PRODUCTION OF Δ-ISOBARS ON OXYGEN NUCLEI IN ^{16}Op-INTERACTIONS AT THE MOMENTUM OF 3.25 GeV/c PER NUCLEON

Y. H. Huseynaliyev

e-mail: yashar_huseynaliyev@comsats.edu.pk

Department of Physics, COMSATS Institute of Information Technology, Islamabad, Pakistan

INTRODUCTION

- The study of non-nucleon degrees of freedom, or collective phenomena in nuclei, is one of the fundamental problems in modern nuclear physics. Excitation of baryon resonances, in particular that of the $\Delta(1232)$ resonance, in a nuclear matter pertains also to this problem. This is because:

  1) the $\Delta(1232)$ resonance can be excited in various strong and electromagnetic processes induced by pions, nucleons, nuclei, photons and electrons;

  2) The experimental results on production of the $\Delta(1232)$ resonance in nuclei are non-trivial and there is variety in their theoretical interpretations, which are mainly ambiguous.
- The process responsible for meson production in central heavy ion collisions at relativistic energies is believed to be predominantly the excitation of baryon resonances during the early compression phase of the collision. In the later expansion phase these resonances decay. In total, the average mass of the excited baryon resonances and the number of pions produced by their decay chains increase with bombarding energy.
- The main result from these studies was that the width and mass of the Δ resonance produced in heavy ion collisions differed significantly from those of the free nucleon $\Delta(1232)$ resonance, and that the properties of hadrons are modified in dense hadron matter created in nucleus-nucleus collisions, which led to a significant mass reduction of $\Delta(1232)$.
- The identification of structures in the invariant mass distribution of correlated proton and pion pairs provides the direct proof that nucleons are excited to high-lying resonances. The major obstacle that should be overcome in reconstructing the invariant mass is the large background of non-correlated $p\pi$ pairs.

AIM

- The main aim of this work is to determine the various physical properties of $\Delta(1232)$ resonances, produced on oxygen nuclei in ^{16}O+*p* collisions at an incident momentum of 3.25 GeV/*c* per nucleon, and compare them with the properties of Δ resonances, produced on heavy tantalum nuclei in C+^{181}Ta [1] collisions at 4.2 GeV/*c* per nucleon, on light carbon nuclei in C+C [2], ^{4}He+C collisions [3] at 4.2 GeV/*c* per nucleon, and π^-+^{12}C interactions [4] at 40 GeV/*c*, and produced on Ni and Au nuclei in near-central Ni+Ni and Au+Au collisions [5,6] at energies between 1 and 2*A* GeV.

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MOTIVATION

- Parameters of free nucleon $\Delta(1232)$: $\langle M_{\Delta} \rangle$ =1232 MeV/c^2
- $\langle \Gamma \rangle$ =115 MeV/c^2
- The experimental results on production of the $\Delta(1232)$ resonance in nuclei are non-trivial and there is variety in their theoretical interpretations, which are mainly ambiguous. In near-central Ni+Ni and Au+Au collisions the average mass shifts about -60 MeV/c^2 and the average widths as low as 50 MeV/c^2 were observed.
- In modern quantum chromodynamics (QCD), the possibility of a phase transition of a nuclear matter into the state of quark gluon plasma is widely discussed and researched. The spectrum of the nuclear matter on the border of the phase transition should be very complex, but it seems undoubted that the lower states of this spectrum are related to excitation of $\Delta(1232)$ and other resonances. Thus, information on the properties of the Δ resonance in the nuclear matter is important for development of one of the most modern directions of physics – the nucleus-nucleus collisions at ultra relativistic energies.

EXPERIMENT

- ***1-м hydrogen bubble chamber of LHE (JINR, Dubna, Russia) exposed to a beam of relativistic oxygen nuclei accelerated to a momentum of 3.25 GeV/c per nucleon***
- ***Statistics - 8712 fully measured $^{16}O+p$ –collision events***
- ***The momenta of particles and fragments were determined from the measured curvatures of tracks (the chamber was placed into magnetic field).***
- ***Singly charged particles: p*** **= 1.25−4.75 GeV/*c*** ***– protons*** **(^{1}H), *p* = 4.75−7.75 GeV/*c*** ***– deuterons*** **(^{2}H) и *p* ≥ 7.75 GeV/*c*** ***– tritium*** **(^{3}H) nuclei. Such a selection allows us to separate the isotopes of hydrogen nuclei with a probability $\geq 96\%$.**

The inelastic cross-section of $^{16}O+p$-interactions at 3.25 GeV/c per nucleon proved to be 334 ± 6 mb

The target protons (recoil protons) could be separated from π^{+} mesons up to the momentum of 1.25 GeV/c in the laboratory frame.

