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Energy scan with Be+Be collisions: cross-section, centrality determination, pion spectra and mean multiplicities

Emil Kaptur* **for the NA61/SHINE collaboration**
Institute of Physics, University of Silesia, Katowice, Poland
E-mail: emil.aleksander.kaptur@cern.ch

Recent results of NA61/SHINE from the ^{7}Be+^{9}Be data taking campaign will be presented. The results will be compared to the NA61/SHINE data on p+p interactions, as well as Pb+Pb data from the NA49 experiment.
The inelastic ^{7}Be+^{9}Be cross-section for beam momenta from 13*A* to 150*A* GeV/c was determined based on measurements of the projectile spectator energy and charge. The Projectile Spectator Detector (PSD), which measures energy emitted in the forward cone allows for a precise centrality selection and determination of the mean number of wounded nucleons. This is possible thanks to the high transverse and longitudinal modularity of the PSD and its excellent energy resolution.
Inclusive double differential spectra of negatively charged pions were measured in four centrality classes. The spectra were obtained using the so called h^{-} method. The method consists of subtracting the small ($< 10\%$) non-pion contribution from distributions of negatively charged hadrons using a Monte-Carlo simulation of this contamination.
First evidence of collectivity in ^{7}Be+^{9}Be collisions is observed. The shape of the mid-rapidity transverse mass spectrum in central ^{7}Be+^{9}Be collisions deviates from the one for p+p interactions in the way observed previously for central Pb+Pb collisions.
Rapidity spectra exhibit asymmetry with respect to mid-rapidity due to various effects which will be discussed. Mean multiplicity of negatively charged pions was extracted from the rapidity distributions by fitting two symmetrically displaced Gaussians with different amplitudes. Mean multiplicity was calculated as the integral of the fitted function. The energy dependence of mean pion multiplicity per wounded nucleon in ^{7}Be+^{9}Be collisions is compared with the corresponding results for p+p interactions and central Pb+Pb collisions in the so-called "kink" plot (related to entropy production).

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*Speaker.

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1. Introduction

NA61/SHINE is a fixed target experiment in the north area of the CERN SPS [1]. Tracking capabilities are provided by the five Time Projection Chambers (TPCs). Two of them (Vertex TPCs) are placed in the magnetic field generated by two superconducting magnets. Another two are a large volume chambers (Main TPCs) providing specific energy loss identification. The fifth chamber (GAP TPC) enhances tracking capabilities of particles with high momentum. Particle identification is supplemented by two Time-of-Flight (ToF) walls. Centrality measurement is carried out with zero degree, compensating, modular calorimeter — Projectile Spectator Detector (PSD).

The NA61/SHINE collaboration records data with numerous types of beams, i.e. ions (secondary Be and primary Ar and Xe) at beam momentum 13A - 158A GeV/c, and (secondary) hadrons (p at 13-158 GeV/c, π^- at 158 and 350 GeV/c, K^- at 158 GeV/c).

2. h$^-$ method

The analysis method used to obtain spectra of negatively charged pions is a so-called "h$^-$ method" [2]. The method exploits the fact that in the SPS energy range more than 90% of primary negatively charged particles produced in inelastic interactions are π^- mesons. The π^- spectra are obtained by subtracting a small non-pion contribution from the spectra of all negatively charged hadrons. The subtracted non-pion contribution is calculated using Monte-Carlo models.

The h$^-$ method allows to obtain a large phase-space acceptance. Acceptance of various identification methods are compared in Fig. 1.

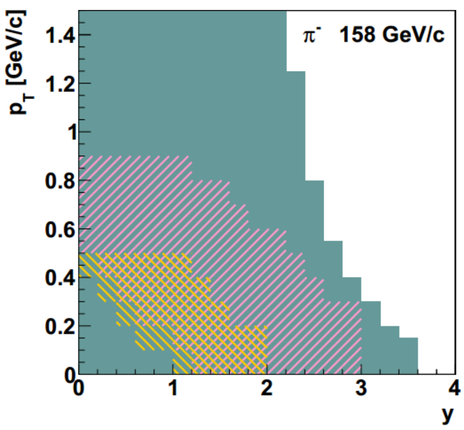

Figure 1: Differences in acceptance of various analysis methods for p+p interactions at beam momenta equal to 158 GeV.
Blue solid area – h$^-$ method, magenta lines – dE/dx identification, yellow lines – dE/dx–tof identification.

