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Abundance of Δ Resonances in ^{58}Ni + ^{58}Ni Collisions between 1 and 2 AGeV

B. Hong[4*], N. Herrmann[4,6], J. L. Ritman[4], D. Best[4], A. Gobbi[4], K. D. Hildenbrand[4], M. Kirejczyk[4,10], Y. Leifels[4], C. Pinkenburg[4], W. Reisdorf[4], D. Schüll[4], U. Sodan[4], G. S. Wang[4], T. Wienold[4], J. P. Alard[3], V. Amouroux[3], N. Bastid[3], I. Belyaev[7], G. Berek[2], J. Biegansky[5], A. Buta[1], J. P. Coffin[9], P. Crochet[9], R. Dona[9], P. Dupieux[3], M. Eskef[6], P. Fintz[9], Z. Fodor[2], L. Fraysse[3], A. Genoux-Lubain[3], G. Goebels[6], G. Guillaume[9], E. Häfele[6], F. Jundt[9], J. Kecskemeti[2], M. Korolija[6], R. Kotte[5], C. Kuhn[9], A. Lebedev[7], I. Legrand[1], C. Maazouzi[9], V. Manko[8], J. Mösner[5], S. Mohren[6], W. Neubert[5], D. Pelte[6], M. Petrovici[1], P. Pras[3], F. Rami[9], C. Roy[9], Z. Seres[2], B. Sikora[10], V. Simion[1], K. Siwek-Wilczyńska[10], A. Somov[7], L. Tizniti[9], M. Trzaska[6], M. A. Vasiliev[8], P. Wagner[9], D. Wohlfarth[5], A. Zhilin[7]

(FOPI Collaboration)

[1] *Institute for Nuclear Physics and Engineering, Bucharest, Romania*

[2] *Central Research Institute for Physics, Budapest, Hungary*

[3] *Laboratoire de Physique Corpusculaire, IN2P3/CNRS, and Université Blaise Pascal, Clermont-Ferrand, France*

[4] *Gesellschaft für Schwerionenforschung, Darmstadt, Germany*

[5] *Forschungszentrum Rossendorf, Dresden, Germany*

[6] *Physikalisches Institut der Universität Heidelberg, Heidelberg, Germany*

[7] *Institute for Theoretical and Experimental Physics, Moscow, Russia*

[8] *Kurchatov Institute, Moscow, Russia*

[9] *Centre de Recherches Nucléaires and Université Louis Pasteur, Strasbourg, France*

*Present address: Korea University, Seoul, South Korea

[10] *Institute of Experimental Physics, Warsaw University, Poland*

Abstract

Charged pion spectra measured in ^{58}Ni-^{58}Ni collisions at 1.06, 1.45 and 1.93 AGeV are interpreted in terms of a thermal model including the decay of Δ resonances. The transverse momentum spectra of pions are well reproduced by adding the pions originating from the Δ -resonance decay to the component of thermal pions, deduced from the high transverse momentum part of the pion spectra. About 10 and 18% of the nucleons are excited to Δ states at freeze-out for beam energies of 1 and 2 AGeV, respectively.

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Relativistic heavy ion collisions are a unique tool to investigate hot and dense nuclear matter in the laboratory [1,2]. In these studies the measurement of pions has attracted much interest since they can be regarded as a potential probe of the processes beyond mere nucleon-nucleon binary interactions in heavy ion collisions [3–7]. According to the results of microscopic model calculations [2], pions are, in principle, expected to contain information from the early stage of the fireball to the freeze-out, since they are produced continuously during the whole reaction process. However, the large pion-nucleon cross section destroys the memory to early times, and the signatures of the reaction dynamics have disappeared by the time of detection. Therefore one will, most likely, observe only the conditions at freeze-out. On the other hand, this knowledge is important in itself, because it gives information on the degree of equilibration. To a large extent, a model that assumes thermal and hadrochemical equilibrium can explain the various particle yield ratios including multistrange particles at AGS and SPS energies [8].