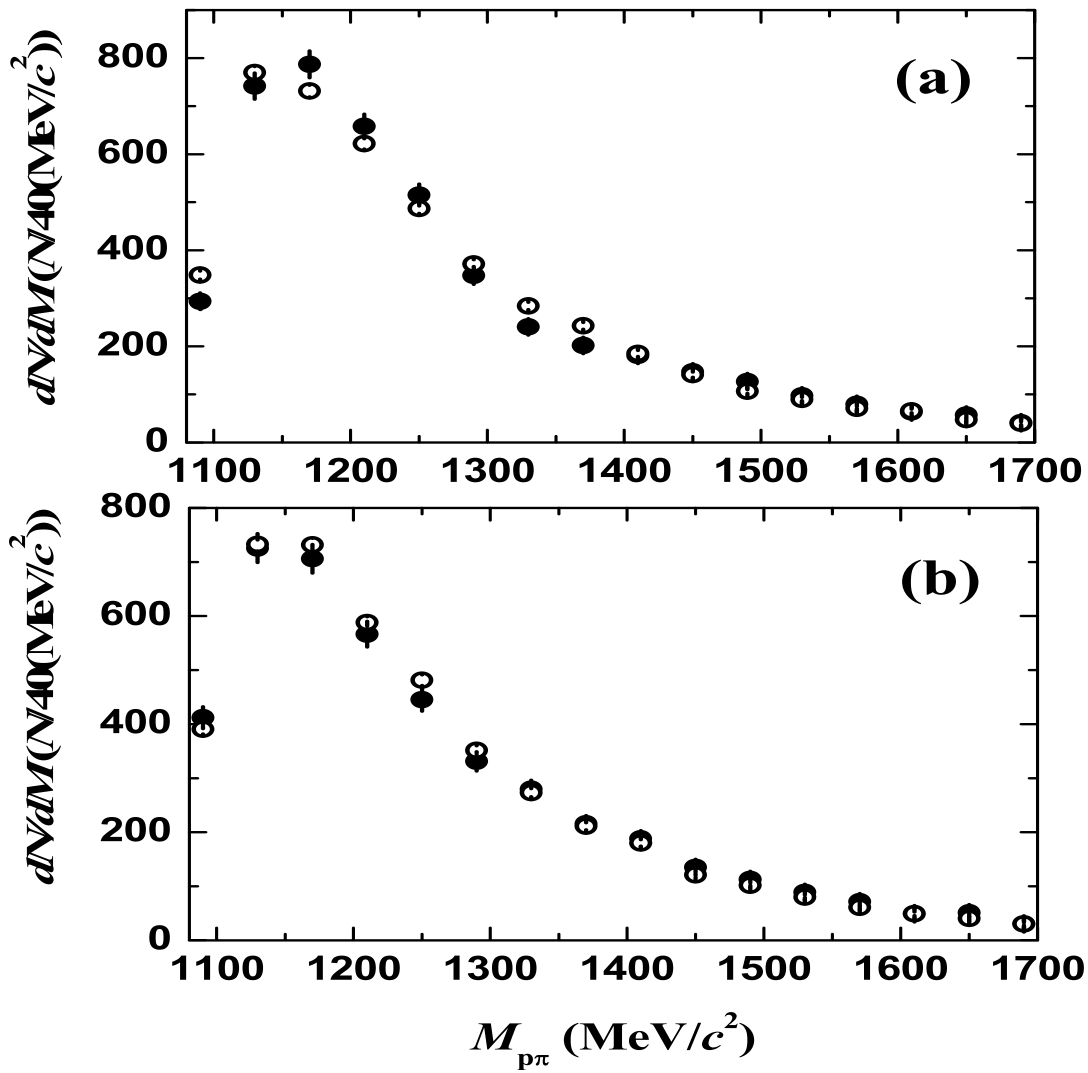
$\frac{\Delta p}{p} \leq 3.5\%$ *for singly charged particles when L* $\geq$ **35 cm.**

- The measured momenta of protons and pions were used to calculate the invariant mass of the $p\pi^{\pm}$ system, M, from the relation

$$M^2 = (E_p + E_\pi)^2 - (\vec{p}_p + \vec{p}_\pi)^2 \quad (1)$$

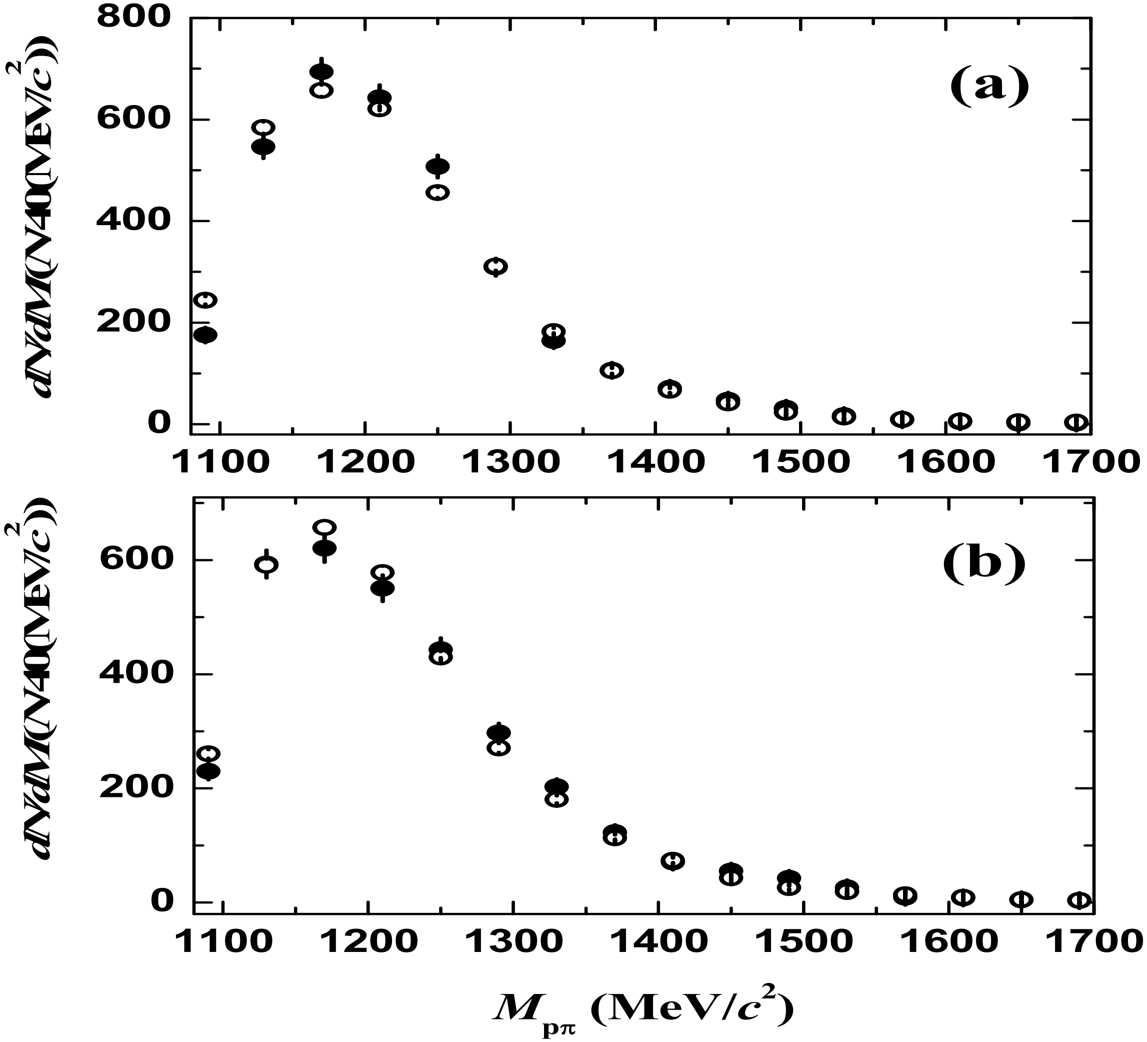
where E_p, E_π, $\vec{p}_p$, $\vec{p}_\pi$ – are the energy and momentum of the proton and pion, respectively.

