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NUCLEAR DELTA EXCITATIONS IN (^{3}He,t) AND RELATED REACTIONS AT ENERGIES FAR FROM THRESHOLD

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INTRODUCTION

Investigations of the spin-isospin excitations of nuclei at excitation energies of ≃300 MeV, where the Δ-isobar plays a dominant role, are being performed so intensively that it is impossible in one talk even to touch upon the majority of the relevant questions.

To understand nuclear matter properties at high excitation energies, the excitation of the internal degrees of freedom of constituent nucleons should be taken into account. It manifests itself mainly as a $N \rightarrow \Delta$ transition. An important role of the Δ in a wide class of nuclear reactions is well-known, and it is very prominent in charge-exchange reactions as was shown, for example, in the p(d,pp)n exclusive reaction[1] for virtual Δ-isobar. A large width and a dominant πN decay of the Δ lead to the Δ-h mode and even to a collective pionic mode[2-3] of nuclear excitations.

To study the properties of nuclear Δ-excitations with the Δ-isobar close to its mass shell, besides the relevant quantum numbers and energy transfers, it is necessary to provide, the following obvious conditions: (i) 3-momentum transfer should be not too high (about several hundred MeV); (ii) the target nucleus with large enough atomic number should be used; (iii) the initial N→Δ transition should occur at high enough local density; (iv) initial projectile kinetic energy (and the projectile) should be chosen so, that the N→Δ transition dominate in the cross section of the relevant "elementary" reaction. To detect a signal of collective excitations, one should compare characteristics of the reaction with nuclear and proton targets taking properly into account competing quasi-free mechanisms.

It was just the strategy realized in Dubna experiments on (^{3}He,t) charge-exchange at $p_\perp \simeq 0$ and small $p_\perp \simeq (350 \div 400$ MeV/c$)$[4-6]. In fact direct experimental studies of the nuclear Δ-excitations with the Δ-isobar near its mass shell started just in these experiments. The first clear signal on collective Δ-h excitations was detected. These results were confirmed by the experiments performed simultaneously by the Saturne group at energies below and close to Δ-production threshold[7-8] and by our analysis[6,9] of the 1 GeV (p,n) reaction data[10].

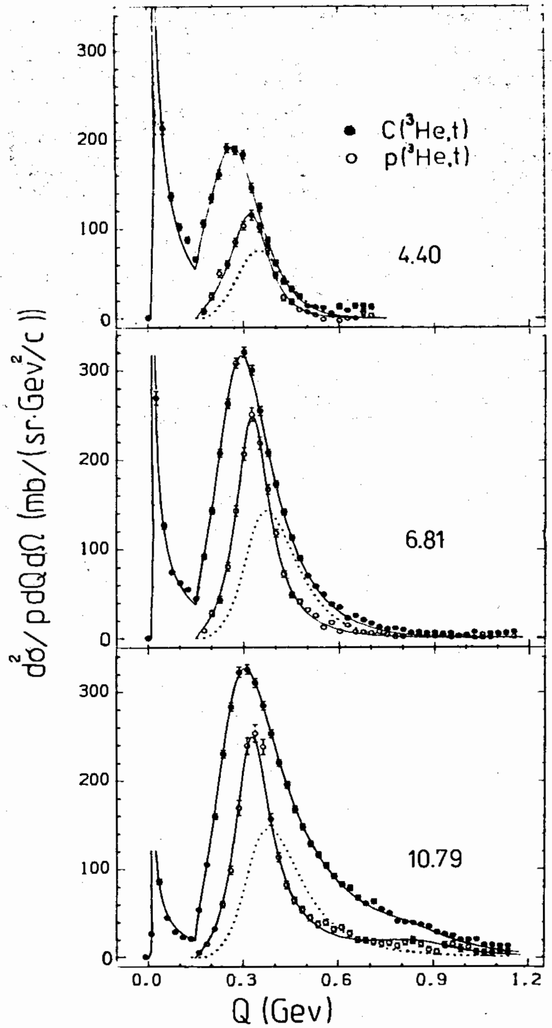

Fig.1 Invariant cross sections of the p(3He,t) (open circles) and C(3He,t) (full circles) charge-exchange at a zero angle. The dotted lines represent our estimations of the quasifree Δ-production contribution. The full lines are a data fit.

