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OBSERVATION OF THE DOMINANCE OF THE TARGET Δ EXCITATION AND THEIR COLLECTIVE NATURE IN THE (^{3}He, t) CHARGE-EXCHANGE AT HIGH ENERGIES

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Spin-isospin excitation of the nuclear matter at high (~ 300 MeV) energy transferred to it are now intensively investigated in experiment, in particular, using the charge-exchange reaction (^{3}He,t) . The interest in this class of reactions stems, first of all, from the possible difference between properties of the free and intranuclear Δ-isobars (as resonating πN system); there may also appear other effects of the collective (not one-nucleon) nature, up to the formation of an isonuclear-type system /1/. Favourable conditions for interaction of a Δ -isobar, produced in a nucleus with other nucleons were provided in our experiments /2,3/, where a comparatively small momentum (300–400 MeV/c) was transferred to Δ since at large initial moments (from 4.4 to 18.3 GeV/c) we have detected tritons at small ($\theta \lesssim 0.4^\circ$) angles. This experiment allowed us to observe for the first time that at high energies the charge-exchange cross section on a nucleus is mainly determined by the contribution from high (~ 300 MeV) spin-isospin excitations of the nuclear matter, and that the behaviour of the cross sections of ^{12}C(^{3}He,t) and p(^{3}He,t) reactions differ qualitatively from each other:
a) the maximum of " Δ-isobar" peak in ^{12}C(^{3}He,t) charge-exchange is shifted towards lower excitation energies as compared to that one in the charge exchange on a free proton; b) the width of the peak is larger than the one for reaction $p(^3\mathrm{He},t)\Delta^{++}$;
c) the ratio of the yield of ^{12}C(^{3}He,t) reaction to that of $P(^3\mathrm{He},t)\Delta^{++}$ reaction is substantially greater than that expected from the Glauber type calculations where the known data on $NN\to N\Delta$ cross sections have been used. The downshift of the isobar peak in ^{12}C(^{3}He,t) reaction cannot be explained by the influence of the Fermi-motion of nucleons in the ^{12}C nucleus. All this tells us

that some collective effects at high (~300 MeV) spin-isospin excitations of the nuclear matter are essential. The one-pion-exchange (OPE) model allows us to established the connection of these effects with analogous phenomena in inelastic (p,n) charge-exchange on nuclei and in the energy dependence of the total πA cross sections, thus revealing a common nature of all these phenomena.

1.1. Momentum spactra of tritons emitted at small angles were measured at a JINR synchrophasotron by a magnetic spectrometer "ALPHA" /5/. A detailed description of the experiment and data processing (unfolding from the spectrometer resolution) can be found in ref. /6/.