- The experimental distribution was obtained combining protons and pions in each individual event.
- The background spectrum was obtained by a Monte-Carlo method. That is, the invariant mass of *p*π pairs selected randomly using a proton from one event and a pion from another event was calculated. To take into account the event topology, only events with equal particle multiplicities were combined.
- As seen from Fig. 1, the invariant mass distribution *dN* / *dM* for both *p*π + and *p*π − pairs does not show a resonance-like structure near Δ *M* = 1232 MeV/*c*2, expected for Δ resonance, and the maxima of distributions are shifted to the values of *M* < 1200 MeV/*c*2. This due to a large background contribution from uncorrelated *p*π pairs. To reduce their contribution as much as possible, the method of analyzing the angle between the proton and pion was used to extract the mass distribution of the Δ resonance.



- **FIG. 1.** The experimental (●) and background (○) invariant mass distributions
- of $p\pi^+$ (a) and $p\pi^-$ (b) pairs in ^{16}O+p collisions at 3.25A GeV/c.

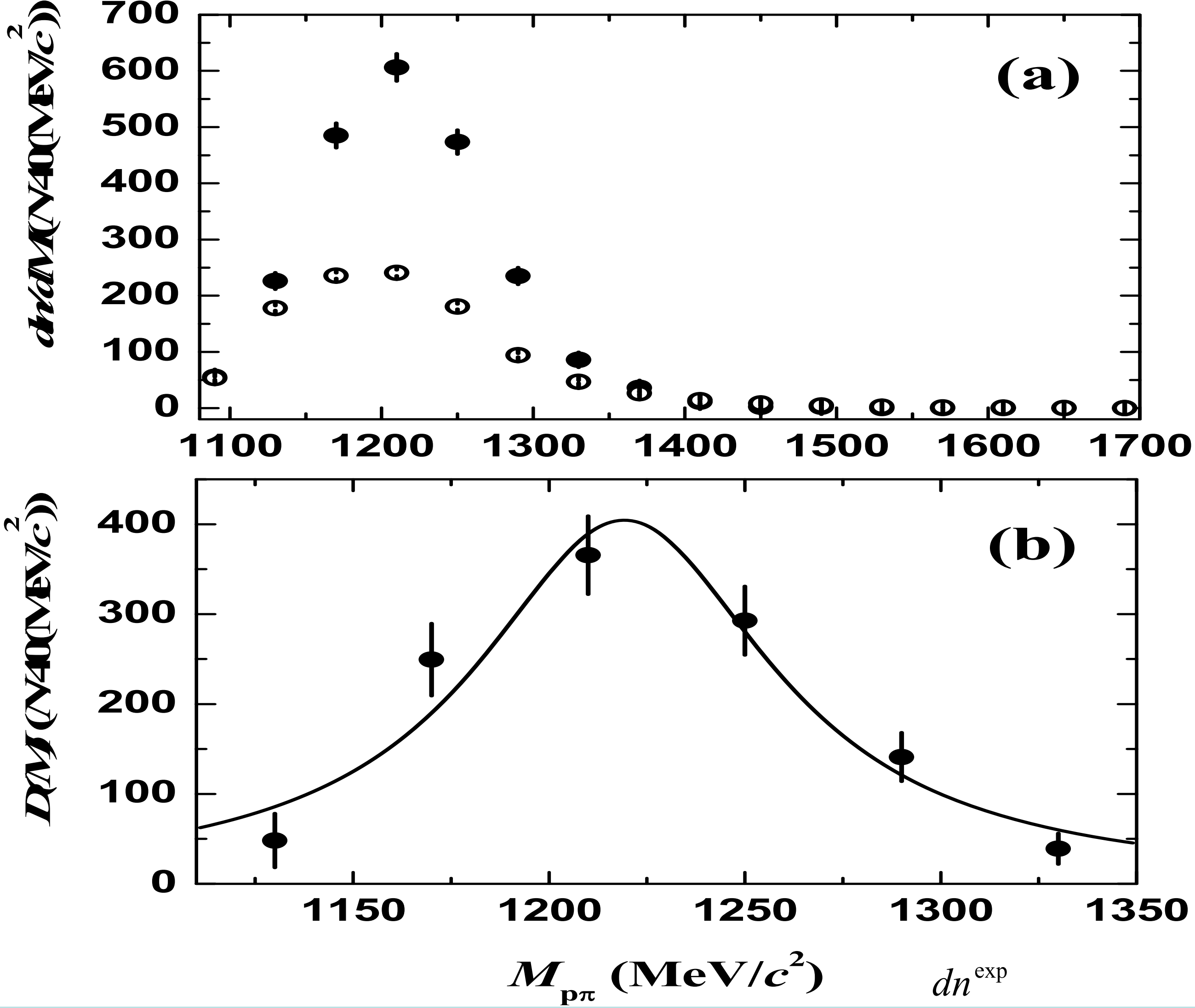
- If the resonance decays in flight, the angle between the outgoing proton and pion, in the laboratory frame, is defined by
-
- $$\cos\alpha = \frac{1}{p_p p_\pi}\left(E_p E_\pi - \frac{M^2{}_\Delta - M^2{}_\pi - M^2{}_p}{2}\right) \quad (2)$$
- where p_p and p_π are the proton and pion momenta, E_p and E_π are the respective energies, and M_Δ = 1232 MeV/c^2. This value was compared with the cosine of experimentally measured angle β ,
- $$\cos\ \beta\ = \frac{\vec{p}_p \cdot \vec{p}_\pi}{p_p p_\pi} \quad (3)$$
- The experimental invariant mass distribution, dn/dM , for $p\pi^\pm$ pairs was constructed using the following criteria:
- 1) Only the combinations satisfying the inequality
- $$|\cos\beta - \cos\alpha| < \varepsilon \quad (4)$$
- were kept, where ε is an arbitrary cutoff parameter theoretically lying in the interval [0, 2], while, if the momenta of protons and pions are measured with high precision, the upper limit of the interval should be low.
- 2) The protons emitted from the projectile oxygen nucleus and having momenta $p \leq 220$ MeV/c in the oxygen nucleus rest frame were treated as evaporated particles and excluded from an analysis.
- 3) The missing mass for proton-pion pairs should be equal to or greater than the nucleon mass.



