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QUASIELASTIC ^{3}Hp SCATTERING AT A 2.5 GEV/C TRITON MOMENTUM

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Abstract

The differential cross sections $d\sigma_{in}/d\Omega$ of the quasielastic ^{3}Hp-scattering at a 2.5 GeV/c tritium momentum (T_p = 318 MeV) have been measured using the ITEP 80 cm hydrogen bubble chamber. The experimental results are compared with the predictions of the Glauber-Sitenko multiple scattering theory combined with the completeness condition for the excited nucleus wave functions. The validity of the Glauber sum rule for the differential cross sections is investigated.

I. Introduction

It is well known that the experiments on high energy hadron-nucleus collisions can provide useful information even if the states of the final nucleus $|f\rangle$ is not measured and the result is the cross section summed over all the possible nuclear states $|f\rangle$. For example, the quasielastic proton-nucleus scattering ($p + A \to p + X$) [1] or noncoherent production of hadronic resonances on nuclei [2] can be mentioned (see the corresponding discussions in refs. [3,4]). The Glauber-Sitenko multiple scattering theory [5,6] combined with the completeness condition of nuclear wave functions leads to the famous sum rule for the differential cross sections

$$\sum_f d\sigma_{fi}/d\Omega = \mathrm{R.H.S.}$$

where right hand side (R.H.S.) can be expressed through the hadron-nucleon scattering amplitudes and the wave function of the nuclear ground state.

Formally the left hand side of the Glauber sum rule (GSR) contains infinite number of terms with eigen-values E_f varying from E_i to ∞. But in concrete experiment the maximum value of E_f is usually restricted by the experimental or kinematic conditions.

Let us consider the quasielastic p^3H-scattering

$$p + {}^3H \to p_F + X \qquad (I)$$

(where p_F is the fast proton in the triton rest frame) and put on the following restriction

$$M_X - M_{^3H} \equiv M^* < \mathcal{E}$$

(where M_X is the effective mass of the excited nuclear state).

When $\mathcal{E}$ does not exeed the energy of the first excited nuclear state the elastic scattering is only possible and only the first term in the sum $\sum_f d\sigma_{fi}/d\Omega$ is different from zero. With $\mathcal{E}$ increasing, the number of possible states giving a contribution to the scattering increases as well and the sum $\sum_f d\sigma_{fi}/d\Omega$ becomes more and more close to the limit fixed by the R.H.S. of GSR. The most interesting question is how fast with $\mathcal{E}$ increasing the GSR is saturated ? Till now this problem has not been investigated in detail. It is only known that when $\mathcal{E} \sim m_\pi$ the description of the quasielastic proton-nucleus cross section by the GSR is good for a small momentum transfer (see [3,7]). Note also that the GSR is based on the completeness condition of nuclear wave functions described by the conventional nonrelativistic nuclear hamiltonian, where only nucleon degrees of freedom are taken into account. Therefore when $\mathcal{E}$ exceeds the pion production threshold there may be the violation of the GSR due to possible manifestations of the meson and quark degrees of freedom.

In this paper we investigate the conditions of validity of the GSR for the description of quasielastic ^{3}Hp-scattering at a 2.5 GeV/c tritium momentum. Till now the quasielastic proton scattering on lightest nuclei has not been investigated systematically. There are only two experimental works on investigation of quasielastic dp-scattering at 3.3 GeV/c [8] and quasielastic pd-scattering at 19.2 GeV/c [9] . The data reported here were obtained at the ITEP 80 cm hydrogen bubble chamber exposed to a separated triton beam. An important feature of the bubble chamber technique is a reliable separation of quasi-elastic channels (in our case the latter are the reaction ^{3}Hp → pdn and ^{3}Hp → pgnn) from the elastic scattering and the reactions with pion production. The main point which we discuss here is how fast the quasielastic ^{3}Hp cross section approaches the limit given by the GSR with the increasing of $\mathcal{E}$.

The outline of this paper is as follows. In Sect. II we explain our experimental method. In Sect. III the theoretical scheme is presented. The results and conclusions are given in Sect. IV.