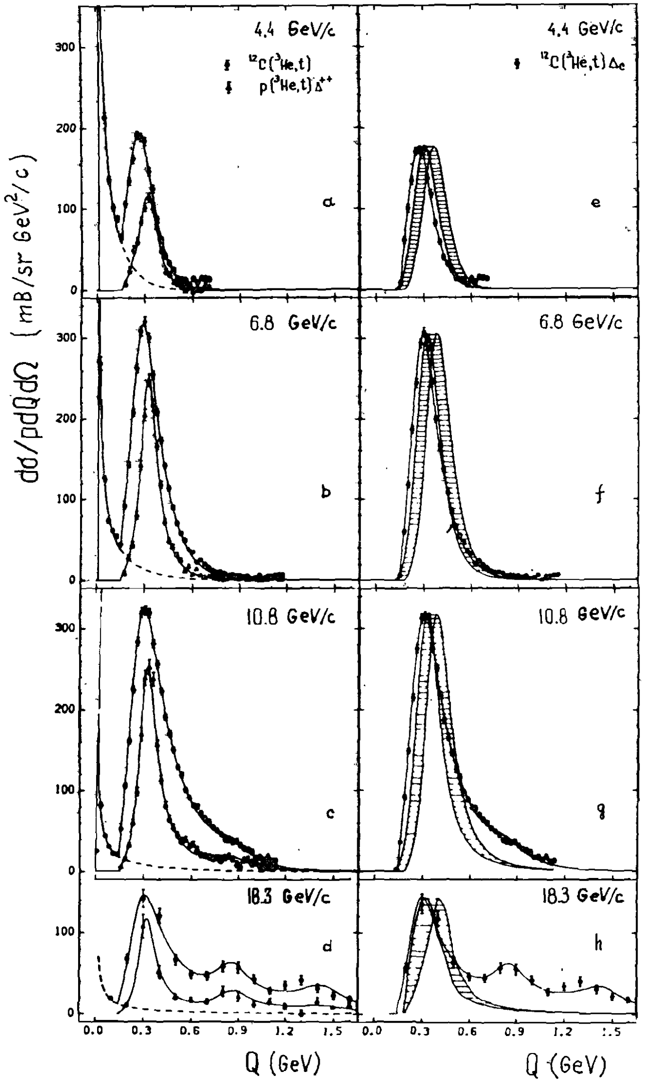
In Figs. 1a-d, we present our measured invariant differential cross sections for the (^{3}He,t) reaction on carbon nuclei and protons as functions of the energy transferred to the target, $Q = E_{^3He} - E_t$. The cross sections of $p(^3$He,t) reaction have a peak in the energy region $Q \sim 300$ MeV, the form of which is well described by a Δ-resonance line /7/ distorted by the ^{3}He nucleus form factor (solid curves in Figs. 1a-d). The Breit-Wigner

Fig.1.

a-d) Invariant cross sections of reactions ^{12}C(^{3}He,t) and p(^{3}He,t) when the effects of energy resolution are taken into account; dashed curves are an expected contribution from the "tail" of the peak of nuclear excitations.

e-h) Invariant cross sections of reaction ^{12}C(^{3}He,t) with excitation of the Δ-isobar obtained after subtracting the contribution from the "tail" of low-Q nuclear excitations; shaded strips are regions of expected cross sections for the quasifree isobar production when the Fermi-motion effects are considered in different ways.

parameters of Δ-resonance, ω_0 and Γ_0, found by analysing the cross sections of charge exchange on protons, are in good agreement with each other at all energies. Their average values $\bar{\omega}_0 = 1234 \pm 3$ MeV and $\bar{\Gamma}_0 = 116 \pm 7$ MeV are consistent with the tabulated values /9/. At momenta above 7 GeV/c in the cross



sections of $p(^3He,t)$ reaction at $Q > 500$ MeV the contribution from the excitations of heavy isobars with isospin 3/2 of families $\Delta(1600)$ and $\Delta(1900)$ is evident. At momentum 18.3 GeV/c that contribution (estimated without introducing a possible nonresonance background) reaches the value of 30-35%.

The charge-exchange cross section on the carbon is characterized by two peaks, at low and high excitation energies. One can see from Fig.1, that with energy increasing the projectile energy the contribution to the charge-exchange cross section on the nucleus from the excitation of nuclear levels fastly decreases and the excitation of Δ-like degrees of freedom in the target-nucleus dominates in the $^{12}C(^3He,t)$ charge-exchange starting from momenta higher than 4.4 GeV/c . In the reaction on nucleus the maximum of the Δ peak is downshifted with Q as compared to the Δ-peak position in the reaction on proton; its width is considerably larger; the ratio of cross sections $\frac{d\sigma}{d\Omega}(c)/\frac{d\sigma}{d\Omega}(p)$ amounts to about 2 (see the Table).