The very first results [4] have shown, that at projectile momenta p_o > 1.4 GeV/c/nucl. the channel with Δ excitations dominates in the cross sections of the (^{3}He,t) reaction at 0^0. The Δ-peak in the cross sections at energy transfers $Q=(E_0-E_t)\simeq 300$ MeV (Fig.1) has clear signatures of its collective nature: (i) it is shifted down on the Q-scale and (ii) its width is almost twice larger than that of the p(^{3}He,t)Δ^{++} cross section. These signatures cannot be due to Fermi-motion effects. Finally,the excitation of heavy isobars has been also noticed at T ⩾ 2.8 GeV/nucl.

The (p,n) data at 1 GeV[11] have demonstrated two other features (Fig.2) which we would like to mention. First, there is no noticeable downshift of the Δ-peak in the d(p,n) reaction. Second, the Δ-peak shape is A-dependent: the larger A the broader peak. This fact was interpreted[6,9] as evidence for an essential contribution from mesonless Δ-deexcitation through NΔ→NN channels. A further analysis[11] of these data has shown that such mesonless channels must be taken into account to describe the angular and A dependence of the integrated (p,n) cross sections.

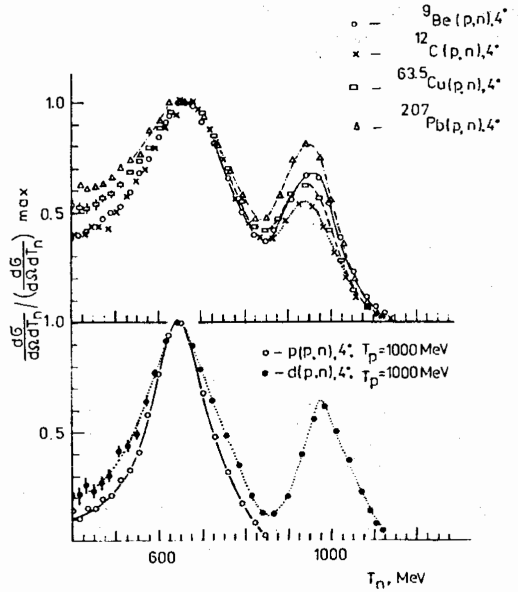

Fig.2 Data on the (p,n) reaction at 1 GeV versus the kinetic energy of neutron. All lines are drawn by hand.

COMPARATIVE ANALYSIS OF (p,n) AND (^{3}He,t) REACTIONS

To understand the energy dependence of the forward (^{3}He,t) and (p,n) cross sections, it is useful to review data on the NN→NNπ reaction, which can be naturally treated as an "elementary" one for inclusive experiments. The total $pp \to pn\pi^+$ cross section/12,13/ is shown in Fig.3. The cross section rises from π-production threshold at ≃796 MeV/c up to its maximum near $p_{lab} \simeq$ 2 GeV/c and then falls down; it can be well described using parametrization/14/ up to about 3 GeV/c. The approximation $\sigma(\text{mbarn}) = \dfrac{187 \pm 12}{s^{1.28 \pm 0.03}}$ (where s (in GeV^2) is the total CM energy squared) works quite well at higher momenta. We also present similar approximations/15/ of

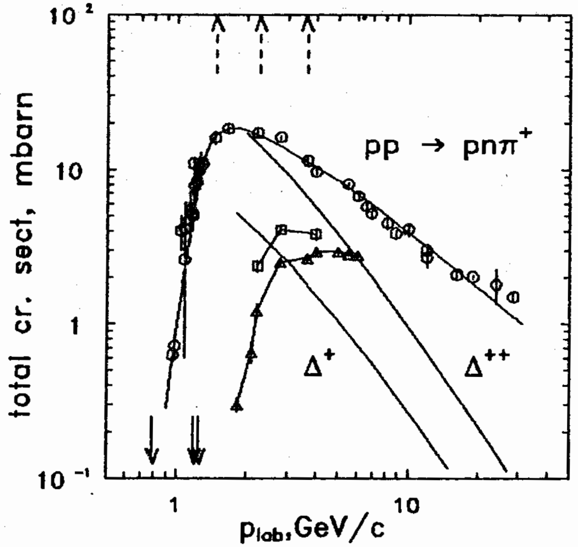

Fig.3 Momentum dependence of total cross sections of the reactions $pp \to pn\pi^+$ (o), $pp \to pp\pi^+\pi^-$ (Δ) and $pp \to pn\pi^+\pi^0$ (squares). The data are taken from refs./12,13/. The full lines represent approximations explained in the text. The single and double arrows indicate the π- and Δ-production thresholds respectively. The dashed arrows indicate the momenta per nucleon, where the Dubna experiments on (3He,t) charge- exchange with Δ-excitation were performed.