The possibility of exciting $\Delta(1232)$ resonances (called Δ in the following) and hence to form so-called Δ matter at incident energies between 1 and 10 AGeV has been investigated theoretically in RQMD simulations [9]. The model predicts about 10 % of the participant nucleons being excited to Δ during the hot and dense phase at 1 AGeV, while at 10 AGeV more than 50 % of the nucleons are excited to baryonic resonances, of which only about half are present as Δ . Pions from the resonance decays show a different phase space distribution depending on their decay momentum [10], and especially the Δ -decay kinamatics has been made responsible for the low transverse momentum (p_t) enhancement at incident beam energies from 1 to 15 AGeV [11–13]. The concave shape found in the Boltzmann (or invariant) spectra of pions at beam energies from 0.5 to 200 AGeV [13–18] confirms the importance of the resonance decay. In this paper we will investigate the Δ population at freeze-out, using the spectral shape of pion distributions obtained in the Ni+Ni system at incident energies varying from 1 to 2 AGeV.

The experiment has been performed with the FOPI detection system [19,20] at the heavy ion synchrotron SIS at GSI by bombarding a ^{58}Ni target of 225 mg/cm^2 thickness

($\approx$ 1 % nuclear interaction length) with ^{58}Ni beams of 1.06, 1.45 and 1.93 AGeV. For the analysis presented here the central drift chamber (CDC), working in the 0.6 T field of a solenoidal magnet has been used for particle identification, and the forward plastic wall for the centrality determination. This azimuthally symmetric wall covers polar angles θ_{Lab} from 7 to 30 degrees, measuring energy loss dE/dx and time of flight of the charged fragments the multiplicity of which (PMUL) is used for centrality selection. The CDC covers θ_{Lab} from 30 to 150 degrees; identification of the pions and other light charged fragments is achieved via dE/dx and momentum measurement. To compare the rapidity distributions at different beam energies we define the normalized rapidity $y^{(0)} \equiv y/y_{cm} - 1$, where y_{cm} is the rapidity of the center of mass system (c.m.). Throughout this paper we use the convention $\hbar$ = c = 1.

We have previously observed that the Boltzmann spectra, $d^2N/m_t^2 dm_t dy^{(0)}$ with $m_t = \sqrt{p_t^2 + m_\pi^2}$ being the transverse mass and m_π the pion mass, of $\pi^\pm$ measured in reactions between 1 and 2 AGeV show a concave shape which can be fitted by the sum of two exponential functions with a χ^2 per degree of freedom ~ 1 in all rapidity bins [15]. Fig. 1 shows, as example, the Boltzmann spectra of π^- at 1.93 AGeV with a cut in PMUL selecting the uppermost 100 mb (or 4% of the total reaction cross section, called PM100 in the following) for different rapidity windows. Only the statistical errors are given in the spectra; the systematic error in the absolute normalization [15], estimated to about 10 %, is not shown. It has been demonstrated that at freeze-out the Δ -decay pions contribute dominantly to the low kinetic energy part, whereas thermal pions contribute predominantly to the high kinetic energy part of the spectra both at SIS and AGS energies [11–13]. Therefore we attribute the high-p_t component of the experimental spectra as being due to thermal pions.

In order to decompose the pion spectra quantitatively we calculate the part arising from Δ decay by a Monte Carlo routine. For the phase space distribution of the Δ at freeze-out, we use the isotropically expanding blast model proposed by Siemens and Rasmussen [21]:

$$\frac{d^2N_\Delta}{p_t dp_t dy} \propto \int_{m_N+m_\pi}^{\infty} dm_\Delta P_\Delta(m_\Delta) E_\Delta e^{-\gamma_r E_\Delta/T} [(\gamma_r + \frac{T}{E_\Delta})\frac{\sinh\alpha}{\alpha} - \frac{T}{E_\Delta}\cosh\alpha], \qquad (1)$$

