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PION MOMENTUM SPECTRA IN NUCLEAR CHARGE EXCHANGE REACTIONS A(t, 3He)

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Investigations of inclusive cross sections in the charge exchange reaction (^{3}He,t) have shown [1, 2] that the Δ peak in the triton energy spectrum was broader and shifted towards a high energy region in case of nuclear targets as compared with charge exchange on hydrogen. In the subsequent experiments this effect was confirmed for a wide energy scale [3] and different projectiles [4]. Effects like de-excitation of delta via the non-mesonic channel [5, 6] $\Delta N \to NN$ or collective effects associated with the Δh propagation [7, 8, 9, 10] were suggested to explain these features. The Δ excitation in the projectile was considered in [11] where it was shown to produce a shift of strength to lower excitation energies, although the peak position was not moved.

Recently experiments using 4π facilities were provided [12, 13, 14]. In this way significant information about the role of effects like non-mesonic decay of the delta isobar $\Delta N \to NN$ was obtained. One of the byproducts of the theoretical studies of this reaction was the finding of coherent pion production as a relevant channel [10, 15, 16]. The peak of this channel is shifted to lower excitation energies and approximately coincides with the peak of the inclusive cross section. Some measurement of this channel have already been reported [17]."Yet, it is important that ... the reactions which one is discussing here are rather complex and there are many reaction channels open which collaborate, or sometimes compete, in producing the observed experimental strength" [18]. Our experiment was devoted to an attempt to find all relevant ingredients of the channel where a single pion was observed in the final state.

The experiments were performed using the GIBS spectrometer facility (streamer chamber with C–1.30 g/cm^2 and Mg–1.56 g/cm^2 targets) in a tritium beam (secondary, produced by the fragmentation of a ^{4}He beam) with mean momentum over a 9 GeV/c region. The details of the experiment were discussed in the previous papers [19]. Here we would like to remind of a short list of the event measurement accuracy available in the analysis. The momenta of all charged particles were measured for all the events. The typical measurement accuracy of momentum was 2-3% for ^{3}He nuclei and 1-2% for π^- and protons. The angles were measured with an error equal approximately to a few milliradians.

All positive secondary particles were regarded as protons and negative particles as π^-. There was no doubt to identify the ^{3}He track. It should be noted that in this analysis only the events where a single π^- accompanies a t$\to^3$He charge exchange were included . Assuming that the reaction occurs on a quasi-free target nucleon, the isotopic relations (see [11]) show that major part of the events with a single π^- should be conditioned by Δ^-–isobar excited on a target neutron. It is not too difficult to calculate the spectra of ^{3}He and pions for this case.

We have used the same formulae and parameters as Jackson [21] to obtain the delta mass distribution:

$$W(\omega) = \frac{\omega_0 \Gamma(\omega)}{0.898\pi[(\omega^2-\omega_0^2)^2+\omega_0^2\Gamma^2(\omega)]};$$

$$\Gamma(\omega) = \Gamma_0 (\frac{q}{q_0})^3 \frac{\rho(\omega)}{\rho(\omega_0)}; \quad \rho(\omega) = [am_\pi^2 + q^2]^{-1};$$

$$a = 2.2; \quad \Gamma_0 = 123 MeV; \quad \omega_0 = 1232 MeV.$$

These formulae provide the $W(\omega)$ distribution of delta mass ω and, subsequently, pion momentum q in the Δ frame. Fig.1a and 1b show that the model is good enough to describe the experimental data [22] for the charge exchange reaction on hydrogen target p(^{3}He,t) at different projectile energies. It should be also emphasized that in our experiment the beam energy was intermediate in comparison with these two reference energies [22]. The same form factor was used as in [22] here.

The next step was to calculate delta excitation on a quasi-free target nucleon with the Fermi momentum distribution proportional to P^2dP with maximum values of 150—200 MeV/c and a mean separation energy of 15—20 MeV a nucleon. The invariant flow was also taken into account.

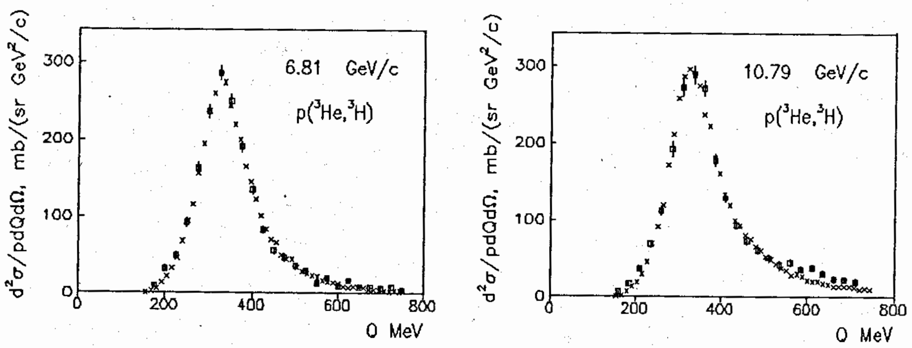

Fig.1a and 1b. Delta production model test. Points × in (a) and (b) calculated for two beam momentum values; □-experimental data [22]. The calculated spectra normalized at the maximum value. Q-projectile-ejectile energy difference.

