CNI polarimetry with $^3$He

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Abstract

By making use of previous analysis of CNI for $pp$ and $pC$ scattering, the spin-flip factor for $np$ scattering is determined as a function of energy and then used to calculate the $p^3He$ asymmetry $A_N(s)'$ arising in $p^3He$ elastic scattering. It is found to be comparable to $A_N(s)$ for $pp$ scattering, but of the opposite sign. It seems that this method could be a practical for measuring the polarization of a $^3He$ beam.
The Coulomb-nuclear interference enhancement (CNI) at small $-t$ has been studied for high energy proton polarimetry for some time and it seems interesting to see how it would work for $^3He$. Nigel Buttimore and Elliot Leader and I looked at this a little about five years ago as part of a program to find an absolute polarimeter for protons [1].

Because $^3He$ is also has spin $1/2$ the formalism is similar to $pp$ [2]; further since the spin of the $^3He$ nucleus is carried by the neutron to a large extent, we will think about this asymmetry as being a polarization measurement of the neutron. Here we will do a very rough calculation which can be improved in several obvious ways.

The most striking difference from $pp$ is that here there are six rather than five amplitudes, the new one corresponding to the neutron ($^3He$) flip and designated as $\phi_6(s,t)$. We can rather generally write (we will neglect $\phi_2, \phi_4$ and set $\phi_3 = \phi_1 = \phi_+^{\prime}$ throughout)

$$\phi_p^{^3He}(s,t) = \frac{3s}{8\pi} \sigma_ppp(s)(i + \rho_{pp}(s))F_H(t),$$

$$\phi_\nu^{^3He}(s,t) = \frac{\tau_{p}\sqrt{-t}}{m} \phi_+^{^3He}(s,t),$$

$$\phi_6^{^3He}(s,t) = -\frac{\tau_{n}\sqrt{-t}}{3m} \phi_+^{^3He}(s,t).$$

The two single spin symmetries, for the proton and the neutron, are

$$A_N \frac{d\sigma}{dt} = -\frac{8\pi}{s} \text{Im}(\phi_+^{\prime} \phi_6^{\prime}),$$

$$A_{N'} \frac{d\sigma}{dt} = \frac{8\pi}{s} \text{Im}(\phi_+ \phi_6^{\prime}).$$

$F_H$ can be calculated by standard Glauber methods. Here we use simply the harmonic oscillator form $F_H(t) = \exp(t(B/2 + a^2/4))$ with $a^2 = 57.4 GeV^{-2}$ for illustration [3]. The $pp$ total cross section $\sigma_{pp}$, the shape parameter $B$ and and the real to imaginary ratio $\rho_{pp}$ are taken from elastic $pp$ data [4]. The value of $\tau_p$ is reasonably well measured at $p_L = 24 GeV/c$ and $p_L = 100 GeV/c$ [5].
We still need $\tau_n$. We can get an approximate idea of its size from data obtained by the RHIC polarimeter group: the elastic scattering can be thought of as taking place through the exchange of $I = 0$ and $I = 1$ particles (or Regge poles); it is known that the $I = 1$ contribution to the non-flip scattering is very small so we can write (approximately)

$$\tau_0 = \tau_p + \tau_n.$$  \hspace{1cm} (0.1)

We can also write

$$\tau_{pC} = \tau_0$$  \hspace{1cm} (0.2)

which is obtained by the RHIC polarimeter group’s proton-carbon measurements at $p_L = 21.7 \, GeV/c$ and $p_L = 100 \, GeV/c$ \cite{5}. So we can determine $\tau_n$ at these two energies at least from

$$\tau_n = 2\tau_{pC} - \tau_p$$  \hspace{1cm} (0.3)

Alternatively, we can use a fit I made to both sets of measurements using a Regge model which then gives $\tau_n(s)$ as shown in Fig. 1:

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Energy Dependence of real and imaginary parts of $pp$ and $np$ spin-flip factors.}
\end{figure}

In order to calculate the CNI analyzing power we need the e.m. amplitudes \cite{1}:

$$\phi_{+}^{em}(s,t) = \frac{2s}{t} \frac{\alpha}{2m\sqrt{-t}} F_{em}(t),$$

$$\phi_{-}^{em}(s,t) = \frac{2s}{t} \frac{\alpha}{2m\sqrt{-t}} \kappa_p F_{em}(t),$$

$$\phi_{6}^{em}(s,t) = \frac{s}{t} \frac{\alpha}{2m\sqrt{-t}} \kappa_n F_{em}(t),$$

where $F_{em}(t) = \exp (a^2 t/4)$. Note that $m$ in all these formulas denotes the proton mass. In the second of these equations one might want to use the $^3He$ ion mass along with the magnetic moment of $^3He$ rather than $\kappa_n = -1.91$ \cite{6}. We leave the expressions this way for consistency with our simple approach.
Let’s look first at the two asymmetries in the absence of hadronic spin flip, Fig. 2:

![Graphs of \( A_N \) and \( A'_N \)]

FIG. 2: Analyzing powers \( A_N \) and \( A'_N \) at \( p_L = 100 \text{GeV/c} \) with zero hadronic spin-flip factor

Now look at the same things in Fig. 3 using the \( \tau \)-values found from the \( pp \) and \( pC \) analysis, Fig. 1: we see that the hadronic spin flip significantly modifies the shape of the

![Graphs of \( A_N \) and \( A'_N \)]

FIG. 3: Analyzing powers \( A_N \) and \( A'_N \) at \( p_L = 100 \text{GeV/c} \) using the non-zero hadronic spin-flip factors in text.

analyzing power curve especially for the neutron and, very important, both asymmetries are large enough that they should be readily measurable.
FIG. 4: Analyzing power $A'_N$ for colliding beams of protons with momentum of 150 GeV/c on a beam of $^3$He at beam momentum $P = 3 \times 150$ GeV/c.

From our experience with $pp$ and $pC$ we would expect at least a 10% measurement of polarization to be possible in this way and should be applicable to colliding beams [7]. An estimate of this for the neutron for 150 GeV colliding beams of $p$ on $^3$He is shown in Fig. 4. The method can be extended to $^3$He $- ^3$He scattering.

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