 channel²⁴. Wire chambers in the beam line allowed tracking of the 100 MeV π^+ beam at a rate of 5 MHz into the target cell. The scattered pions were momentum analyzed in the QQD magnetic spectrometer. Position information from two additional wire chambers between target and QQD resulted in satisfactory vertex reconstruction and in clean identification of scattering events originating inside the glass cell. Normalized momentum spectra observed at $\theta_{lab}=80^\circ$ for target spin up and down are shown in Fig. 9. The elastic ^3He peak has a large analyzing power whereas the background to both sides of the peak which is ascribed to excited states of N_2 in the target has negligible analyzing power. The broad peak at large energy losses (> 20 MeV) has a contribution from quasielastic inclusive scattering from ^3He .

The analyzing power at three angles is shown in Fig. 10 together with two optical model predictions by Landau²². The asymmetries are extraordinarily sensitive to the spin density in ^3He derived from the magnetic form factor for ^3He , $F_{mag}(q)$. The solid (dashed) lines correspond to the lower (upper) bound for fits of $F_{mag}(q)$ from early data by Collard *et al.*²⁵ It appears worthwhile to repeat the calculation²² using recent more accurate data²⁶ for $F_{mag}(q)$ which appear to favor the lower bound (solid line) in agreement with the A_y data. It would also be of interest to obtain π^- data which are predicted to be much less sensitive to $F_{mag}(q)$.

Fig. 9. Momentum spectra for elastic scattering of 100 MeV π^+ from ^3He . The upper spectrum is for target spin up, the lower spectrum for target spin down. The smooth, continuous background is ascribed to inelastic scattering from N_2 and to quasielastic scattering from ^3He .

Fig. 10. Asymmetries for elastic scattering of 100 MeV π^+ from polarized ^3He . The theoretical curves were calculated with a microscopic momentum space optical potential²². The solid and dashed curves are for lower and upper limits to fits of the magnetic form factor from an early experiment²⁵.

The analyzing power observed at $\theta_{c.m.} = 84.5^\circ$ is much larger than any previously observed polarization effect in pion scattering from nuclei, i.e. from ^6Li (Ref. 27), ^{13}C (Ref. 28), or ^{15}N (Ref. 27). As a very rough guideline, the maximum asymmetries appear to decrease with the number of nucleons in the valence shell.

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