Table

Beam momentum, GeV/c	Position of the Δ-peak maximum, MeV		FWHM, MeV		$R_\Delta = \dfrac{\frac{d\sigma}{d\Omega}(c)}{\frac{d\sigma}{d\Omega}(p)}$
	$p(^3He,t)$	$^{12}C(^3He,t)$	$p(^3He,t)$	$^{12}C(^3He,t)$	
4.40	322 ± 2.5	274 ± 2.5	138	182	1.82 ± 0.05
6.81	327 ± 1.5	295 ± 1.5	129	204	1.77 ± 0.03
10.79	327 ± 2	305 ± 2	129	257	1.95 ± 0.03
18.3	–	–	–	–	2.14 ± 0.17

The peak of low-lying nuclear excitations in the reaction $^{12}C(^3He,t)^{12}N^*$ was approximated on the basis of data from ref./8/. The peak of Δ-excitations was approximated by the same Breit-Wigner function as in the case of the charge-exchange

reaction on hydrogen (solid curves in Figs. 1a-d). The Breit-Wigner parameters ω_0 and Γ_0 for the Δ-peak in reaction $^{12}C(^3He,t)$ satisfactorily agree with each other at all energies. However, their averages $\bar{\omega}_0^C = 1304 \pm 10$ MeV and $\bar{\Gamma}_0^C = 330 \pm 20$ MeV are essentially different from those obtained for reaction $p(^3He,t)$. (The parameters have been found under the assumption that the Δ-isobar is produced on a nucleon being at rest in the nucleus).

At momenta $P_{^3He} \geqslant 10.79$ GeV/c and at $Q > 600$ MeV the contribution from excitation of heavier isobars with isospin 3/2 is also observed; at the momentum 18.3 GeV/c it amounts to about 40% .

1.2. The difference between the characteristics of Δ-excitations of nuclei and protons cannot be explained within the so-called mechanism of "quasifree Δ-production" . Really, in this case the shape of the Δ-peak will be defined by the convolution of the cross section of "elementary" $p(^3He,t)\Delta^{++}$ reaction on a free proton with the momentum distribution of nucleons in carbon $\rho(\vec{P}_N)$:

$$\frac{d\sigma(c)}{P_t\, d\Omega\, dQ} \sim \int d\vec{P}_N\, \rho(\vec{P}_N)\, I(\vec{P}_N)\, \frac{d\sigma(p)}{P_t\, d\Omega\, dQ}(t(Q), \omega'(Q,\vec{P}_N)), \qquad (1.1)$$

where $I(\vec{P}_N)$ is the ratio of fluxes of initial particles for the reaction $p(^3He,t)\Delta^{++}$ on a nucleon at rest and on a nucleon moving with momentum $\vec{P}_N$; the energy of such a nucleon is given by the relation

$$E_N = M_A - M_{A-1} - \frac{P_N^2}{2M_{A-1}} = m_N - \varepsilon_{SEP} - \frac{P_N^2}{2(M_A - m_N - \varepsilon_{SEP})}, \qquad (1.2)$$

where M_A is the mass of a target-nucleus, m_N is the nucleon mass, ε_{SEP} is the separation energy:

$$-\varepsilon_{SEP} = M_A - M_{A-1} - m_N , \qquad (1.3)$$

M_{A-1} is the mass of a system of (A-1) nucleons. In the calculations of effects of the Fermi-motion we have used for a minimal value of the separation energy (16 MeV) and also mean values of ε_{sep} taken from the data on electron scattering /19/ : 22 MeV (the average energy of nucleon separation from carbon), 17.5 MeV (the average energy of separation of a nucleon from p-shell), and 38.1 MeV (the same from s-shell). We have also used momentum distributions of nucleons in carbon following both from the harmonic-oscillator model and Fermi-gas model. Calculations of the convolution (1.1) were carried out in two variants.