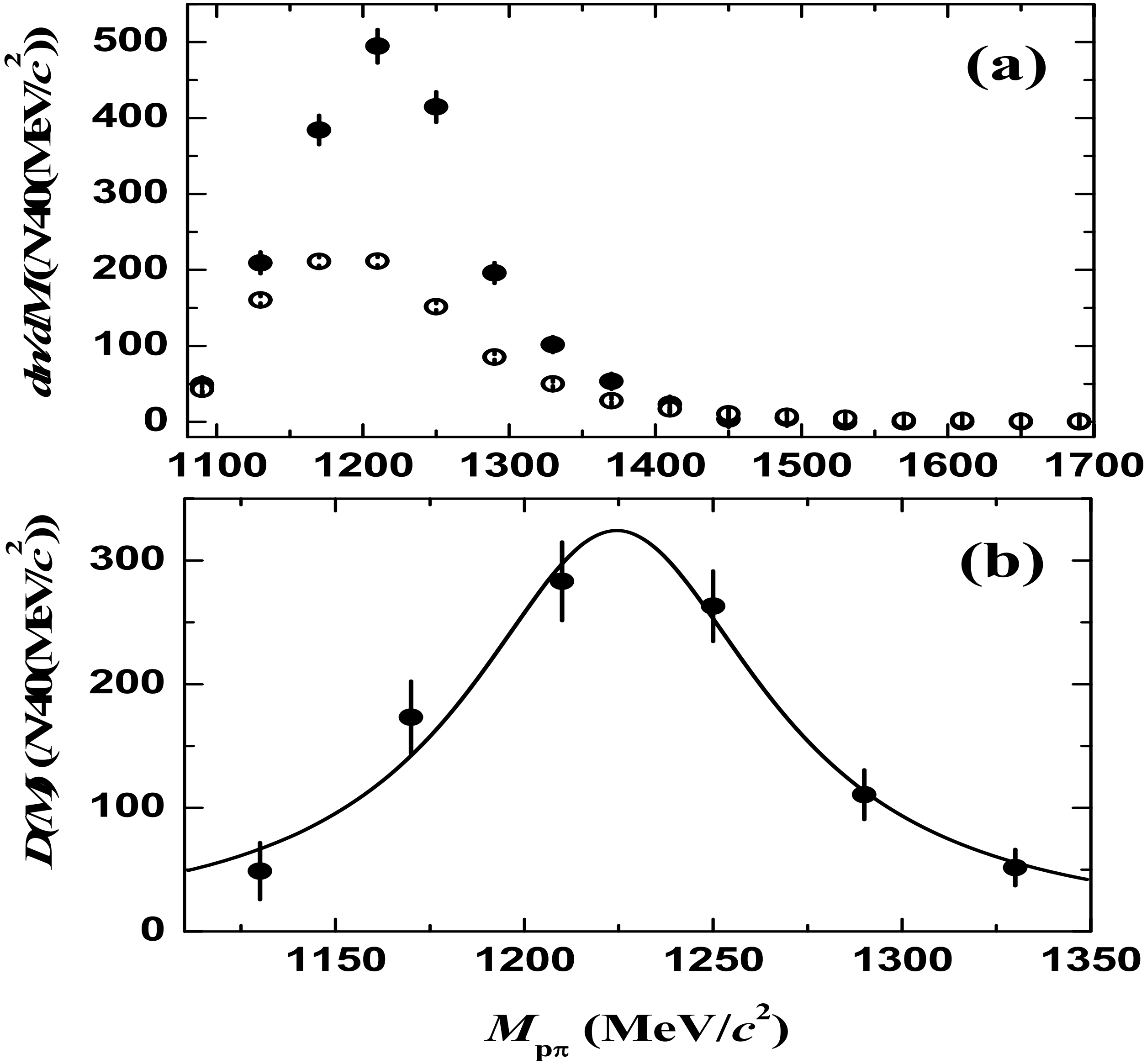
- **FIG. 2.** The experimental (●) and background (○) invariant mass distributions of $p\pi^+$ (*a*) and $p\pi^-$ (*b*) pairs in ^{16}O+*p* collisions at 3.25*A* GeV/*c* obtained using the cutoff parameter $\varepsilon = 0.15$.

- In the light of the above-mentioned, the further search for the mass distributions of resonances, produced on oxygen nuclei in ^{16}O+p collisions at 3.25A GeV/c, was performed in region $\varepsilon < 0.15$.
- To extract the mass distribution of the resonance and obtain the best background distribution for each ε value, the following procedures were performed. The distribution of differences between experimental and background invariant mass distribution, given by
- $$D(M) = \frac{dn^{\exp}}{dM} - a\frac{dn^{b}}{dM} \qquad (5)$$
- was analyzed, where a is the coefficient varying from 0 to 1.
- Interpreting the distribution $D(M)$ as a pure signal, it was approximated in region 1110 ÷ 1350 MeV/c^2 by a relativistic Breit-Wigner function
- $$b(M) = C\frac{\Gamma M M_{\Delta}}{(M^2 - M^2{}_{\Delta})^2 + \Gamma^2 M^2{}_{\Delta}} \qquad (6)$$
- where M_{Δ} and Γ are the mass and width of the resonance, and C – the normalization coefficient. The data set $D(M)$ for different values of parameters ε and a was fitted by the Breit-Wigner function $b(M)$ and the value of χ^2 was found for each fit. During these procedures, the parameter ε was varied from the value of 0.010 to 0.150 with the step of 0.001, and a varied from 0.0 to 1.0 with the step of 0.01 for each ε value. The parameters M_{Δ} and Γ were determined by minimizing the difference $|D(M) - b(M)|$.
- The minima of χ^2 functions gave the following values:

$\varepsilon(\Delta^{++}) = 0.071$, $\varepsilon(\Delta^{0}) = 0.057$, $a(\Delta^{++}) = 0.49$, and $a(\Delta^{0}) = 0.51$.