the data/13,16/ on the $pp \to n\Delta^{++}$ and $pp \to p\Delta^+$ cross sections which fall down as $\simeq s^{-2.3}$ over the momentum interval up to ≃ 30 GeV/c.

We conclude/16/ that the total cross section of the $pp \to pn\pi^+$ reaction near its maximum is almost completely due to Δ-excitation. Keeping in mind that Δ-production threshold is about T≃647 MeV, and taking into account that at $p_{lab} \geqslant$ 3-4 GeV/c the Δ-production does not dominate in the $\sigma(pp \to pn\pi^+)$, we also conclude, that optimum conditions to study nuclear Δ-excitation are in the projectile kinetic energy interval from ≃800 up to ≃3 GeV/nucleon. The experiments at the Dubna synchrophasotron were performed just within this optimum energy region.

Discussing the energy dependence of the (^{3}He,t) cross sections, it is necessary to take properly into account the ^{3}He→t transition formfactor because at a fixed triton emission angle and a fixed energy transfer $Q = E_0 - E_t$ the 4-momentum transfer t depends on projectile energy E_0. This dependence is quite strong at E_0 close to Δ-production threshold and therefore the formfactor distorts drastically the cross sections measured near threshold (Fig. 4) apart from the distortion caused by phase space restrictions.

We have assumed/15/ that the energy dependence of the charge-exchange (CEX) forward cross sections follows the energy dependence of the relevant "elementary" reaction cross section and the transition ^{3}He formfactor also affects the observable energy dependence in the (^{3}He,t) case. Following this ansatz, we have calculated the so-called "reduced" cross sections $\bar{\sigma}$ at base energy E_{ob}(chosen at 800 MeV/A):

$$\bar{\sigma} = \frac{C(E_{oi})}{3F(t)} \cdot \frac{d^2\sigma[A(^3He,t)]}{pdQd\Omega}$$, where $F(t) = \exp(-27.74|t|)$ is the magnetic transition ^{3}He → t formfactor; the factor $C(E_{0i}) = \sigma(pp \to pn\pi^+)|_{E_{ob}} / \sigma(pp \to pn\pi^+)|_{E_{oi}}$ compensates the energy dependence of the "elementary" reaction.

The quantities $\bar{\sigma}$ for the p(p,n) and p(^{3}He,t) reactions are presented in Fig. 5a. The data were taken from refs./5,10,13,18/. Taking into account the experimental uncertainties, one can see a remarkable agreement between all

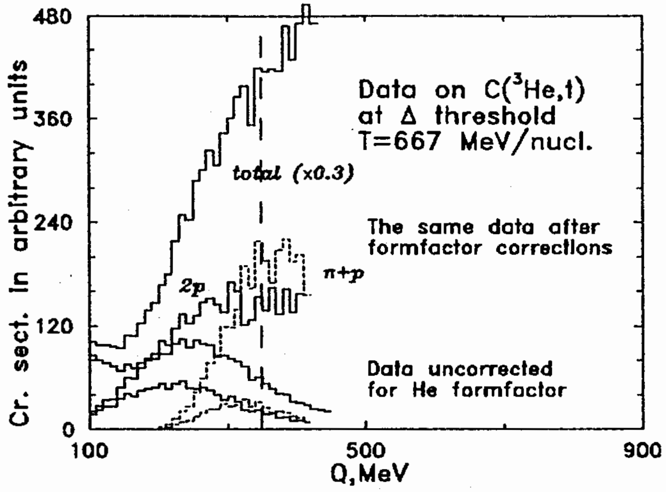

Fig.4 Data on C(3He,t) charge- exchange at T=667 MeV/nucl. taken from ref./17/ with- and without compensation of the 3He formfactor. The Q-spectra of tritons accompanied by the emission of two protons (2p events) or a πp pair (π+p events) from the target are presented. The total spectrum is also shown. The data corrected for the formfactor are normalized as explained below in the text.