II. Experimental technique

The 80 cm liquid hydrogen bubble chamber was exposed to the separated 2.5 GeV/c triton beam of the ITEP proton synchrotron. The chamber was situated in the 2.05 T magnetic field. The circulating 9.7 GeV/c proton beam interacted with 1 x 2 x 15 mm^3 beryllium target. The magnetic system selected the secondary 2.5 GeV/c positive particles emitted at 92 mrd. The triton beam was formed by a two-stage electrostatic separator. The contamination of the beam (mainly by protons) was less than2%. Moreover the protons can be separated from tritons by visual estimation of the track ionisations. About 80 000 pictures with an average intensity of 10 tritons per frame were taken. The pictures were double scanned with the overall efficiency of more than 95%. In the course of scanning two-prong ^{3}Hp-interactions were selected for the analysis. For measurements there were used the semiautomatic devices and automatic PSP-2 system (similar to HPD) in minimum guidance mode. The ASP program developed in ITEP was used for the spatial reconstruction and kinematic fit. About 22 000 two-prong events were selected.

The quasielastic ^{3}Hp-scattering (I) is contributed by two channels: $^3Hp \rightarrow dpn$ (i) and $^3Hp \rightarrow pnnp$ (ii). The events of the reactions (i) and (ii) were identified by momentum analysis combined with the ionisation data. Due to the fact that the short track events corresponding to the slow recoil protons can easily be lost we do not present here the differential cross sections $d\sigma_{in} / d\Omega$ for $\cos\theta >$ .96, where θ is the proton scattering angle in the tritium rest frame. The cross sections and the statistics of the reactions (i) and (ii) are given in ref. [10] .

III. Theoretical consideration

To describe the quasielastic ^{3}Hp-scattering we use the Glauber-Sitenko multiple scattering theory [5,6] . The amplitude describing the proton-nucleus scattering with a transition of nuclear state from $|i\rangle$ to $|f\rangle$ has the following formin the rest frame of initial nucleus [3] :

$$F_{fi}(k,\Delta) = \frac{ik}{2\pi}\int e^{i\vec{\Delta}\vec{b}}\,\Psi_f^*(\{\vec{r}_j\})\Gamma(\vec{b},\vec{s}_1,\dots,\vec{s}_A)\Psi_i(\{\vec{r}_j\})\delta\Big(\sum_{j=1}^{A}\vec{r}_j/A\Big)d\vec{r}_1\dots d\vec{r}_A d^2b \qquad (1)$$

where k is the momentum of the incident proton,

$\vec{\Delta}$ is the momentum transfer,

$\vec{r}_j \equiv (\vec{s}_j, z_j)$ is the coordinate (transversal and longitudinal) of the j-th nucleon in a nucleus,

$\Psi_i \ (\Psi_f)$ is the wave function of initial (final) nuclear state,

$\Gamma(\vec{b}, \vec{s}_1, \ldots, \vec{s}_A)$ is the nuclear profile function.

The differential cross section of quasielastic scattering is defined as follows

$$\frac{d\sigma_{in}(k,\Delta)}{d\Omega} = \sum_{f \neq i} |F_{fi}(k,\Delta)|^2 = \sum_f |F_{fi}(k,\Delta)|^2 - |F_{ii}(k,\Delta)|^2 \qquad (2)$$

where F_{ii} is the elastic scattering amplitude.

Starting from exp. (1) and using the completeness condition of the nuclear wave functions $\sum_f |f\rangle\langle f| = I$ we get the following expression for the first term in the right hand side of exp. (2)

$$\sum_f |F_{fi}(k,\Delta)|^2 = \left(\frac{k}{2\pi}\right)^2 \int e^{i\vec{\Delta}(\vec{b}-\vec{b}')} |\Psi_i(\{\vec{r}_j\})|^2 \Gamma(\vec{b}, \vec{s}_1, \ldots, \vec{s}_A) \Gamma^*(\vec{b}', \vec{s}_1, \ldots, \vec{s}_A) \delta(\sum_j \vec{r}_j/A) d\vec{r}_1 \ldots d\vec{r}_A d^2b\, d^2b' \qquad (3)$$

In exps. (1) and (3) the δ -function $\delta(\sum_j \vec{r}_j/A)$ describes the center-of-mass correlations. These corrections are important for small momentum transfer (see, for example, refs. [11,12] where the corrections due to the center-of-mass correlations are discussed in detail).