where m_N is the nucleon mass, $E_\Delta = \sqrt{p_\Delta^2 + m_\Delta^2}$ and p_Δ are the total energy and momentum of the Δ in the c.m., $\gamma_r = 1/\sqrt{1-\beta_r^2}$, and $\alpha = (\gamma_r \beta_r p_\Delta)/T$. For the freeze-out temperature (T) and radial flow velocity (β_r), the results from Ref. [15] are used, e.g. $T = 92$ MeV and $\beta_r = 0.32$ at 1.93 AGeV, obtained in analyses of the high-p_t part of pion, proton and deuteron spectra at midrapidity. We adopt an isotropically emitting source scenario that describes the high p_t part of the pion spectrum very well. It should be noted, however, that the proton rapidity distributions are more elongated and the apparent temperatures near target rapidity are smaller as compared to the expectations from an isotropically radiating source [15]. Most probably this is caused by the interaction of participating nucleons with some spectator remnants or partial transparency of the system. For those scenarios a reliable prescription for the Δ phase space distribution does not exist at the moment. The Δ mass distribution, $P_\Delta(m_\Delta)$, is parameterized by a relativistic Breit-Wigner form [22] as follows:

$$P_\Delta(m_\Delta) \propto (\frac{1}{q^2}) \frac{\Gamma_\Delta^2(q)}{(m_\Delta^2 - \bar{m}_\Delta^2)^2 + \bar{m}_\Delta^2 \Gamma_\Delta^2(q)}, \tag{2}$$

where

$$\Gamma_\Delta(q) = \bar{\Gamma}_\Delta (\frac{q}{\bar{q}})^3 \frac{1 + (R_1 \bar{q})^2 + (R_2 \bar{q})^4}{1 + (R_1 q)^2 + (R_2 q)^4} \tag{3}$$

is the momentum dependent width of the Δ , q is the momentum of the pion in the Δ rest frame. We chose $\bar{\Gamma}_\Delta = 112$ MeV, $\bar{q} = 227$ MeV, $R_1 = 0.0042$ MeV^{-1} and $R_2 = 0.0032$ MeV^{-1}. The maximum of $P_\Delta(m_\Delta)$ is fixed to the free Δ mass, i.e. $\bar{m}_\Delta = 1232$ MeV.

After superposition with the spectra of thermal pions the results of the model calculation are shown by the black solid lines in Fig. 1. We use for all rapidity bins only one normalization factor for the relative abundance of the decay pions with respect to thermal pions. The overall agreement between the model and data is rather good except at very low m_t ($m_t - m_\pi \leq 0.12$ GeV), where the data exceed the model calculations at all rapidities. In order to explain this difference, one may need to consider the decrease of the effective Δ mass as shown, e.g. by the thermal model including the $\pi-$nucleon loop correction to the Δ self-energy calculation [12]. The decomposition of π^- spectra into π_T (dashed line) and

π_Δ (dotted line) at midrapidity is also displayed in Fig. 1, demonstrating that the low-p_t enhancement of the pion spectra is consistent with the contribution from Δ decay. The influence of the p_t resolution (σ_{p_t}/p_t) on the π_Δ spectra which worsens from 4 % at $p_t \leq 0.5$ GeV to about 9 % at $p_t = 1.5$ GeV [23] has been tested, too: a slight effect can be found only for $m_t - m_\pi \geq 1$ GeV, and it does not affect our results.

The influence of higher-mass baryonic resonances (e.g. N*(1440), N*(1520) and N*(1535)) has been studied using the hadrochemical equilibrium model [8,24]. The model parameters, chemical freeze-out temperature T_C and baryon chemical potential μ_B, are adjusted to reproduce the measured particle yields of high-p_t (thermal) pions, protons, deuterons and η's [15,25]. The temperatures T_C from the hadrochemical equilibrium model agree with those from the radial flow analysis, T, within 8 % [24]. The Boltzmann spectra of pions from the N* resonance decay at midrapidity are also shown in Fig. 1, calculated with the proper branching ratios under the assumption of isotropic expanding thermal distributions of primary resonances (Eq. 1) with a fixed mass. The total contribution of N* resonances to our estimation of the Δ abundance is at most 5%, in agreement with earlier RQMD and BUU studies [9,26]; hence this contribution is neglected in the current analysis.