For the ^{7}Be+^{9}Be data the acceptance of h$^-$ method was extended to backward rapidity. An example of acceptance in ^{7}Be+^{9}Be data for two beam momenta and centralities is shown in Fig. 2 as two dimensional (rapidity — y, transverse momentum — p_{T}) spectra of negatively charged pions. Figure 2 show that high acceptance of the h$^-$ method is weakly dependent on centrality or beam momentum.

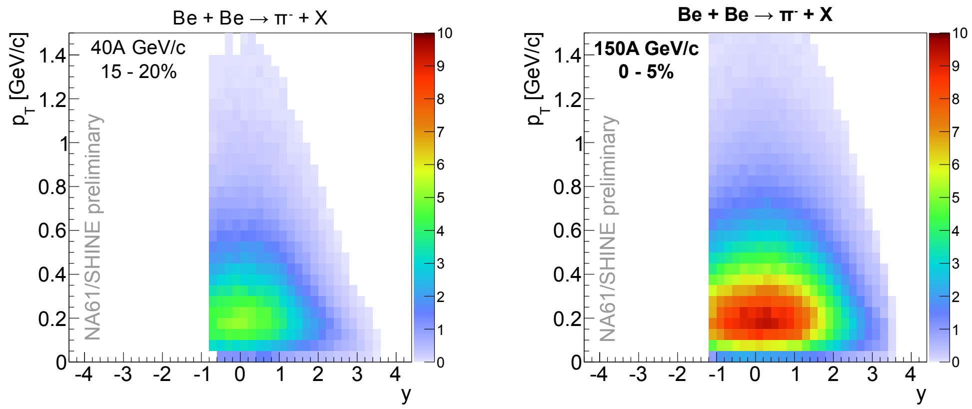

Figure 2: Double differential ($d^2n/(dy dp_T)$) spectra of negatively charged pions.
Left: 40*A* GeV/c, 15–20% centrality; *Right*: 150*A* GeV/c, 0–5% centrality

The EPOS model [3], used for calculation of the non-pion contribution, was tested on p+p data. The K^-/π^- ratio at midrapidity (main contribution to the correction) from the EPOS model describes data within 5% precision, as visible in Fig. 3.

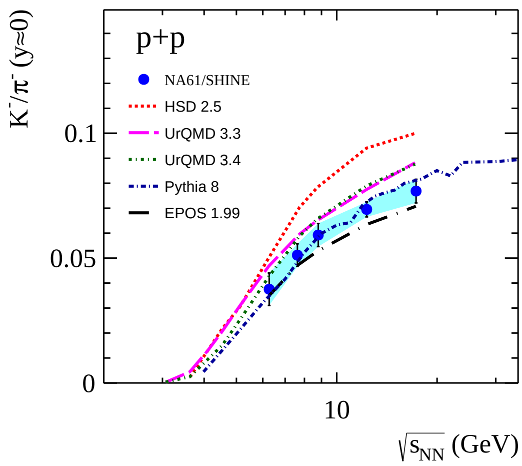

Figure 3: The K^-/π^- ratio at $y \approx 0$ measured by NA61/SHINE [4] in comparison with Monte-Carlo models.

3. Results

Preliminary results were obtained for ^{7}Be+^{9}Be inelastic interaction at five beam momenta (20*A*, 30*A*, 40*A*, 75*A* and 150*A* GeV/c) and four centrality classes (0–5%, 5–10%, 10–15% and 15–20%). The results from ^{7}Be+^{9}Be data are shown only with statistical errors, unless stated otherwise.

3.1 Inelastic cross section measurement

The inelastic cross section of ^{7}Be+^{9}Be interactions were measured previously only at 1.45*A* GeV/c beam momentum [5]. NA61/SHINE measurements are available at the beam momenta equal to 13*A*, 20*A* and 30*A* GeV/c [6].