Let us apply exps. (2)-(3) to the description of ^3Hp-scattering. The oscillator model can be taken as a good approximation for the ground state density of ^3H nucleus $\rho(\{\vec{r}_j\}) \sim \prod_{j=1}^{3} e^{-\vec{r}_j^{\,2}/R^2}$. Taking into account that at our energy the radius of NN interaction is small as compared to the nuclear radius we can express the quasielastic ^3Hp-scattering differential cross section through the differential pp- and pn-elastic scattering cross sections and the oscillator parameter a_0^2 :

$$\sum_f |F_{fi}(\kappa,\Delta)|^2 = \frac{d\sigma^{pp}(\kappa,\Delta)}{d\Omega}\left(1-\frac{\sigma^{pn}}{\pi a_0^2}+\frac{(\sigma^{pn})^2}{3(\pi a_0^2)^2}\right)+2\,\frac{d\sigma^{pn}(\kappa,\Delta)}{d\Omega}\left(1-\frac{\sigma^{pn}+\sigma^{pp}}{2\pi a_0^2}+\frac{\sigma^{pp}\sigma^{pn}}{3(\pi a_0^2)^2}\right)+$$

$$+\left(\frac{d\sigma^{pn}(\kappa,\Delta/2)}{d\Omega}\right)^2\varphi(\kappa)+2\,\frac{d\sigma^{pn}(\kappa,\Delta/2)}{d\Omega}\,\frac{d\sigma^{pp}(\kappa,\Delta/2)}{d\Omega}\,\psi(\kappa,\Delta)+$$

$$+\left(\frac{d\sigma^{pn}(\kappa,\Delta/3)}{d\Omega}\right)^2\frac{d\sigma^{pp}(\kappa,\Delta/3)}{d\Omega}\,\xi(\kappa,\Delta) \qquad (4)$$

$$\varphi(\kappa)=\frac{1}{4\kappa^2\beta_{pn}^2 a_0^2}\left(1-\frac{2\sigma^{pp}}{3\pi a_0^2}\right)$$

$$\psi(\kappa,\Delta)=\frac{1}{2\kappa^2(\beta_{pn}^2+\beta_{pp}^2)a_0^2}\left(1-\frac{2\sigma^{pn}}{3\pi a_0^2}\right)\exp\left(\frac{\Delta^2(\beta_{pp}^2-\beta_{pn}^2)^2}{4(\beta_{pp}^2+\beta_{pn}^2)}\right)$$

$$\xi(\kappa,\Delta)=\frac{1}{3\kappa^4(2\beta_{pp}^2+\beta_{pn}^2)\beta_{pn}^2 a_0^4}\exp\left(\frac{2\Delta^2(\beta_{pp}^2-\beta_{pn}^2)^2}{9(2\beta_{pp}^2+\beta_{pn}^2)}\right)$$

where $\frac{d\sigma^{pp}}{d\Omega}$ ($\frac{d\sigma^{pn}}{d\Omega}$) and β_{pp}^2 (β_{pn}^2) are the differential cross sections averaged over the spins and the slope parameter of pp (pn) elastic scattering, σ^{pp} (σ^{pn}) is the pp (pn) total cross section, a_0 is the tritium nuclear radius (a_0 = 1,7 Fm).

In the right hand side of exp. (4) there may be separated the contributions of the single (the first and the second terms), double (the third and forth terms) and triple (the last term) noncoherent scattering. The single and double noncoherent scattering terms contain the screening factors which appear due to the coherent rescattering of incoming and outgoing waves on spectator nucleons. Note that only if the contribution of the single noncoherent scattering term with the screening factor were taken into account it would correspond to the DWBA. In our case this approximation is not good enough because the contribution of double noncoherent scattering term is about 15%. As for the triple noncoherent scattering term its contribution is small (about 1.5%).