The concave shape in the pion spectra can also be found in transport models [26,27], although the high-p_t pions are of different origin there. Within these models, all pions stem from the decay of resonances. Pions in the high-p_t tail have decoupled earlier from the system ($free$ pions), when more energetic resonances were populated. The pion spectra are obtained by integrating over the complete compression expansion cycle. However, when analysing the result of the reaction under the assumption of a sudden freeze-out, the spectrum of the $free$ pions exhibits an exponential shape as obtained for the thermal pions in the present equilibrium model.

To estimate the yields of all pions (π^-_{All}) and that of the low-p_t pions (π^-_{Low}) we have integrated the fitted function (sum of two exponentials) over the whole range $p_t = 0$ to ∞ and for the low-p_t exponential only, respectively. Since the slope parameter of the low p_t component from the two exponential fit agree with those of the pion spectra from Δ decay

within 6% for all beam energies, we simply take π_{low} multiplied with the proper isobar ratio as measure of the total number of Δ in the system. The resulting $dN/dy^{(0)}$ spectra are shown in the top panel of Fig. 2 for the three beam energies under the PM100 cut. Note that only data for $y^{(0)} < 0$ are measured, and then reflected to $y^{(0)} > 0$, employing the symmetry of the colliding system. The total π^- yield per event, $n(\pi^-)$, is summarized in the second column of Table I. The number of participant nucleons (A_{part}) is calculated via the geometrical model [23]; for PM100 events in Ni + Ni collisions one obtains 101 $\pm$ 8 nucleons in the central fireball. In comparison to the earlier BEVALAC data for Ar + KCl [6], our measurement of the π^- multiplicity per participant nucleon, $n(\pi^-)/A_{part}$, is about 15 % lower than the mean value given there; within the error bars both measurements are compatible. The ratio π^-_{Low}/π^-_{All} is shown in the bottom panel of Fig. 2, where the dashed lines represent the mean of the ratio for the whole rapidity bins given also in the third column of table I. The systematic error of π^-_{Low}/π^-_{All} introduced by using the exponential fit at low p_t rather than the π_Δ spectrum is estimated to less than 2%. The ratio decreases from about 77 % to 66 % as we increase the beam energy from 1.06 to 1.93 AGeV. At 14.6 AGeV this π^-_{Low}/π^-_{All} ratio was determined to 33 $\pm$ 5 % [13].

Having this information, we can now estimate the Δ abundance $n(\Delta)$ at freeze-out by means of the following relation:

$$n(\Delta) = n(\pi^-) \times f_{isobar} \times (\frac{\pi^-_{Low}}{\pi^-_{All}}), \tag{4}$$

where

$$f_{isobar} \equiv \frac{n(\pi^+ + \pi^0 + \pi^-)}{n(\pi^-)} = \frac{6\ (Z^2 + N^2 + NZ)}{5\ N^2 + NZ} \tag{5}$$

is the prediction of the isobar model [1] (N is the number of neutrons, Z the number of protons). For the energy range considered here, this model describes the relative abundance of pions in central collisions within 10% [23,28]. For ^{58}Ni one obtains f_{isobar}=2.84. Note that for the present system N is close to Z, hence one does not expect big deviations from f_{isobar}=3 in any model. Eq. 4 contains the implicit assumption that the ratio π_{Low}/π_{All} is

the same for π^+, π^0 and π^-. From our analysis the spectra of π^+ and π^- at a given rapidity are known to be identical for transverse momenta from 170 MeV to about 800 MeV, the value up to which π^+ can reliably be identified in the experiment. Below p_t = 170 MeV, the π^- yield starts to exceed that of the π^+, which is attributed to the Coulomb effect. The results for the ratio $n(\Delta)/n(\text{nucleon} + \Delta)$ are summarized in the last column of Table I. The number of nucleons excited to the Δ resonance at freeze-out increases from 10 $\pm$ 2 % at 1.06 AGeV to 18 $\pm$ 4 % at 1.93 AGeV. These values are diplayed in Fig. 3 together with the result of 36 $\pm$ 5 % from a measurement at 14.6 AGeV [13]. Having determined the ratio $n(\Delta)/n(\text{nucleon} + \Delta)$, one can estimate the freeze-out temperature within the context of the hadrochemical equilibrium model [8]. The results are summarized in Table II together with those of the radial flow analysis [15]; both analyses are in good agreement.