the data sets, obtained in different reactions and at various energies, not only in the Δ-peak shape but also in its magnitude. This "universality" can open the way to obtain experimental information on transition formfactors of exotic radioactive nuclei using charge exchange reactions on proton or deuterium targets, for example (^{6}He,^{6}Li) or (^{11}Li,^{11}Be). For the 800 MeV p(p,n) data a small enhancement at Q≃500 MeV arises due to the final state interaction between nucleons as shown in ref/18/ (the corresponding kinematic region moves quickly to higher Q-values with increasing E_0 and escapes the region of our interest at T_0=1 GeV). The full line in Fig.5a corresponds to the p(p,n) invariant cross section at $\vartheta=0^0$ and T=800 MeV calculated in the π- and ρ-meson exchange picture taking into account interference between all relevant diagrams and the Landau-Migdal parameter $g'_{N\Delta}\simeq 0.3$ as well. It agrees with the data quite satisfactorily.

The same procedure was applied to the d(p,n)/10/ and d(p,p′Δ^0) data/19/ on quasi-free Δ^0 production taking the relevant isospin factor into account and treating the pp → nΔ^{++} reaction as an "elementary" one for the latter set. In this case the Δ-peak is not shifted as can be seen from Fig.5b (the vertical dashed line marks the Δ-peak position in charge-exchange on a proton target, see Fig.5a). The width of the Δ-peak is slightly larger due to Fermi-motion.

To apply the above procedure to the data obtained with a nuclear target, it is necessary to take into account different absorption factors of the projectile-ejectile passing through the target nucleus. This has been made reducing the (^{3}He,t) data to the (p,n) ones; the results are plotted in Fig.5c.

A remarkable "scaling" is again evident for the inclusive data obtained at energies far from Δ-threshold. A clear shift of about 30-40 MeV to lower Q is also evident. It does not depend on the type of projectiles and their energies.

The data from KEK/19/ on quasi-free Δ^0 production demonstrate a shift to higher Q-values because the Δ-isobar is created on a bound nucleon. So, it is clear that the downshift of the nuclear Δ-peak cannot be explained by the Fermi-motion effects. Moreover, quasi-free Δ-production can contribute only about 50% (or less) to the total integrated cross section as predicted/5,6,9/.

We can conclude that the reaction mechanisms of both reactions are in principle the same and the energy dependence of the forward charge-exchange cross sections follows the energy dependence of the relevant "elementary" reaction cross sections.

It should be noted that the inclusive Saturne data/17/ at threshold energy (uppermost histogram in Fig.5c) must deviate from the higher energy ones at Q ⩾ 300 MeV due to other mechanisms making large contribution in this region. This follows from the results on the pp → nX reaction/13,18/ and their analysis. The C(^{3}He,t)pp and C(^{3}He,t)πp data/17/ obtained at Saturne will be discussed a little later.