Exp. (2) with F_{fi} given by (4) determines the sum rule for the quasielastic ^{3}Hp-scattering. The contribution of the elastic ^{3}Hp-scattering $|F_{ii}|^2$ into the right hand side of exp. (2) is important only at small momentum transfer. To calculate it we used the scheme developed in [13] and applied to the description of the elastic ^{3}Hp-scattering at 2.5 GeV/c in our previous paper [14] . This scheme is based on the multiple scattering theory with eikonal propagators and takes into account the spin-isospin structure of NN scattering amplitude which is important for correct description of the elastic ^{3}Hp and ^{3}Hep-scattering at medium energies.

Note that the expression (4) for $\sum_f |F_{fi}|^2$ is in fact valid in much broader interval of momentum transfer than it is assumed in the standart Glauber-Sitenko theory. The same expression can be derived in the framework of Watson multiple scattering theory using the weak coupling and quasifree scattering limits [15] . Nevertheless the following conditions should be satisfied for the validity of exp. (4) : $k \gg m\bar{v}$ and $|\vec{k} - \vec{\Delta}| \gg m\bar{v}$, where $\bar{v}$ is the average velocity of nucleons in a nucleus. Moreover the special forms of the double and triple noncoherent scattering terms which appear in (4) are valid for the gaussian parametrisation of $d\sigma^{NN}/d\Omega$ as a function of the momentum transfer squared. Having in mind all this reasons we apply exp. (4) only to forward scattering angles $\theta \leqslant 45°$

in the tritium rest frame.

The main properties of the NN interaction at the energy considered are the small inelastisity $\sigma_{tot}^{NN} \simeq \sigma_{el}^{NN}$ (σ^{pp} = = 24 mb, σ^{pn} = 35 mb) and the small magnitudes of slope parameters as compared to the nuclear radius squared (β_{pp}^2 = = 0.35 (GeV/c)$^{-2}$, β_{pn}^2 = 2 (GeV/c)$^{-2}$ [16]). All this leads to a strong compensation of the screening correction to the single scattering term in (4) with the double noncoherent scattering term. The latter property of the NN-interaction also gives rather weak dependence of $\Psi(k,\Delta)$ and $\xi(k,\Delta)$ in exp. (4) from the momentum transfer.

For numerical calculations NN elastic differential cross sections were reconstructed using the phase shift analysis of refs. [17] .

IV. Results and conclusions

In fig. there are plotted the differential cross sections $d\sigma_{in}/d\Omega$ of quasielastic ^{3}Hp-scattering (I) at the tritium rest frame as the functions of $\cos\Theta$. Five series of the experimental points correspond to the restrictions with $\mathcal{E}$ = 25, 50, 100, 150 MeV and without restriction. The solid curve is calculated in the framework of Glauber-Sitenko multiple scattering theory (the GSR for the differential cross sections). With the increase of $\mathcal{E}$ the experimental points approach the limit given by GSR. It can been seen that the speed of saturation of GSR is extremely dependent on $\cos\Theta$. For $\cos\Theta$ = 0.9 the saturation of GSR within the experimental accuracy happens at $\mathcal{E} = 100$ MeV, but for $\cos\Theta = 0.75$ it happens at higher magnitude of $\mathcal{E} = 150$ MeV. The upper limit of $\mathcal{E}$ at $T_p = 318$ MeV is equal to 250 MeV.

The theoretical curve for $d\sigma_{in}/d\Omega$ is in a good agreement with the experimental data up to $\cos\Theta = 0.7$, for larger angles the effects of the recoil particles phase space are important. They are neglected in exp. (4). The sharp dip in $d\sigma_{in}/d\Omega$ for $\cos\Theta \to 1$ is related to the compensation of scattering and elastic cross sections (see exp. (2)).