In summary, we have studied the pion phase space distribution in terms of the thermal model including pions from the decay of Δ resonances in addition to the thermal pions. The good agreement between the data and model gives confidence that the low-p_t enhancement in the pion spectra is due to the pions from the Δ decay. When the beam energy is increased from 1.06 to 1.93 AGeV this low-p_t enhanced part of the pion spectra decreases from 77 % to 66 % of the total pion multiplicity, while the number of nucleons excited to Δ at freeze-out increases from 10 to 18 % of all nucleons. The freeze-out temperature which is estimated from the ratio $n(\Delta)/n(\text{nucleon} + \Delta)$ is found to be in good agreement with the results of the radial flow analyses. The direct reconstruction of the Δ by an invariant mass analysis of (πp)- pairs is underway [29], which will allow to compare the results of the two different analyses in the future.

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TABLES

TABLE I. Summary of results for Ni + Ni collisions at the various incident energies (centrality cut PM100): Average number of π^- per event (2nd column), fraction of the low-π_t pion component (3rd column) and derived relative number of nucleons excited to Δ at freeze-out (last column).

E_{beam}/A(GeV)	$n(\pi^-)$	$\pi^-_{Low}/\pi^-_{All}(\%)$	$n(\Delta)/n(\text{nucleon}+\Delta)(\%)$
1.06	3.6 ± 0.4	77 ± 4	10 ± 2
1.45	5.8 ± 0.6	68 ± 4	13 ± 3
1.93	8.5 ± 0.9	66 ± 3	18 ± 4

TABLE II. Comparison of T in MeV obtained in this work (Δ) and in a radial flow analysis [15].

E_{beam}/A(GeV)	Δ	Flow
1.06	75 ± 5	79 ± 10
1.45	80 ± 7	84 ± 10
1.93	89 ± 9	92 ± 12

FIGURES

FIG. 1. Boltzmann spectra of π^- for different windows in normalized rapidity (Ni + Ni collisions at 1.93 AGeV under selectivity cut PM100, see text for definition); the two upper curves have been multiplied by the factors 10^2 and 10^4, respectively. The black solid lines represent the model calculations including the thermal pions (dashed) as well as pions from the Δ decay (dotted). Pions from the decay of higher baryonic resonances, e.g. from $N^\star(1440)$ (dash-dotted), $N^\star(1520)$ (grey solid-a) and $N^\star(1535)$ (grey solid-b) decays, are shown as well.