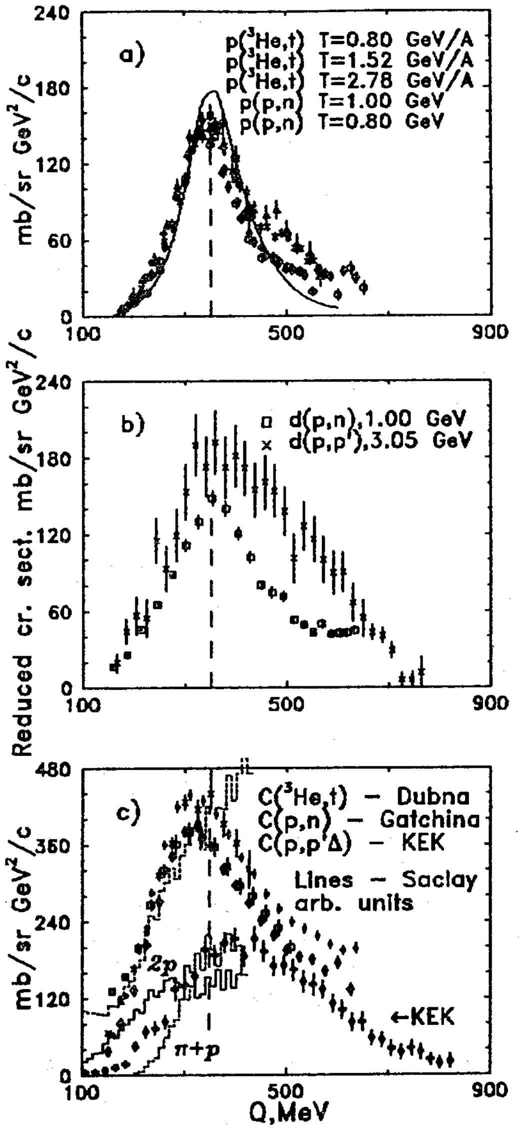

Fig.5 Reduced cross sections of the (3He,t), (p,n) and (p,p'Δ) reactions. The Saclay data are normalized to the KEK ones at the maximum of the triton Q-spectrum with π+p selection. A detailed description of the figure is given in the text.

ANGULAR DEPENDENCE OF THE CHARGE EXCHANGE REACTION WITH Δ-EXCITATION AND TOTAL CROSS SECTIONS

At energies far from Δ-threshold the angular (or $p_\perp^2$) dependence of the CEX cross section with nuclear Δ-excitations can be extracted from the 1 GeV (p,n) data[10] obtained at 4 different angles. It was measured at 1.6 GeV/nucl. in the (^{3}He,t) experiment[20]. The p(^{3}He,t) and C(^{3}He,t) cross sections integrated over the Δ-peak region have a similar $p_\perp^2$ dependence (Fig.6). The slope parameters are 44 ± 19 and 38 ± 10 GeV^{-2}/c^{-2} for the p(^{3}He,t) and C(^{3}He,t) cross sections, respectively. These values are very close to the sum of the slope parameter of the pp → NΔ differential cross section (about 11 GeV^{-2}/c^{-2}) and the ^{3}He formfactor slope (about 27 GeV^{-2}/c^{-2}).

Integrating the measured $d\sigma/d\vec{p}_\perp$ cross sections, the first estimation of the total cross sections of the (^{3}He,t) reaction with Δ-excitations at T≃1.6 GeV/nucl was obtained[20]: $\sigma^p_{CEX,\Delta}$=0.6 ± 0.3 mb and $\sigma^C_{CEX,\Delta}$=1.4 ± 0.4 mb.

The angular dependence of the A(p,n) reaction with Δ-excitations does not differ from that in the p(p,n) case as well because $d\sigma/d\Omega[A(p,n)_\Delta B] = N_{eff} d\sigma/d\Omega[p(p,n)\Delta]$ as shown in

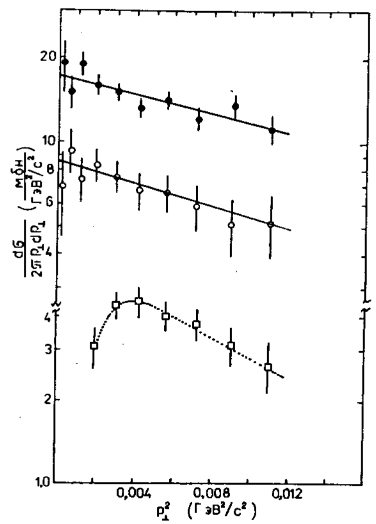

Fig.6 Cross sections of the (^{3}He,t) reaction integrated over the Δ-peak (Q ⩾ 150 MeV). Full circles – C(^{3}He,t), open ones – p(^{3}He,t), squares – "quasielastic" charge exchange (Q ⩽ 150 MeV). Full lines – exponential fit to determine the slope parameters, dashed line is drawn by hand.

ref.[11,15,21]. Here N_{eff} is the effective number of nucleons participating in the process.

It has been argued[11,15,21] that the N_{eff} should depend on the atomic number of target nuclei as $æ_1 A^{1/3}+æ_2 A^{2/3}$. The latter term stems from the NΔ interaction with nucleons of the target nucleus; NΔ → NN and NΔ → NΔ (elastic or charge exchange) channels are possible. The same A-dependence should be for the total CEX cross sections (with Δ-excitations).