- FIG. 3. (*a*) − The experimental invariant mass distribution $\frac{dn^{exp}}{dM}$ (●) and the best
- background distribution $a\frac{dn^{b}}{dM}$ (○) for $p\pi^+$ pairs in ^{16}O+*p* collisions at 3.25 *A* GeV/*c*
- obtained using the best values of parameters ε and a ; (*b*) − The corresponding difference (●) between the experimental invariant mass distribution and the best background distribution for $p\pi^+$ pairs obtained at the best values of parameters ε and a along with the corresponding Breit-Wigner fit (solid line).



- **FIG. 4.** The same as in **FIG. 3** for $p\pi^-$ pairs.

- To estimate the fraction of π^+ and π^- -mesons coming from Δ^{++} and Δ^0 resonance decay relative to the total number of π^+ and π^- -mesons, respectively, produced on oxygen nuclei in ^{16}O+*p* collisions at 3.25*A* GeV/*c*, the following formulae were applied using the above obtained best experimental and background spectra:

$$R(\pi^+/\Delta^{++}) = \frac{\int_{M_p+M_\pi}^{M_x} \left(\frac{dn^{\exp}}{dM} - a \cdot \frac{dn^b}{dM} \right) dM}{N_{in}^{^{16}\mathrm{O}p} \cdot 0.5 \cdot n(\pi^+)} \qquad (7)$$

- where $M_p + M_\pi$, the sum of proton and pion masses, and 1400 MeV/c^2 are the lower and upper limits of integration, respectively, $N_{in}^{^{16}\mathrm{O}p}$= 7961 − the total number of inelastic ^{16}O+*p* interaction events, $n(\pi^+)$ =0.51 ± 0.01 − the mean multiplicity of π^+ -mesons per event in ^{16}O+*p* collisions at 3.25*A* GeV/*c*. The coefficient 0.5 in the formula takes into account that approximately 50% of - mesons in ^{16}O+*p* collisions at 3.25*A* GeV/*c* are produced on target protons; and analogously for the fraction of π^- -mesons coming from Δ^0 decay we have

$$R(\pi^-/\Delta^0) = \frac{\int_{M_p+M_\pi}^{M_x} \left(\frac{dn^{\exp}}{dM} - a \cdot \frac{dn^b}{dM} \right) dM}{N_{in}^{^{16}\mathrm{O}p} \cdot n(\pi^-)} \qquad (8)$$

- where $n(\pi^-)$ =0.30 ± 0.01 is the mean multiplicity of π^- -mesons per event in ^{16}O+*p* collisions at 3.25*A* GeV/*c*.

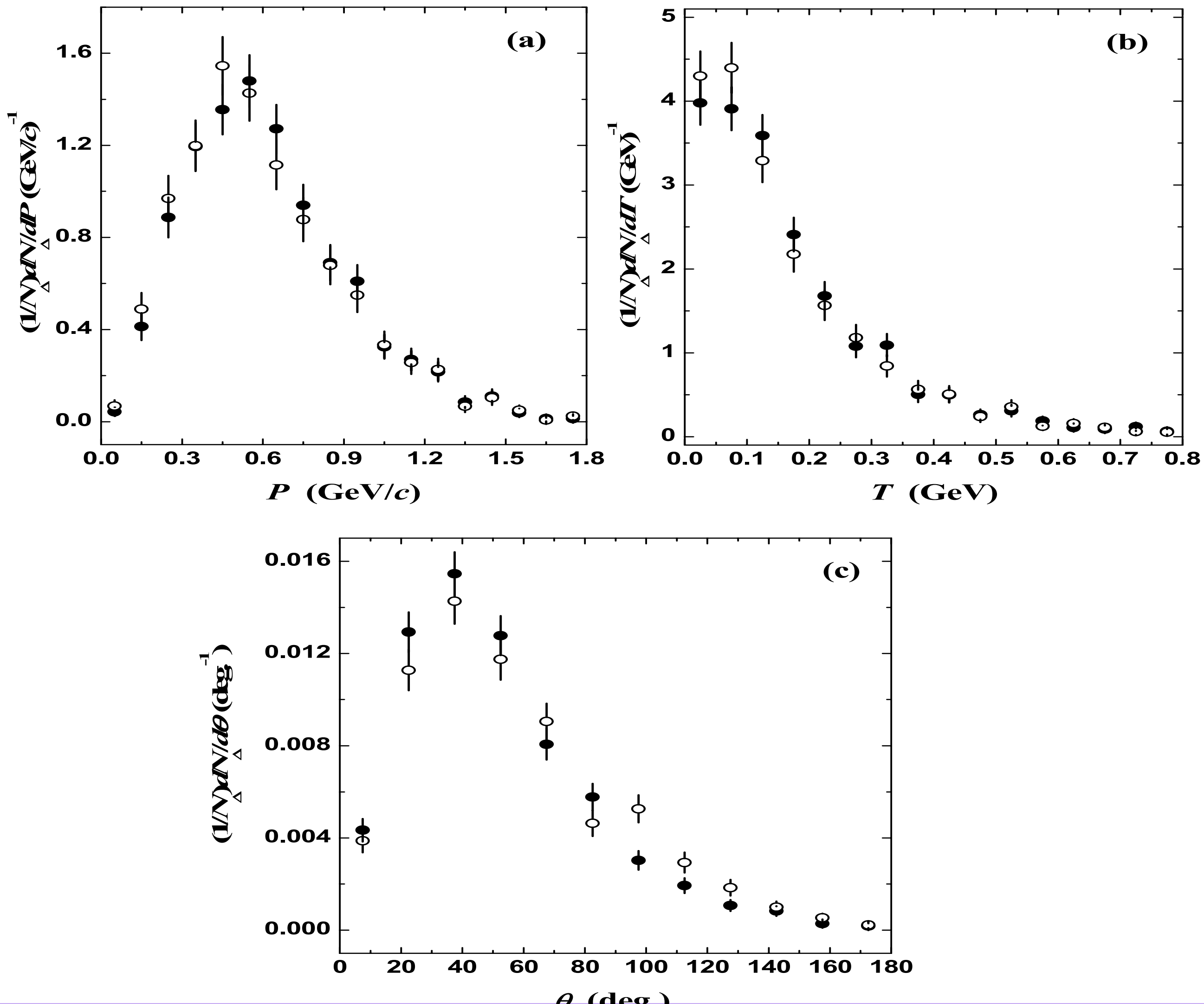
TABLE I. The experimental values of the masses, widths, fractions of charged pions, $R(\pi/\Delta)$, for Δ^{++} and Δ^{0} resonances, produced on oxygen nuclei in ^{16}O+p interactions at 3.25A GeV/c.