Fig. 1

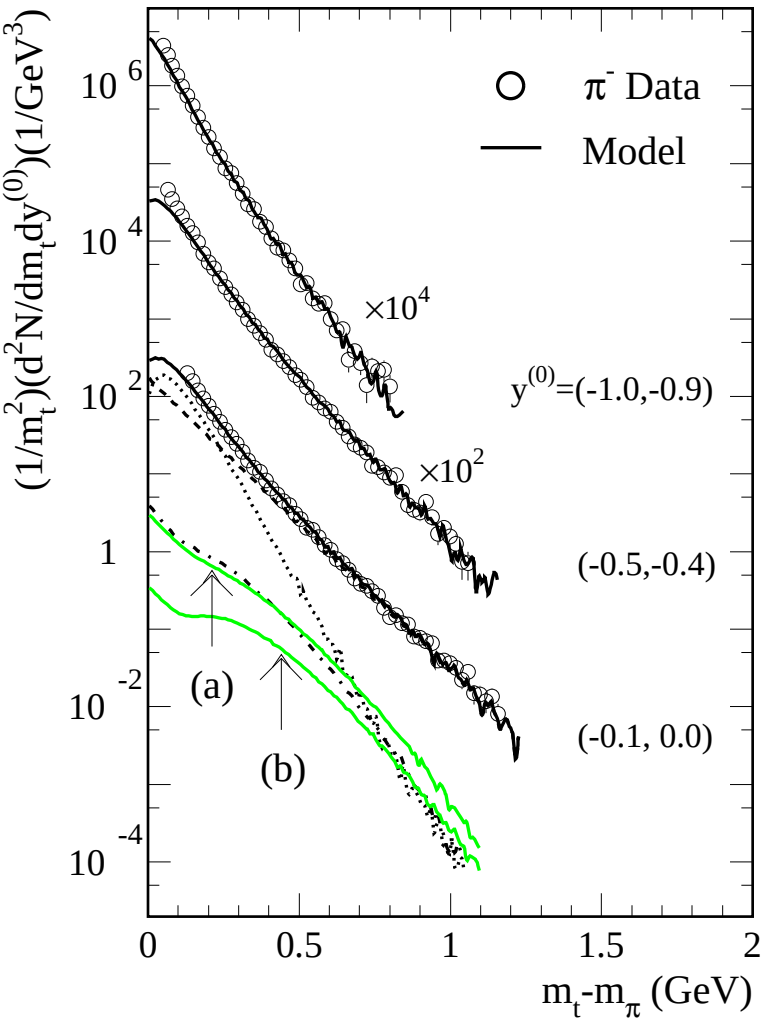

FIG. 2. Top: Rapidity spectra of π^- at 1.06, 1.45 and 1.93 AGeV under the centrality cut PM100. The solid circles represent the integrations from $p_t = 0$ to ∞ of the fit with two exponentials (π^-_{All}), while the open circles represent the integrations of the low-p_t exponential fit only (π^-_{Low}). Bottom: Ratio of π^-_{Low}/π^-_{All}; the dashed lines represent the mean values of the ratio for all rapidities.