It is interesting to note that in the interval $0.7 \leq \cos\Theta \leq 0.9$ the differential cross section of quasielastic ^{3}Hp - scattering (I) is close to the sum $2d\sigma_{pp}/d\Omega + d\sigma_{pn}/d\Omega$ (dash-dotted curve in fig.) which corresponds to the single noncoherent scattering terms in exp. (4) without screening corrections. The same curve follows from the pole model when the final state interaction of spectator nucleons is taken into account [10,18]. These surprisingly close results of diagram approach and Glauber approximation for $d\sigma_{in}/d\Omega$ are closely connected with the strong compensation of multiple scattering terms in exp. (4) which happens for small inelasticity and flat angular dependence of NN interaction (see Sect. 3) and are specific for medium energies. As it was mentioned in Introduction any exceeding of the experimental data over the GSR limit could be treated as manifestation of the meson or quark degrees of freedom. For example, during the collision it is possible to produce a multiquark bag in which the quarks are not confined in three-quark clusters (nucleons) but distributed over all volume of a bag. Those multiquark bag states which are predicted in 6q and 9q systems (see refs. [19-20]) are not included into the GSR. Within the experimental errors (which are ~ 5%) we do not see any essential exceeding of the experimental points over the limit predicted by GSR which would manifest the production of the multiquark states. In search of those states new experimental information on interaction of hadrons with few nucleon systems would be of great interest.

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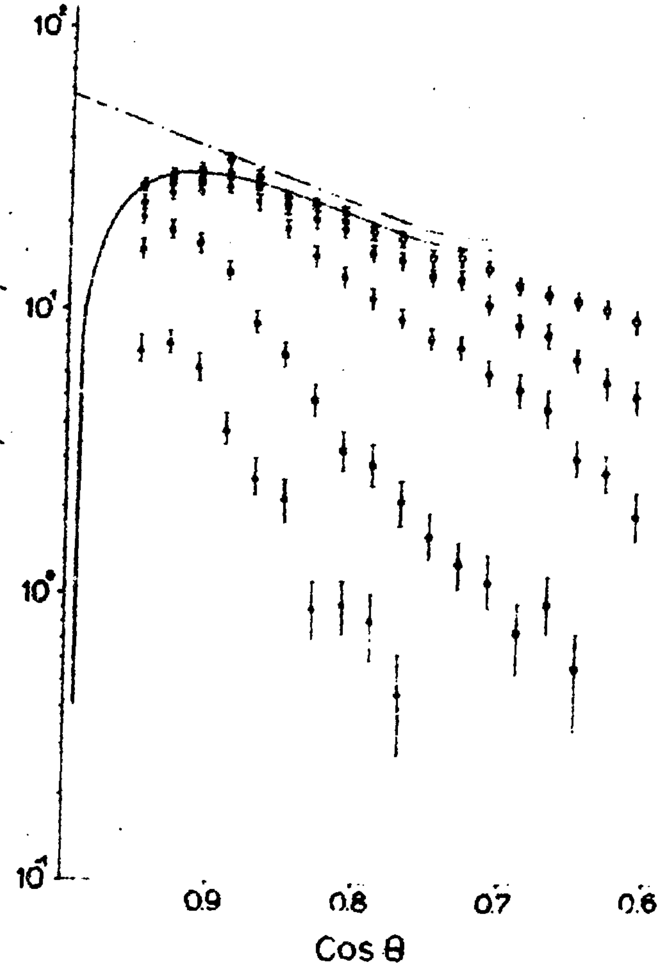

The differential cross sections $d\sigma_{in}/d\Omega$ of quasi-elastic ^{3}Hp-scattering at 2.5 GeV/c (T_p = 318 MeV) in the tritium rest frame as a function of COS θ^p. The experimental points correspond to the following restrictions (see text): ▲ - $\mathcal{E}$ =25 MeV, ■ - $\mathcal{E}$ =50 MeV, ♦ - $\mathcal{E}$ = 100 MeV, ● - $\mathcal{E}$ =150 MeV, ⊖ - all events (which corresponds to $\mathcal{E}$ = 250 MeV the upper limit at T_p = 318 MeV). The solid cutve is calculated in the framework of Glauber-Sitenko multiple scattering theory (the GSR for cross sections). The dashdotted curve represents the sum of the differential elastic cross sections of proton on separated nucleons of ^{3}H nuclei at our energy.

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