In the first variant, it was assumed that the parameters ω_o and Γ_o of the Breit-Wigner function are the same as for the reaction on a free proton. As an argument ω'^2 for the cross section of reaction $p(^3He,t)\Delta^{++}$ we took the quantity

$$\omega'^2 = (Q+E_N)^2 - (\vec{P}_{3He} - \vec{P}_t + \vec{P}_N)^2 \qquad (1.4)$$

meaning the total energy squared in the c.m.s. of an intranuclear nucleon and a virtual pion exciting it. Kinematically, this calculation corresponds to the production of a free Δ-isobar on a nucleon with a mass smaller than the mass of a free nucleon (due to its coupling in a nucleus). Therefore, the excitation of the isobar of "nominal" mass $\omega_o = 1232$ MeV requires a higher energy transfer than in the reaction on a free proton. This method gives a wider Δ-peak and an upward shift of its maximum by (30–40) MeV in contrast to the experiment (where down-shift is observed).

In the second variant, it has been assumed that the resonance in the system "virtual pion + intranuclear nucleon" is formed at the same relative momentum in the c.m.s. of those particles as in the scattering of real pions on a free proton. In this variant, the Δ-peak gets wider and is shifted towards smaller Q. However, the shift of the maximum at momenta larger than 4.4 GeV/c is negligible, and at 4.4 GeV/c it amounts to about 25 MeV, which is significantly smaller than the experimentally observed one (at 4.4 GeV/c it equals 48+4 MeV).

To estimate the charge-exchange cross section on carbon, we have used the Glauber-Sitenko model assuming quasifree Δ-production and using the known data on the cross sections of "elementary" $pp \to n\Delta^{++}$ reaction. At the same time we have computed the differential cross sections $\frac{d\sigma}{p\, d\Omega dQ}$ of charge-exchange on protons. The calculated cross sections are in good agreement with the data /6/, but the ratio $R_\Delta = \frac{d\sigma(c)}{d\Omega} \Big/ \frac{d\sigma(p)}{d\Omega}$ is more than twice as small as the experimental ratio (see the Table).

Thus, on the basis of the assumption of a quasifree production of Δ-isobars in a nucleus one cannot explain basic peculiarities of the charge-exchange (^{3}He,t) cross sections on carbon.

2.1. The effects, we have observed in the (^{3}He,t) charge-exchange on carbon, should also appear in other reactions with the production of isobars in nuclei when comparatively small longitudinal and zero transverse momenta are transferred to the target. They should first be looked for in the (p,n) charge-exchange at intermediate energies. Nucleon-nucleon reactions in that region of energies are analysed within the OPE model. It provides a suitable basis for determining the connection between (^{3}He,t), (p,n), and other reactions. By using the diagram of Fig.2, one may show that the cross sections of $p(^3He,t)\Delta^{++}$ and $p(p,n)\Delta^{++}$ reactions are connected by

$$\frac{d\sigma}{P_t\, d\Omega dQ}(^3He,t) = \frac{m_p\, P_{3He}}{\pi\,\omega}\, g_{rs}(t)\, e^{R^2t/3} \frac{d\sigma}{dt\, d\omega}(pp \to n\Delta^{++}), \qquad (2.1)$$

where $\exp(R^2t/3)$ is a form factor of the ^{3}He nucleus (R = 1.8 fm), $g_{rs}(t) \simeq g_{rs}(0) = 0.7$ is the Glauber-Sitenko

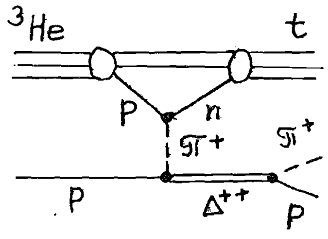


Fig.2. Main OPE diagram for the p(^{3}He,t) reaction.

correction for rescattering of a target nucleon and produced Δ-isobar by projectile nucleons, t is the 4-momentum transfer squared. The $pp \to n\Delta^{++}$ cross sections were calculated by the OPE model /4/ with the use of data on $\sigma_{tot}(\pi^+p)$. The results of calculations are in good agreement with our data and Saclay data /8/ (see Figs.3 and 4). This testifies to the earlier conclusion /2,3/ that at energies higher than 800 MeV/nucl. a dominant mechanism of the reaction p(^{3}He,t) with emission of tritons at small angles is the Δ^{++} production in the target.