Resonance	M **(MeV/c^2)**	Γ **(MeV/c^2)**	$R(\pi/\Delta)$ (%)
Δ^{++}	**1218 ± 3**	**93 ± 8**	**57 ± 6**
Δ^{0}	**1224 ± 4**	**96 ± 10**	**41 ± 4**

TABLE II. The mean values of the masses, widths, and fractions of charged pions, coming from Δ decay, for Δ resonances, produced on oxygen nuclei in ^{16}O+p interactions at 3.25A GeV/c, on heavy tantalum nuclei in C+^{181}Ta collisions at 4.2A GeV/c, on carbon nuclei in C+C and ^{4}He+C collisions at 4.2A GeV/c and in π^{-}+^{12}C interactions at 40 GeV/c.

Reaction, p_0	$\langle M_\Delta \rangle$ (MeV/c^2)	$\langle \Gamma \rangle$ (MeV/c^2)	$\langle R \rangle$ (%)
^{16}O+p, 3.25A GeV/c	**1221 ± 4**	**95 ± 9**	**~ 50 ± 5**
C+^{181}Ta, 4.2A GeV/c	**1224 ± 1**	**88 ± 5**	**64 ± 5**
C+C, 4.2A GeV/c	**1231 ± 4**	**89 ± 8**	**55 ± 5**
^{4}He+C, 4.2A GeV/c	**1228 ± 2**	**84 ± 6**	**55 ± 4**
π^{-}+^{12}C, 40 GeV/c	**1223 ± 3**	**89 ± 8**	**6 ± 1**

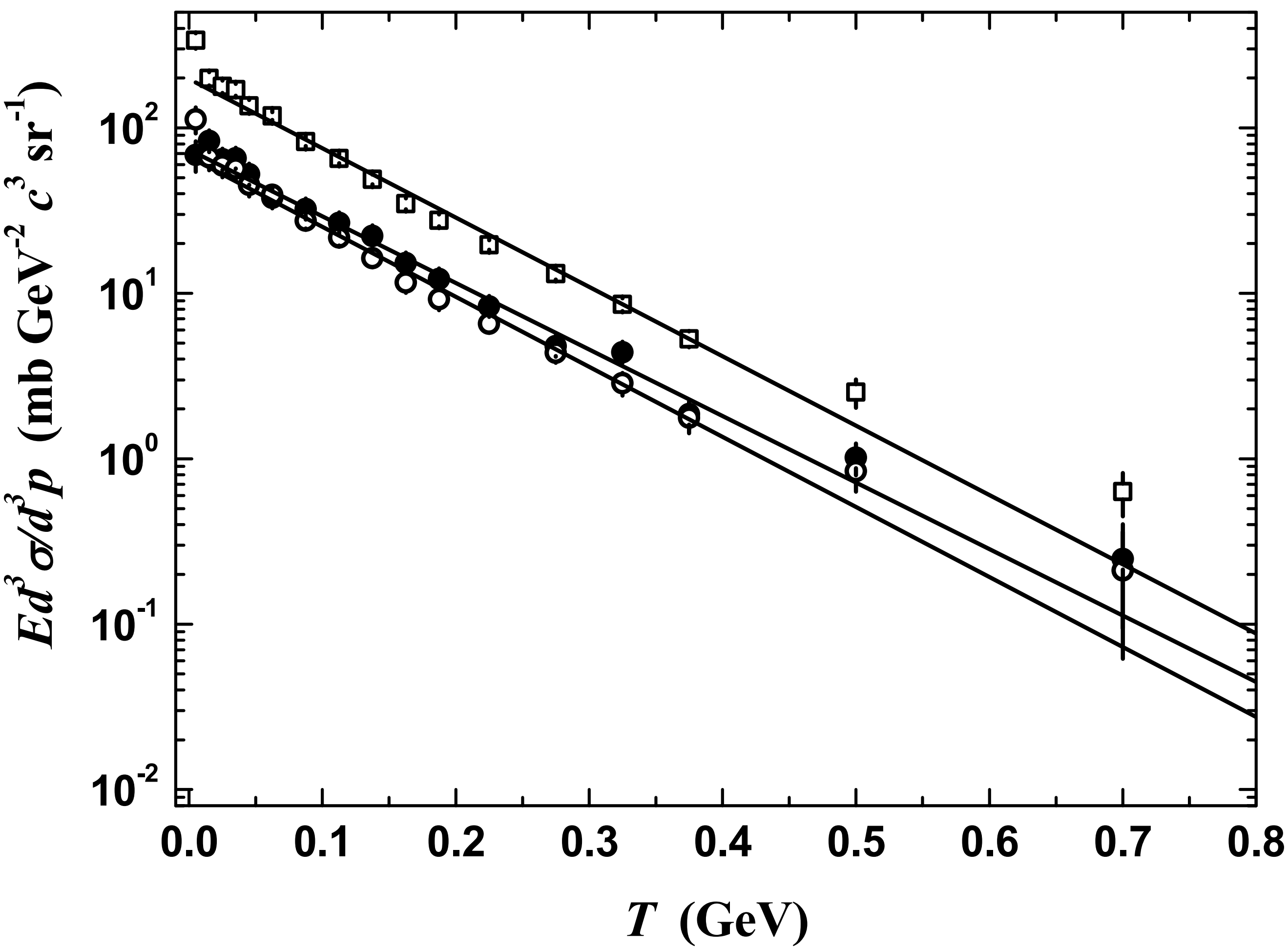
- We used all $p\pi^+$ and $p\pi^-$ pairs contributing to the experimental invariant mass distributions in Fig. 3(a) and Fig. 4(a), respectively, obtained using the best values of cutoff parameter ε . The momenta and energies of proton and pion from each pair were Lorentz transformed from the laboratory to the oxygen nucleus rest frame, i.e. to the antilaboratory frame. The momentum, kinetic energy, and emission angle of the Δ resonance for each $p\pi$ pair was calculated in the oxygen nucleus rest frame using the relations
- $$p_\Delta = \left| \vec{p}_p + \vec{p}_\pi \right| \quad (9)$$
- $$T_\Delta = \left(p_\Delta^2 + M_\Delta^2\right)^{1/2} - M_\Delta \quad (10)$$
- and
- $$\theta_\Delta = \arccos\left(\frac{p_\Delta^L}{p_\Delta}\right) \quad (11)$$,
- respectively, where $\vec{p}_p$ and $\vec{p}_\pi$ are the proton and pion momenta in the oxygen nucleus rest frame, M_Δ – the invariant mass of $p\pi$ pair calculated in the laboratory frame, and p_Δ^L is the longitudinal momentum of Δ in the oxygen nucleus rest frame. To account for the background contribution into the experimental invariant mass distribution of $p\pi$ pairs in Fig. 3(a) and Fig. 4(a), the calculated kinematical characteristics of Δ for each $p\pi$ pair were taken with a weight
- $$w = \left(\frac{\frac{dn^{\exp}}{dM} - a \cdot \frac{dn^{b}}{dM}}{\frac{dn^{\exp}}{dM}} \right)_{M = M_{p\pi}} \quad 12)$$,
- determined at $M = M_{p\pi}$ using the experimental and background invariant mass distributions of $p\pi$ pairs obtained at the best values of ε and a .