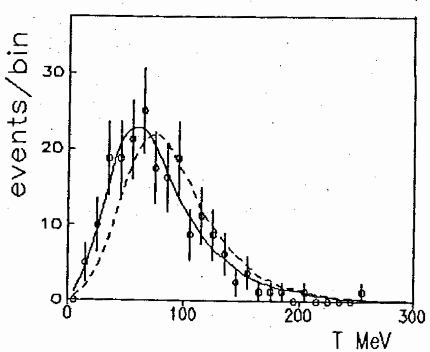

Fig.2. Kinetic energy for backward pions. o-experimental data, dotted curve—calculation with ω_0=1232 MeV, solid curve calculated for ω_0=1192 MeV.

We have provided a lot of tests that have shown that the pion momentum spectrum is rather insensitive to the choice of the parameters: Fermi momentum and separation energy. Indeed, if they varied within rather wide

limits, the form of the calculated distribution as well as the peak position are modified by a few MeV only. On the contrary, the calculated peak was shifted by a 13 MeV value according to the experimental one (see the Fig.2) in case of ω_0=1232 MeV (dotted curve), and therefore ω_0=1192 MeV should be used for the best fit (see the solid curve). An analogous effect was reported in [13, 14] when a $\simeq$30 MeV reduction of π^+p effective mass was observed in Δ^{++} production in the charge conjugate reaction. It was shown [23] that this reduction of the measured delta mass could be connected with delta selfenergy in nucleus in a complicated way.

Especially it should be noted that only backward pions (with a negative value of longitudinal momentum) were used in the analysis discussed above. In our experiment pions with the negative longitudinal momentum cannot be produced in projectile excitation or in coherent pion production process. This means that the analyzed ensemble is practically free from non-delta pions and therefore was used to normalize the calculated spectra.

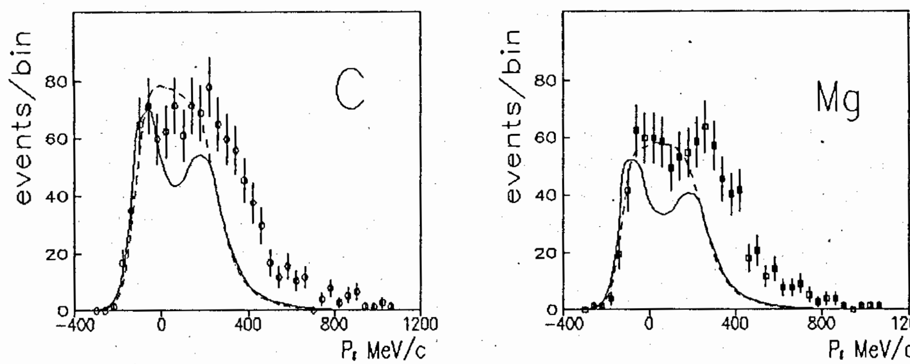

Fig.3.o-pion longitudinal momentum (P_π^l) spectrum (experiment) for Mg and C targets. The calculated spectra for Δ on assumption of isotropic (dotted) and cos$^2\Theta$ (solid) angular distributions.

Namely, the calculated spectra of longitudinal momenta of pions presented in Fig. 3 were normalized in comparison with the experimental spectrum for $p_l^\pi < 0$. It was assumed that the delta was excited on a target nucleon and ω_0=1192 MeV was used instead of the nominal ω_0=1232 MeV. The assumption of one pion exchange (OPE) provides a 1+3cos$^2\Theta$ angular distribution for pions which is clearly seen as two peaks on the calculated spectrum (Θ is an angle between the direction of the incident nucleon and π^- in the Δ rest frame). One can see that in this ensemble of events (when a single pion was observed) only 60—70 % of pions can be produced by delta de-excitation in the target. This conclusion is stable and cannot be distorted significantly by changing the limits for Fermi momentum and separation energy, by account of beam momentum distribution or trigger acceptance etc. The branching ratio was slightly changed assuming the isotropic distribution of pions (which is possible in case of ρ exchange), but the main result was firm for all assumptions—at least 30% of the single pion events are not due to the excitation of Δ^- on a target neutron. These non-delta events in subsequent analysis will be designated as X. The branching ratio (BR) of X events to all single pion events (topology $1\pi^-0p$) depending on the hypothesis of angular distribution ($1+3\cos^2\Theta$ or isotropic) is presented in Table 1.