The measurements were performed using a scintillator counter (S4) placed on the beam-line between VTPC-1 and VTPC-2. The counter measures sum of the squares of charges coming through the scintillator. When the beam particle interacts inelastically upstream of the counter it breaks up and the signal from the counter decreases.

The measurements were done in two configurations: with target inserted in the beam and with target removed from the beam. The target removed measurement was carried out to subtract background from ^{7}Be beam interactions with the detector material.

The spectrum of the S4 counter for well-defined ^{7}Be beam tracks is presented in Fig. 4. for target inserted and target removed configurations. The large peak above channel 90 represents the non-interacting beam ions, whereas the region below is populated by interactions. The peaks around channels 25 and 40 represent singly (protons, deuterons and tritons) and doubly (He) charged particles. In target removed configuration one can clearly seen smaller number of interactions.

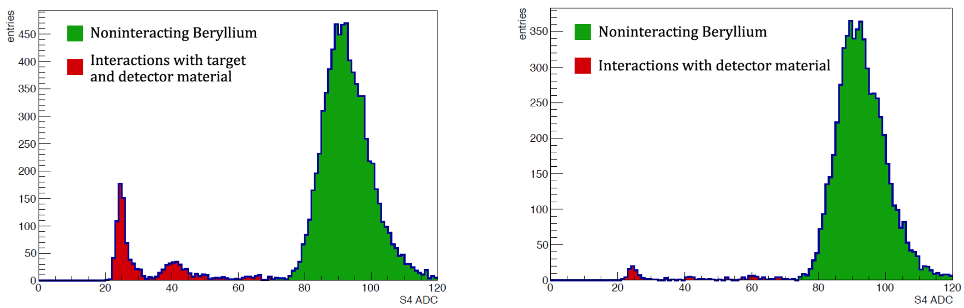

Figure 4: Spectrum of S4 counter. *Left*: target inserted configuration; *Right*: target removed configuration.

The interaction probability P is defined as ratio of the number of well defined beam particles with S4 signal below the Be cut to the total number of well defined beam particles.

The probability of interactions in the target is given by the formula which includes effects related to the change of normalization due to beam attenuation in the target:

$$P_{\text{int}} = \frac{P_{\text{I}} - P_{\text{R}}}{1 - P_{\text{R}}},$$

where P_{I} is the interaction probability in target inserted configuration and P_{R} is the interaction probability in target removed configuration.

The cross section can then be calculated from P_{int} and the known properties of the target as:

$$\sigma_{\text{inel}} = \frac{1}{\rho L_{\text{eff}} N_{\text{A}}/A} P_{\text{int}}, \qquad L_{\text{eff}} = \lambda_{\text{abs}}(1 - e^{-L/\lambda_{\text{abs}}}), \qquad \lambda_{\text{abs}} = \frac{A}{\rho N_{\text{A}} \sigma_{\text{inel}}}$$

where ρ, L, A are the density, length, atomic number of the target and N_{A} is Avogadro's constant.

The measurements, shown in Fig. 5, are in good agreement with an earlier measurement at lower beam momentum and with calculations using the Glissando Glauber model [7].

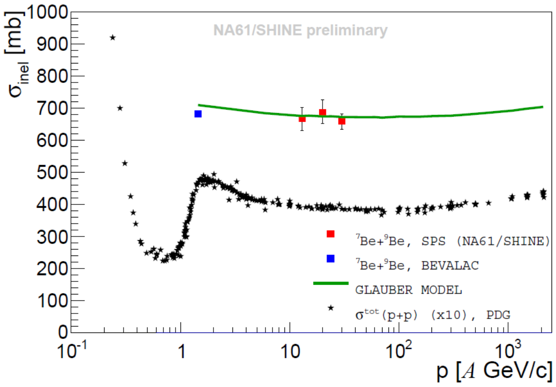

Figure 5: Inelastic cross section of ^{7}Be+^{9}Be interactions as a function of beam momentum. Total cross section for p+p interactions is shown for a comparison.