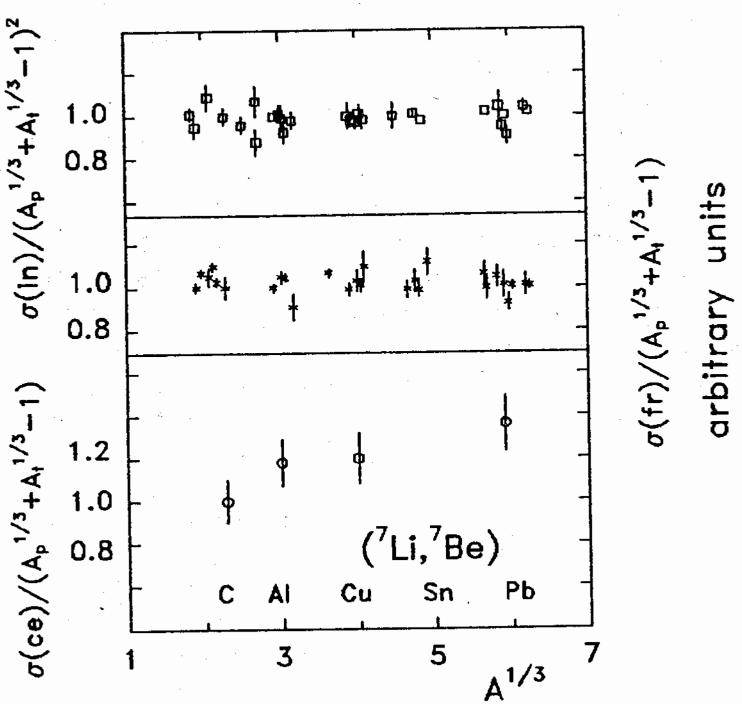

Fig.7 Dependence of the total inelastic cross section σ(in), the total fragmentation cross section σ(fr) and the total CEX cross section σ(ce) on the atomic number of target nuclei in 7Li interactions. The figure is taken from ref./23/.

The total cross sections of the $(^7Li,^7Be)$ and $(t,^3He)$ reactions have been measured recently at a projectile energy of ≃2.2 GeV/nucleon[22]. The experiment was performed at the Dubna synchrophasotron with the HYBS setup[23]. The measured cross sections are the sum of the "quasielastic" CEX and Δ-excitation cross sections. In fact, the contribution from the nuclear Δ-excitation region dominates[5,6] at energies far from threshold; the estimated contribution of the "quasi-elastic" CEX is about 10-12% at T = 2.2 GeV/nucl.

The A-dependence of the $(^7Li,^7Be)$ total cross sections follows qualitatively the predicted one (see Fig.7). The A-dependence of $\sigma^{inel.}_{tot}$ and σ^{fragm}_{tot} are also shown for comparison. The 1-st cross section behaves like $(A^{1/3}_{proj}+A^{1/3}_{targ}-b)^2$, the 2-nd one like $(A^{1/3}_{proj}+A^{1/3}_{targ}-b)$ with b=1. If there were no secondary interactions of the created Δ-isobar (i.e. quasi-free production should take place), the CEX cross sections would have the same A-dependence as the fragmentation cross sections. In fact, the observed A-dependence is $\sigma_{CEX}=C_1(A^{1/3}_{proj}+A^{1/3}_{targ}-1)+C_2 A^{2/3}_{targ}$ with $C_1/C_2=0.088 \pm 0.040$. The cross sections are rather small; for example, σ(ce) on carbon target is 0.29±0.03 mb. A similar behaviour has been demonstrated in the A(p,n) case[11,21].

SEMI-EXCLUSIVE EXPERIMENTS ON Δ-EXCITATION IN NUCLEI

The first data demonstrating the effects of secondary NΔ → NN interactions in exclusive type experiments, have been obtained as a byproduct of the experiment[19] on quasi-free Δ-production in the A(p,p′) reaction. "Wrong" π^+p pairs, with effective mass in the Δ-region, emitted from a nuclear target, were detected. This can occur just due to the $p\Delta^+ \to n\Delta^{++}$ secondary process after inducing the Δ^+ in the $p(p,p')\Delta^+$ primary reaction.