Table 1. Branching ratio (BR) of X events

Target	BR_{1+cos^2}	$BR_{isotropic}$
C	37±4 %	29±4 %
Mg	43±5 %	33±5 %

The mean values of pion longitudinal momenta indicates a significant fraction of non-delta pions as well. Indeed, the calculated mean value for pions from the $\Delta(1232)$ excited on a quasi-free target nucleon was equal to 87 MeV/c and independent of the parameters used in the calculation as discussed above. The experimental values were much above the calculated one: 200±10 MeV/c in case of the magnesium target and 190±10 MeV/c in case of carbon one.

For the pions of the X group it is also shown that the pions carry off the major part of projectile-ejectile longitudinal momentum difference meanwhile the momentum of the recoil particle (target) is low. The experimental data on the mean longitudinal momenta of He ($< p^l_{He} >$) and pions ($< p^l_\pi >$) for all events of the topology $1\pi^-0p$ as well as the same values calculated for the delta excited on a target nucleon allowed us to derive the equations for X group pions:

$$\begin{aligned} &< p_t > - < p^l_{He} > - < p^l_\pi > \quad < 180\ MeV/c \quad (Mg) \\ &< p_t > - < p^l_{He} > - < p^l_\pi > \quad < 150\ MeV/c \quad (C) \qquad (1) \\ &< p^l_\pi > /(< p_t > - < p^l_{He} >) \quad > 0.7 \quad (Mg) \\ &< p^l_\pi > /(< p_t > - < p^l_{He} >) \quad > 0.7 \quad (C) \qquad (2) \end{aligned}$$

where $< p_t >$ was the mean momentum of the projectile—tritium. While the beam momentum spread was accounted as well as acceptance of the trigger counters the result was practically independent of these details.

Now let us analyze some possible processes which can produce high longitudinal momentum pions.

If the resonances N(1440) and N(1520) with isospin 1/2 or $\Delta^0(1232)$ are excited on a target nucleon, then they decay into $\pi^0 n$, $\pi^- p$, $\pi^0\pi^0 n$, $\pi^+\pi^- n$ or $\pi^0\pi^- p$. One can see that in these decays π^- if produced is associated with a proton or π^+ and cannot be registered as a single pion event. However, there is a nonzero probability to observe a single π^- when a slow proton is absorbed in the target. In this

case the longitudinal momentum of the registered π^- can be high enough to add this event to the group X. Calculations were provided for these reaction channels, and the fraction of absorbed protons was estimated to be approximately equal to 20% of Δ^0 decays with charged secondaries and 10% in case of N(1440,1520) decays. The total number of events $1\pi^-1p$ observed in our experiment was equal to 20% of the number of single π^- events. This means that the admixture of absorbed proton events cannot exceed 3% of intrinsic single π^- ($1\pi^-0p$) events if all $1\pi^-1p$ states are produced by the decay of resonances. So, these channels are not the major source of 30—40 % BR for X events.

An additional argument against the proton absorption hypothesis can be found in the analysis of the reaction on Ne gas. There was no proton absorption (a 50 cm range for 5 MeV protons), but the mean value of π^- longitudinal momentum 210±30 MeV/c was of the same order as in case of solid targets (Mg and C).

Considering the excitation of $\Delta^-(1620)$ in the target, we have calculated the mean values of π^- longitudinal momenta: approximately 290 MeV/c in case of two-particle decay and 200 MeV/c for three-body decay. To explain the measured mean momentum of pions by the influence of these pions, it is necessary to suggest that $\Delta(1620)$ should be excited more frequently than $\Delta(1232)$. However, the experimental data on the inclusive spectra of tritons in the reaction $C(^3He,t)$ show [3] that the strength of $\Delta(1620)$ does not exceed a few percent of that for $\Delta(1232)$. Moreover, the calculations show that the $\Delta(1620)$ decay kinematic properties contradict eq.(1,2).

The longitudinal momenta of nonresonant pions produced in the target nucleus are determined by phase volume and the calculated mean value was less by factor of 3–4 in comparison with the projectile–ejectile momenta difference contradicting eq. (1,2).

On the other hand one can see that eq.(1,2) are natural for two processes: coherent pion production in the target and for projectile excitation.

However, according to the calculations of [10, 16, 24] as well as our estimations, the momentum distribution of coherent pions in case of Δ-isobar excitation in the target should be quite narrow with a mean value of 230—280 MeV/c. The experimental distribution is peaked at 350—400 MeV/c with the mean value over the same region. Considering the excitation of Δ-isobar in the projectile, one can obtain a wide spread of pion momenta with a tail up to high values. However, the peak of the distribution is estimated to be at 150 MeV/c. Therefore the pions from the projectile cannot form a maximum at 400 MeV/c. If a higher mass resonance in the projectile is considered, then a maximum is shifted towards a lower momentum region. Thus these processes can provide a part of X group pions, but they are not sufficient to explain the distribution maximum at 400 MeV/c. This experimental peak can be regarded as evidence of coherent pion production via the excitation of resonances N(1440) or/and N(1520) in the target nucleus. It should be noted that we had used a more simplified model than in the calculations for delta, and therefore more accurate calculations as well as higher statistics of experimental data are desirable.

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