- **FIG. 5.** The reconstructed momentum (*a*) , kinetic energy (*b*), and emission
- angle (*c*) distributions of Δ^{++} (●) and Δ^0 (○) resonances, produced on oxygen nuclei in ^{16}O+*p* collisions at 3.25 *A* GeV/*c*, in the oxygen nucleus rest frame, normalized to the total number of respective Δ .

TABLE III. The mean values of momenta, kinetic energies, and emission angles of Δ^{++} and Δ^{0} resonances, produced on oxygen nuclei in $^{16}O+p$ interactions at 3.25*A* GeV/*c*, in the oxygen nucleus rest frame.

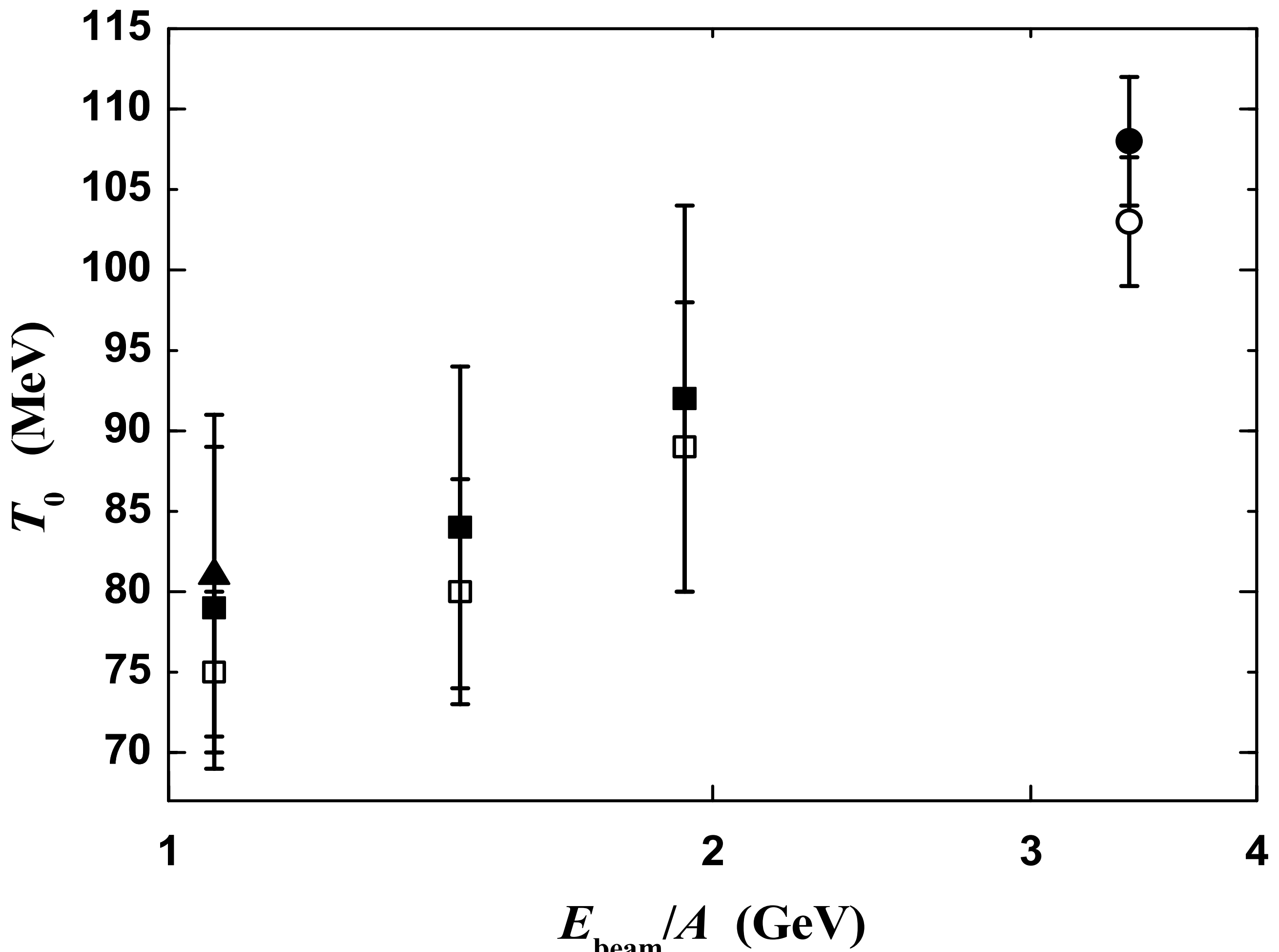
Resonance	$\langle P \rangle$ (MeV/*c*)	$\langle T \rangle$ (MeV)	$\langle \theta \rangle$ (deg.)
Δ^{++}	620 ± 9	171 ± 5	52 ± 1
Δ^{0}	602 ± 10	164 ± 5	56 ± 1