We have also performed an analogous OPE analysis for data on the reaction p(p,n) Δ^{++} obtained at energies 600–1000 MeV /10,11/ under conditions similar to that used in our experiments /2,3/ and in experiments at Saclay /8/. From Fig.5 it is seen that the OPE calculation is in good agreement with data /10/. Comparison of the results of OPE with data /11/ on the reaction p(p,n) for energies T_p = 798, 764 and 647 MeV is shown in Fig.6. It is clear that the OPE in version /4/ well reproduces the data at 798 and 764 MeV (within to normalization accuracy $\simeq$ 15%) around the isobar peak but in a low-energy part of the spectrum a discrepancy is observed. The latter is not a consequence of a particular version of the OPE model. In ref. /11/ it is shown that in the low energy part of the neutron spectrum at low initial energies ($\lesssim$ 700 MeV) the final state proton-neutron interaction (FSI) gives a large contribution to the cross section. It may, in particular, result in the formation of deuterons (the cross section of $pp \to d\pi^+$ reaction has a maximum at T_p = 600

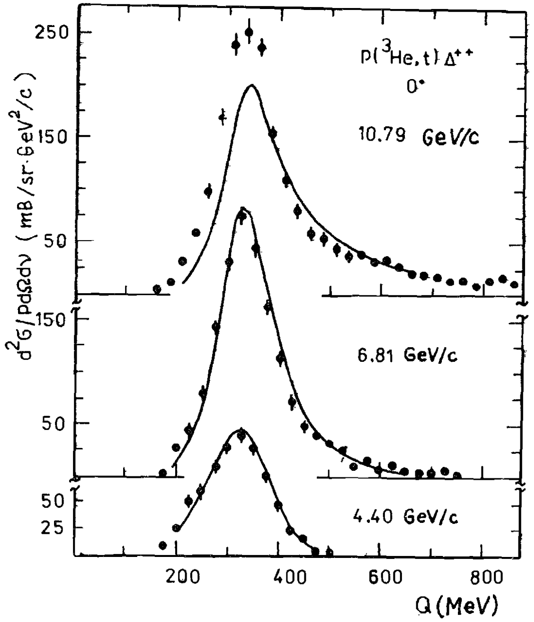


Fig. 3a. Invariant cross sections for the reaction p(^{3}He,t)Δ^{++} from ref./6/. The curves represent our OPE calculation.

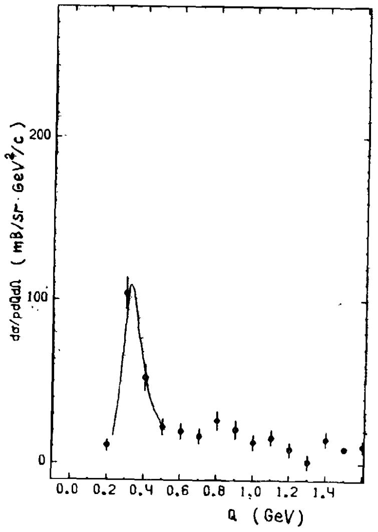


Fig. 3b. Invariant cross sections for the reaction p(^{3}He,t)Δ^{++} from ref./6/. The curve is calculated by the Glauber-Sitenko model.