Fig. 2

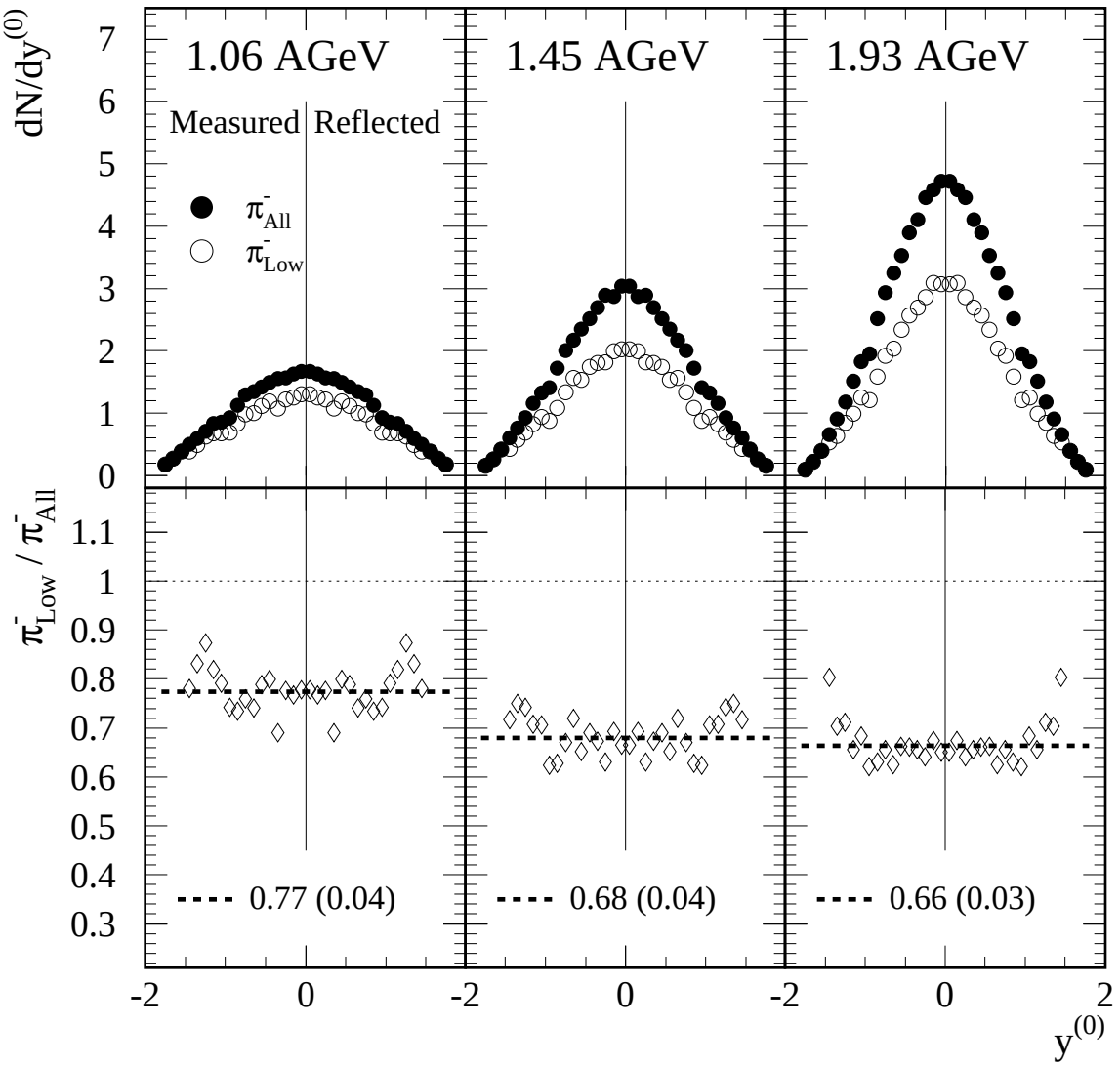

FIG. 3. Ratio $n(\Delta)/n(\text{nucleon} + \Delta)$ at freeze-out as a function of the beam energy. The open square is the result of the analysis of experiment E814 at 14.6 AGeV [13].
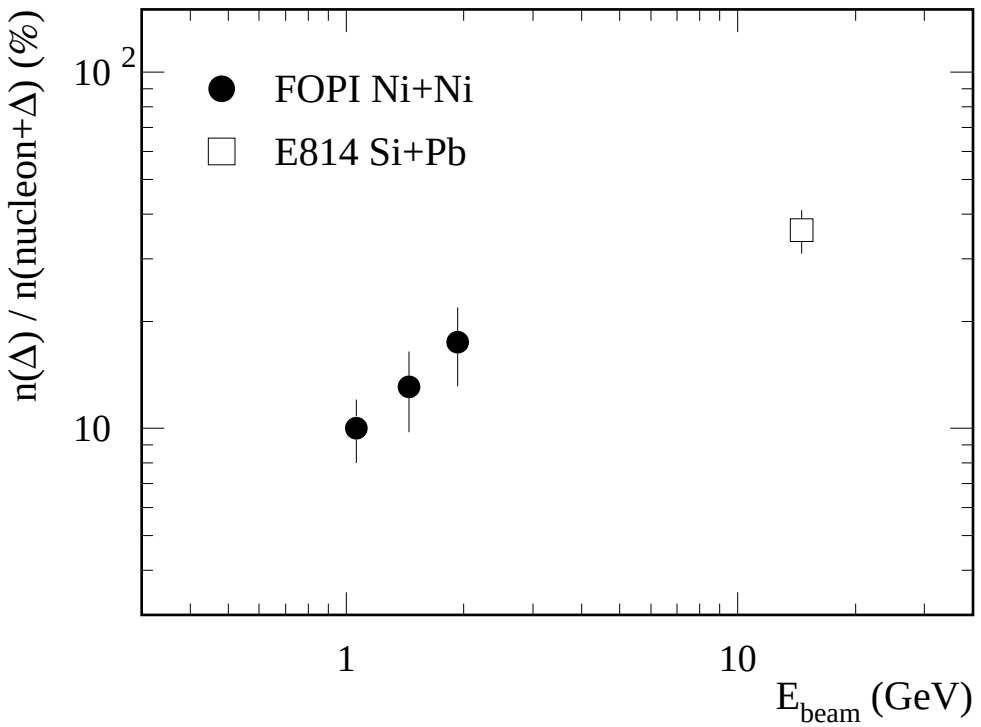
Fig. 3