NN\((1S_0)\) pairs in \(^3\)He and in \(p^3\)He backward elastic scattering

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It is shown that the shoulder observed in the cross section of \(p^3\)He backward elastic scattering at proton beam energies of 0.4 – 0.7 GeV can be explained by the mechanism of virtual \(\pi\)-meson production with a dominant contribution from the subprocesses \(pd^* \rightarrow \eta\) and \(p(pp) \rightarrow \pi^+\), where \(d^*\) denotes the singlet deuteron and the \(pp\) pair is in the \(1S_0\) state. At high energies, 1–3 GeV, the mechanism of \(np\)-pair transfer dominates and probes high-momentum \(NN\((1S_0)\) correlations in \(^3\)He.

Over the past few years \(p^3\)He backward elastic scattering has been investigated \([1,2]\) on the basis of the DWBA using a 3\(N\) bound-state wave function obtained from solving the Faddeev equations for the Reid RSC \(NN\) potential. Those studies suggested that this process at beam energies \(T_p > 1\) GeV can give unique information about the high momentum component of the \(^3\)He wave function \(\varphi^{23}(q_{23},p_1,\ldots)\), and specifically for high relative momenta, \(q_{23} > 0.6\) GeV/c, of the nucleon pair \(\{23\}\) in the \(1S_0\) state and low momenta of the nucleon “spectator” \(p_1 < 0.1\) GeV/c. Here \(\varphi^{23}\) is the first Faddeev component of the full wave function of \(^3\)He, \(\Psi(1,2,3) = \varphi^{23} + \varphi^{31} + \varphi^{12}\). The calculations presented in Refs. \([1,2]\) demonstrate the dominance of the mechanism of sequential transfer (ST) of the proton-neutron \((np)\) pair (Fig.1a) over a wide range of beam energies, \(T_p = 0.1–2\) GeV, except for the region of the ST dip at around 0.3 GeV. Other mechanisms of two-nucleon transfer, such as deuteron exchange, non-sequential \(np\) transfer \([1]\), and direct \(pN\) scattering \([3]\) involve very high internal momenta in the \(^3\)He wave function in \(q_{23}\) as well as in \(p_1\) and, as a consequence, give much smaller contributions. As is shown here (see for details Ref. \([4]\)), the region of the ST dip (0.4–0.7 GeV) is dominated by the triangle diagrams of one pion exchange (OPE) with the subprocesses \(pd^* \rightarrow \pi^0\) and \(p(pp) \rightarrow \pi^+\) (Fig.1b), where \(d^*\) and \(pp\) are the spin-singlet \(1S_0\) deuteron and diproton, respectively.

In Ref. \([2]\) the deuteron contribution to the cross section of \(p^3\)He scattering within the OPE mechanism is expressed via the experimental cross section of the reaction \(pd \rightarrow \pi^0\), without elaboration of its concrete mechanism. In order to calculate the contribution of the meson production on the \(d^*\) and on the diproton in \(^3\)He, we use the \(d^* + p\) and \((pp) + n\) configurations of \(^3\)He calculated in Refs. \([5,6]\) and adopt the spec-
Figure 1. Right panel: The ST (a) and OPE (b) mechanisms of elastic \( p^3He \) scattering, and the spectator mechanism of \( p(NN) \rightarrow 3He \pi \) (c). Left panel: Cms cross section of \( p^3He \rightarrow 3He p \) at the scattering angle \( \theta_{cm} = 180^\circ \) versus the proton beam energy. Calculations on the basis of the OPE model with the \( \pi NN \) cut-off momentum \( \Lambda_\pi = 1.3 \) GeV/c: 1 – for \( d \) in the intermediate state, 2 – \( d + d^* + pp \). The result for the nondistorted ST cross section is given by the dotted line 3 (divided by factor of 3 to normalize on the experiment at 1.5 GeV). The dashed curve 4 shows the slope for the counting rule \( \frac{d\sigma}{dt} \sim s^{-22} \). Experimental data are from Refs. [7] (○), [9] (filled square), [10] (open square), [11] (●), and [12] (filled triangle).

Because of the specific spin structure of the OPE amplitude there is no interference between the triplet (\( M_d \)) and singlet (\( M_{d^*} + M_{pp} \)) amplitudes in the spin-averaged sum:

\[
|M_d + M_{d^*} + M_{pp}|^2 = |K|^2 \left\{ |G_d T_d|^2 + \frac{1}{3} |G_{d^*} (T_{d^*} + 2 T_{pp})|^2 \right\}. \tag{1}
\]

Here \( T_\alpha (\alpha = d, d^* \text{ and } pp) \) is the meson production amplitude \( p(NN)_\alpha \rightarrow 3He \pi \) and \( G_\alpha \) is the structure factor \( [4] \). The factors \( \frac{1}{3} \) and 2 in the second term in the curly brackets of Eq. (1) are combinations of isospin coefficients. Furthermore, we assume that the subprocess \( pN \rightarrow (NN)_s \pi \) dominates in the upper vertex of the diagram in Fig. 1c: and that the amplitude \( pN \rightarrow (NN)_s \pi \) is negligible. This is true in the \( \Delta^- \)-
region [14]. With this approximation there is a relation between the amplitudes of the processes \( pd^* \to ^3\text{He}\pi^0 \) and \( p(pp)\to ^3\text{He}\pi^+ \) which follows from isospin invariance, namely \( T_{pp} = 2 T_{d^*} \). After that one gets the relation \( |T_{d^*} + 2T_{pp}|^2 = 25|T_d|^2 \). Therefore the combined contribution of \( T_{d^*} + T_{pp} \) is significantly larger than that of the deuteron and can be expressed via the experimental cross section of the reaction \( pd \to ^3\text{He}\pi^0 \) taken here from Ref. [15]. Distortions are included in the factor \( K \).

The results of our calculation are shown in Fig. 1. Evidently, the OPE model with deuteron exchange (curve 1) yields a reasonable description of the energy dependence of the cross section for \( T_p = 0.4 - 1.5 \text{ GeV} \). However, due to distortions, taken into account here in eikonal approximation, the \( d \) contribution turns out to be one order of magnitude smaller than the data. The contributions of the singlet deuteron \( d^* \) and of the \( pp \) pair bring the calculation in qualitative agreement with the data (curve 2).

One can see from curve 3 in Fig. 1 that the ST mechanism, calculated here with the 3N wave function [16] resulting from the CD Bonn potential, is significant at beam energies \( T_p = 0.9 - 1.5 \text{ GeV} \) and it definitely dominates at low (\( T_p < 0.3 \text{ GeV} \)) and high (\( T_p > 1.5 \text{ GeV} \)) energies. Since at sufficiently high relative \( NN \) momenta the concept of having individual nucleons inside nuclei is expected to fail, we show in Fig 1 for comparison, also the slope of the cross section as it follows from quark counting rules [8] for direct (without baryon exchanges) mechanism. Obviously, this slope differs from the one of the ST and OPE mechanisms.

In conclusion, our calculations suggest that the shoulder in the \( p^3\text{He} \to ^3\text{He}p \) cross section at 0.4-0.6 GeV is mainly due to the OPE mechanism with the singlet \( NN(1S_0) \) pairs in \( ^3\text{He} \). A measurement of spin observables, planned at 0.2-0.4 GeV [17] could give additional information here.

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