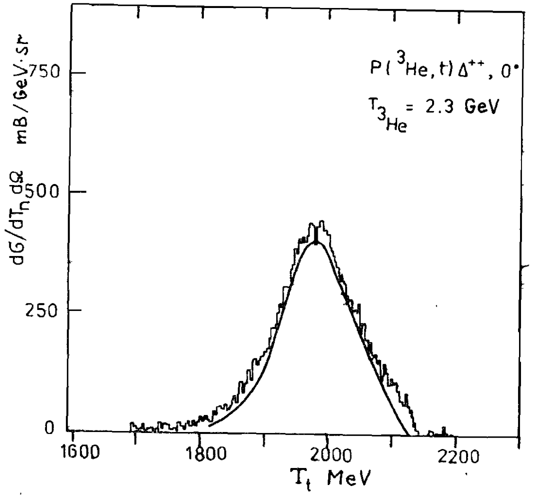


Fig. 4. Cross section of the reaction p(^{3}He,t) (histogram /8/). The solid curve is our OPE calculation.

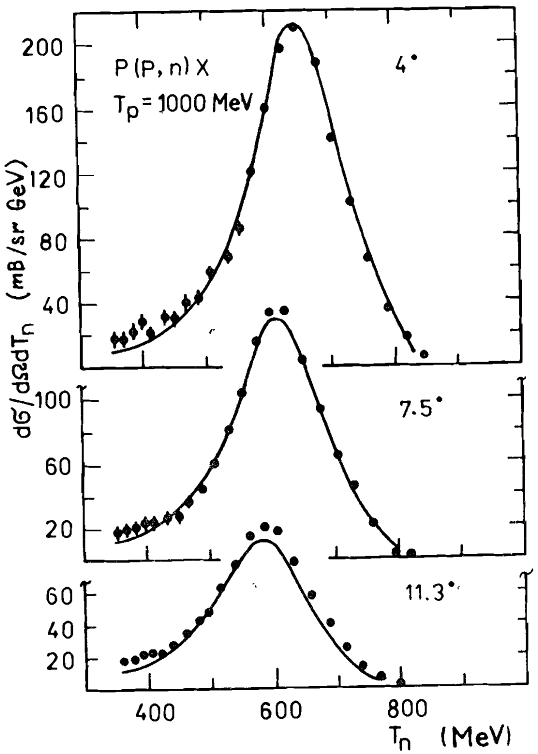


Fig.5. Cross sections of the reaction $p(p,n)$ at 1000 MeV /10/. The curves are our OPE calculations with the spectrometer resolution effects taken into account. For angles 7.5^o and 11.3^o the proton initial energy was varied within limits of its accuracy (2%, /10/ ; it was taken 980 MeV (7.5^o) and 990 MeV (11.3^o)). This affects only the position of maximum of the resonance peak without changing its shape and height.

MeV). Therefore, the calculation for the $p(^3He,t)\Delta^{++}$ reaction at 500 MeV/c diverges from the data /8/ almost by an order, when FSI is neglected.

Thus, at energies above 700 MeV per nucleon and small emission angles of the detected particles a good description of

the $p(^3He,t)$ and $p(p,n)$ reactions around the isobar peak is achieved within the one-meson-exchange model (taking into account only the contributions from pion exchanges).

2.2. A good OPE-description of the $p(^3He,t)$ and $p(p,n)$ data (at energies above 700 MeV per nucleon) using known π^+p total cross sections allows us to assume that the observed downshift of the isobar peak and its widening in the $(^3He,t)$ charge-exchange