3.2 Centrality determination

Spectra of negatively charged pions were calculated in four centrality bins. The centrality is defined as the fraction of the inelastic cross section selected using energy deposited in the forward calorimeter — Projectile Spectator Detector (PSD). However, thanks to the modularity of the PSD, the acceptance of the detector can be changed in the off-line analysis. By selecting smaller acceptance one may lose some of the projectile spectators, but also decrease background from particles produced in the collision within detector acceptance. On the other hand, by selecting larger acceptance, all of the projectile spectators are registered, but also more background particles are seen.

The final results depend on the chosen acceptance of the PSD. For low beam momenta the dependence is strongest. The total multiplicity of π^- mesons as a function of centrality is shown in Fig. 6 for beam momentum equal to 20*A* GeV/c. In the worst case the spread of the points for different acceptances is equal to at most 5%.

3.3 Rapidity spectra of negatively charged pions

Rapidity spectra of negatively charged pions were obtained from the double differential spectra in y and p_{T} (Fig. 2) by integrating over available transverse momentum acceptance and extrapolating small contribution ($< 1\%$) of high p_{T} region by exponential function.

The spectra were fitted with the two Gaussian functions symmetrically displaced from mid-rapidity. The fitted Gaussian functions have the same widths but, due to asymmetry of the colliding system (^{7}Be+^{9}Be), different amplitudes. The extension of the acceptance into the backward rapidity allowed to perform stable fit.

Example rapidity spectra for 20*A* and 150*A* GeV/c beam momenta are shown together with data from p+p interactions in Fig. 7.

The width of the spectra was calculated as a standard deviation of the fitted function. The widths of the rapidity distribution divided by the beam rapidity for the five beam momenta for the

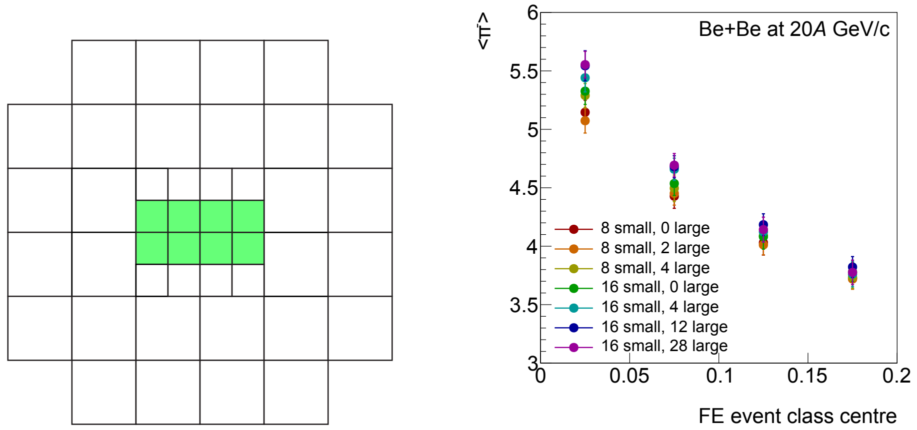

Figure 6: PSD front face, an example module selection marked by green colour *(left)*. Sensitivity of the multiplicity of negative pions to the acceptance of centrality detector as a function of Forward Energy (FE) event class centre (centrality) *(right)*.