The data from Saturne[17] (Fig.4 and 5c) demonstrate importance of the ΔN → NN channel (events of the 2p type) which contributes just to the region of low Q-values. The shape of the "π+p" part of the triton spectrum agrees rather well with the KEK quasi-free data. Unfortunately, the phase space restrictions at threshold energy make it difficult to draw definite conclusions concerning relative weights of various Δ-deexcitation channels.

The first data on topological characteristics of the $A(t,{}^3He)$ reaction have been recently obtained at energies far from threshold[24] with the Dubna HYBS setup (Table 1).

Table 1. Number of A(t,3He) events with different topology. Mean 3He momentum is quoted for some Mg(t,3He) charge-exchange classes of events. The triton beam momentum is p_0=9.1±0.06 GeV/c; σ_p≈0.4 GeV/c. Neutral particles are unobservable; "π" denotes π^- meson; π^+ mesons can be identified as protons.

Type of events													
"0"	π	πp	π2p	π3p	π4p	π5p	p	2p	3p	4p	2π	2πp	2π2p
$Ne(t,{}^3He)$ total: 110 events													
	36	13	10	4	4	1	24	6	2	0	1	0	0
$Mg(t,{}^3He)$ total: 1711 events													
693	568	132	24	7	1	0	212	52	7	1	5	7	2
$\langle p_{3He} \rangle$, GeV/c													
8.92 ±0.02	8.74 ±0.02	8.56 ±0.04					8.80 ±0.03	8.64 ±0.06					

There are such classes of events, which cannot be explained within the quasi-free Δ-production framework (for example, "p" and "2p" topologies) and confirm unambiguously the complicated nature of nuclear Δ-excitations. It should be mentioned that the inverse $(t,{}^3He)$ reaction is being investigated instead of $({}^3He,t)$ for the first time.

SUMMARY

A collective nature of nuclear Δ-excitations, first observed in the Dubna experiments[4,5], is now confirmed in a large number of experiments on charge-exchange including exclusive ones. All experimental observation can be qualitatively understood with the Δ-h and collective pionic modes of nuclear excitations[2,3,25]. The energy dependence of the CEX forward cross sections and their angular dependence can be explained. By the way, the "Δ-dominance" effect can be qualitatively interpreted: the

cross section of the quasielastic CEX on nuclei should fall down as s^{-2} as it follows from the pn → np data while the inelastic CEX cross sections fall down as $s^{-1.3}$ (after passing the maximum near T = 1 GeV/nucl.).

Collective modes of nuclear excitations are coupled in the standard Δ-hole model with the longitudinal nuclear response function; in the transverse one collective effects are usually not expected. But some evidences for a possible downshift of the nuclear Δ-peak in the (π^-,π^0) reaction[26] and for a q^2-dependent shift of the Δ-peak centroid in Δ-electroproduction in nuclei were obtained[27]; in both cases the transverse nuclear response is probed. So, further efforts to clarify the problem are needed.

As a concluding remark, we would like to point to an other almost untouched problem: do collective excitations with strangeness exist when a broad Y^- resonance is excited in nuclei? By analogy with πA physics, the first impression

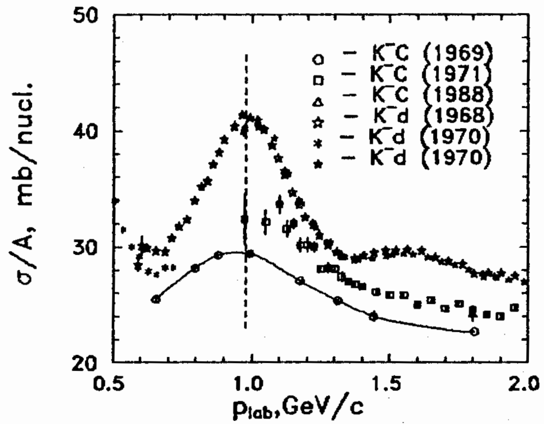

Fig.8 Total cross section of K C̄ and K d̄ scattering. The vertical line marks the position of the peak maximum in σ_{tot}(Kd). The full line corresponds to a cubic spline fit. The data are taken from refs.[28,29].

can be received looking at the energy dependence of the K^-A total cross sections in the region around 1 GeV/c K^- momenta. Unfortunately, the available data are very scarce (Fig.8). This question is now completely open.

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