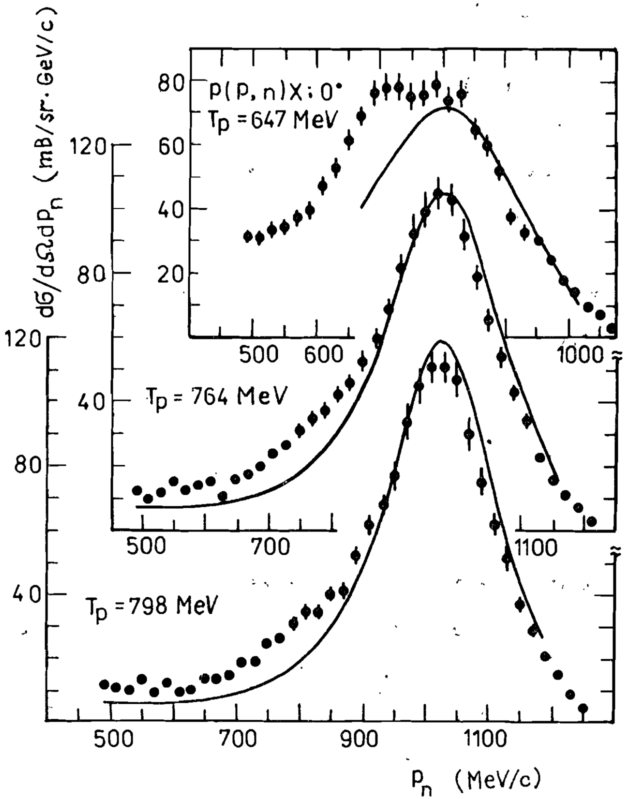


Fig.6. The cross sections of reaction $p(p,n)$ measured in ref./12/. To compare the shape of calculated and measured (up to normalization ±15%) spectra, the calculated cross sections are multiplied by factor 0.85 for energies 764 and 798 MeV.

on a nucleus (as compared to the charge-exchange on a proton) should be governed by the energy dependence of total πA cross sections, and these peculiarity should be present also in the charge exchange A(p,n) with excitation of isobars. Data on the A(p,n) charge exchange with excitation of isobars in nuclei have been obtained in refs. /10,13/, however, the authors have not carefully compared them with their own data on the p(p,n) reaction /10,11/ and have reported nothing about the Δ-downshift. As we expect the careful comparison indeed reveals a noticeable shift of the Δ-peak towards lower excitation energies and its widening as compared to the isobar peak in cross sections of the p(p,n) charge-exchange.

For the total cross sections of πA interaction the down shift of the maximum of the resonance and its broadening were observed in 1970 /14/. Qualitatively, theoretical analysis of possible sources of that shift /15,16/ has revealed that a successful description of the characteristics of πA interaction in the vicinity of the resonance requires a correct consideration of the influence of collective effects of nuclear matter both on the properties of an intranuclear nucleon and Δ-isobar in a nucleus and also on the very process of transition of the nucleus from a usual state to a state with Δ-excitation. Note is to be made that analogous effects of the downshift and broadening of the isobar peak have recently been observed also in scattering of electrons by nuclei /17 and 18/ when the kinematic conditions of (e,e') experiments have been favourable for the interaction of an isobar produced in a nucleus with the remaining nucleons of the nucleus.

3. So, from the results of our measurements of differential cross sections of the (^{3}He,t) charge exchange on carbon nuclei and protons it follows that: a) the reaction on a nucleus at high energies proceeds mainly through the excitation of Δ-isobars;

b) It is impossible to reduce the process of that excitation to the quasifree production of Δ-isobar on an individual moving intranuclear nucleon and a subsequent free motion of the isobar through the nucleus, i.e., collective effects caused by other nucleons are important /2,3/. From the results of our analysis the (^{3}He,t) charge-exchange /2,3,6,8 / and (p,n) charge-exchange /10,11/ data we may conclude that the collective phenomena in Δ-excitations of a nucleus in these reactions and in πA interactions in the resonance region /14-16/ have a common origin.

For a further experimental study of the Δ-isobar excitations in nuclei, it seems necessary, together with the detection of a fast particle at small angles (for instance, a triton in the (^{3}He,t) charge-exchange), to separate different channels of deexcitation of a Δ-excited nucleus. Of a special interest is the separation of decay channels of a Δ-excited nucleus without emission of pions from channels with their emission.

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References

1. Grishin V.G., Podgoretsky M.I. JINR, P-1508, Dubna, 1964; Leksin G.A. In:"Problemy Sovr.Yad.Fiziki", M., Nauka, 1972, p.511.