- **FIG. 6.** The reconstructed invariant cross-sections of Δ^{++} (●) and Δ^0 (○) ((□) − taking into account the $\Delta^0 \rightarrow n + \pi^0$ decay channel of Δ^0) resonances with respect to their kinetic energy in the oxygen nucleus rest frame along with the corresponding fits (solid lines)
- by the function $f(T) = A_0 \cdot \exp(-T / T_0)$.

TABLE IV. Parameters of approximation of reconstructed spectra of invariant cross-sections of Δ resonances, produced on oxygen nuclei in ^{16}O+p interactions at 3.25A GeV/c, by the function $f(T) = A_0 \cdot \exp(-T/T_0)$.

Resonance	A_0 (mb GeV^{-2} c^3 sr^{-1})	T_0 (MeV)	$\chi^2/\text{n.d.f.}$
$\Delta^{++} \rightarrow p\pi^+$	**73.6 ± 3.8**	**108 ± 4**	**0.74**
$\Delta^0 \rightarrow p\pi^-$	**66.9 ± 3.8**	**103 ± 4**	**0.85**
$\Delta^0 \rightarrow N\pi$	**197.8 ± 6.2**	**103 ± 3**	**2.57**



- **FIG. 7.** The dependence of the freeze-out temperature (T_0) on the beam energy: (●) and (○) $-T_0$ obtained for Δ^{++} and Δ^0 resonances, respectively, produced on oxygen nuclei in $^{16}O+p$ collisions at 3.25*A* GeV/*c*
- ($E_{\text{beam}} \approx 3.4A$ GeV); T_0 obtained from the radial flow analysis (■) and using the hadrochemical equilibrium model (□) for Δ resonances produced in Ni+Ni collisions at 1.06, 1.45, and 1.93*A* GeV; (▲) – T_0 obtained from the radial flow analysis for Δ resonances produced in Au+Au collisions at 1.06*A* GeV.

SUMMARY

- **About 50% of charged pions, produced on oxygen nuclei, were estimated to come from decay of Δ^0 and Δ^{++} resonances, produced on oxygen nuclei in ^{16}O+*p* interactions at 3.25*A* GeV/*c*.**
- **On the whole, the average mass shifts of Δ resonances, produced on oxygen, carbon, and tantalum nuclei, are in agreement with the result of theoretical work, where the mass of the $\Delta(1232)$ resonance was calculated to be shifted by ≈ –10 MeV/c^2 when corrections due to the nucleon interaction in the πN loop of the Δ self energy are taken into account.**
- **The mean widths of Δ resonances, produced on oxygen nuclei in ^{16}O+*p* collisions at 3.25*A* GeV/*c*, on heavy tantalum nuclei in C+^{181}Ta collisions at 4.2*A* GeV/*c*, on carbon nuclei in C+C and ^{4}He+C collisions at 4.2*A* GeV/*c* and in π^-+^{12}C interactions at 40 GeV/*c*, coincided within statistical uncertainties, being independent of the nucleus mass and initial energy and making up on average ~ 90 ± 10 MeV/c^2.**
- **The normalized momentum as well as kinetic energy distributions of Δ^0 and Δ^{++} resonances , produced on oxygen nuclei in ^{16}O+*p* interactions at 3.25*A* GeV/*c*, coincided within statistical errors. The mean momenta and kinetic energies of Δ^{++} and Δ^0 also coincided within statistical errors, making up on average $\langle P \rangle$ ≈ 610 MeV/*c* and $\langle T \rangle$ ≈ 170 MeV. Also the mean emission angles of Δ^0 and Δ^{++} resonances proved to be close to each other.**
- **The temperatures, T_0 , obtained for Δ^{++} and Δ^0 resonances, produced on oxygen nuclei in ^{16}O+*p* interactions at 3.25*A* GeV/*c* ($E_{\text{beam}} \approx 3.4$ *A* GeV), coincided within errors and proved to be 108 ± 4 and 103 ± 4 MeV, respectively. The values of T_0 for Δ^{++} and Δ^0 resonances, produced on oxygen nuclei in ^{16}O+*p* interactions at 3.25*A* GeV/*c* ($E_{\text{beam}} \approx 3.4$ *A* GeV), were compared to the freeze-out temperatures of Δ obtained from the radial flow analysis as well as using the hadrochemical equilibrium model for Ni+Ni collisions at 1.06, 1.45, and 1.93*A* GeV, and Au+Au collisions at 1.06*A* GeV.**
- **Although the values of T_0 obtained for Δ , produced in Ni+Ni, Au+Au, and ^{16}O+*p* collisions at energies between 1 and 3.4*A* GeV, practically overlapped within error limits, an increase of the freeze-out temperature with beam energy up to 3.4*A* GeV was observed.**

THANK YOU!