2. a) Vorobyov G.G. et al. In: Proc. of II-d Seminar "Programm of the Exper.Investigations on INR Acad.of Sci. of USSR Meson Facility", 23-27 Apr. 1983 (Zvenigorod), p.313, M., 1984.

b) Ableev V.G. et al. JINR, E1-83-486, Dubna, 1983; See also contributed papers on "Few-Body X" ed.by B.Zeitnitz, 1984, v.II, p.267; Elsevier Sci.Publ. B.V. 1984, PANIC, Book of Abstracts, ed.by E.Guttner, B.Porh, G.zu Putlitz, 1984, v.II, p.L-24, Heidelberg; "Nucleus-Nucleus Collisions II", ed. by B.Jakobsson, K.Aleklett (Visby, Sweden), v.1, p.169, 170, Lunds Reprocentralen, 1985.

3. a) Ableev V.G. et al. JINR, E1-84-438, Dubna, 1984;

b) Ableev V.G. et al. In:"Nucleon-Nucleon and Hadron-Nucleus Interactions at Intermediate Energies", Gatchina, Symposium 23-25 Apr. 1984, LNPI, p.293, Leningrad, 1984.

c) Ableev V.G. et al. Pis'ma ZhETF, 1984, 40, p.35 (JETP Lett., v. 40, p.763, 1984).

4. Wolf G. Phys.Rev., 1969, 182, p.1538.

5. Ableev V.G. et al. PTE, 1983, N 1, p.33.

6. Ableev V.G. et al. JINR, P1-86-435, Dubna, 1986.

7. Jackson J.D. Nuovo Cim. 1964, 34, p.1344.

8. Ellegaard C. et al. Phys.Rev.Lett., 1983, 50, p.1745; Phys. Lett., 1985, 154B, p.110;
Gaarde C. In: "Nuclear Structure 1985", ed. by R.Broglia, G.B.Hagemann, B.Nerskind, Elsevier Sci.Publ., B.V., 1985, p.449.

9. "Review of Particle Properties", 1982, p.217 , CERN, Geneva, 1982.

10.a) Baturin V.N. et al. Jad.Fiz., 1980, 31, p.396. and references therein.

b) Baturin V.N. et al. Pis'ma ZhETF, 1979, 30, p.86 and references therein.

11. Glass G. et al. Phys.Rev. 1977, D15, p.36.

12. Richard-Serre C. et al. Nucl.Phys. 1970, B20, p.413.

13. Bonner E. et al. Phys.Rev. 1978, C18, p.1418.

14. Ignatenko A.E. et al. ZhETF, 1956, 31, p.544; DAN, 1955, 103, p.395; Binon F. et al. Nucl.Phys. 1970, B17, p.188; 1971, B33, p.421; 1972, B40, 608 (E); Marshall J.F. et al. Phys.Rev., 1970, C1, p.1685; Wilkin C. et al. Nucl. Phys. 1973, B62, p.61; Caris J.C. et al. Phys.Rev. 1962, 126, p.295; Crozon M. et al. Nucl. Phys., 1965, 64, p.567.

15. See, for example, earlier works:
Ericson T.E.O., Hufner J. Phys.Lett., 1970, B33, p.601; Locher M.P. et al. Nucl. Phys., 1971, B27, p.598; Bethe H.A. Phys.Rev.Lett., 1973, 30, p.105; Dover C.B., Lemmer R.H. Phys.Rev., 1973, C7, p.2312; Barshay S. et al. Phys.Lett., 1973, 43B, p.271.

16. For example, Freedman R.A. et al. Phys.Lett., 1981, 103B, 397 and references therein.

17. Barreau P. et al. Nucl. Phys., 1983, A402, p.515.

18. O'Connel J.C. et al. Phys.Rev.Lett., 1984, 53, p.1627.

19. Falk W.R. et al. Phys.Rev., 1986, C33, p.989 and references therein.

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