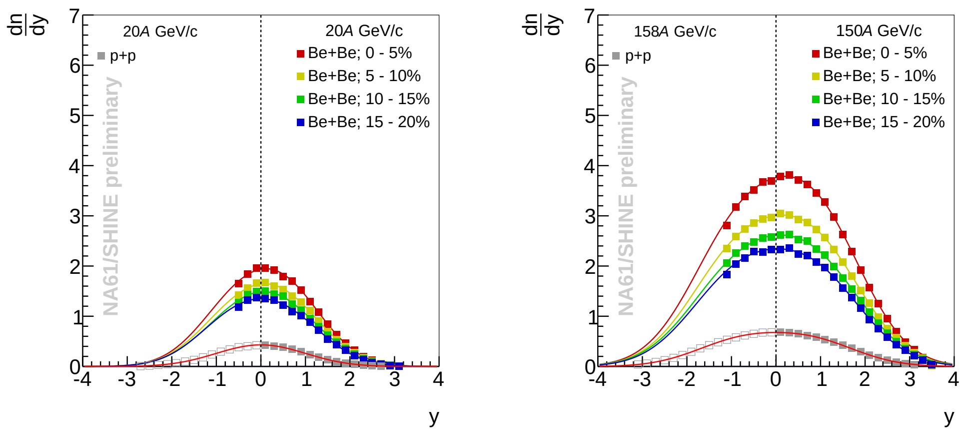

Figure 7: Rapidity spectra of π^- mesons for ^{7}Be+^{9}Be and p+p interactions at 20*A* GeV/c *(left)* and 150*A* GeV/c *(right)*.

most central ^{7}Be+^{9}Be data are shown together with the world data for p+p and Pb+Pb interactions [8, 9] in Fig. 8.

The width of the rapidity distribution of the negatively charged pions exhibits monotonic behaviour with collision energy. However, at any given beam energy, the dependence of the width on the system size is non-monotonic. The width of the p+p distribution is the smallest one, Pb+Pb is in the middle, while ^{7}Be+^{9}Be is the largest.

In comparison with ^{7}Be+^{9}Be and Pb+Pb collisions p+p interactions have large isospin asymmetry. The simplest way to account for the isospin effects is to calculate average spectra of negatively and positively charged pions. The only available data on positively charged pions spectra in large acceptance in p+p collisions in the SPS energy range is available at 158 GeV/c from NA49 experiment [10]. At this beam momentum the differences in the width of the rapidity distribution

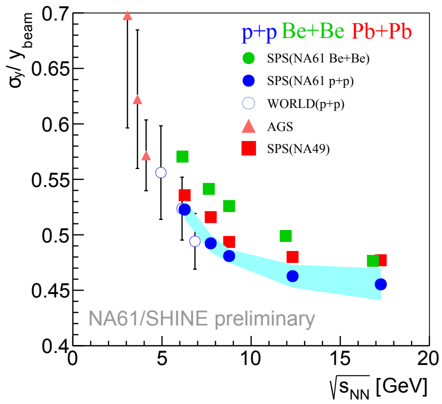

Figure 8: Width of the rapidity distribution of π^- mesons divided by the beam rapidity as a function of collision energy for p+p, ^{7}Be+^{9}Be, Pb+Pb.

for different system sizes are the smallest. Nevertheless, by taking into account the isospin asymmetry of p+p interactions the monotonicity of the width of the rapidity distribution as a function of system size is restored (Fig. 9).

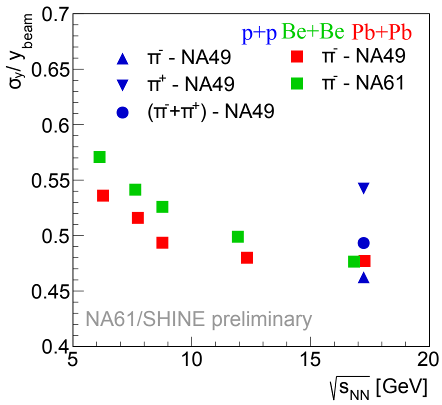

Figure 9: Width of rapidity distribution of π^- mesons produced in p+p, ^{7}Be+^{9}Be and Pb+Pb interactions divided by the beam rapidity as a function of collision energy. At 158 GeV/c the width for π^+ and $\pi^+ + \pi^-$ mesons in p+p interactions is shown [10]

3.4 Transverse mass spectra of negatively charged pions

The transverse mass spectra at mid-rapidity for four centrality classes of ^{7}Be+^{9}Be collisions as well as p+p and central Pb+Pb data are shown in Fig. 10. The spectra were fitted with an exponential function in the range $0.18 \leq m_T - m_0 \leq 0.72$ GeV/c^2. The p+p data are well fitted by the exponential function, while both ^{7}Be+^{9}Be and Pb+Pb data deviate from the exponential fit at both low and high m_T.

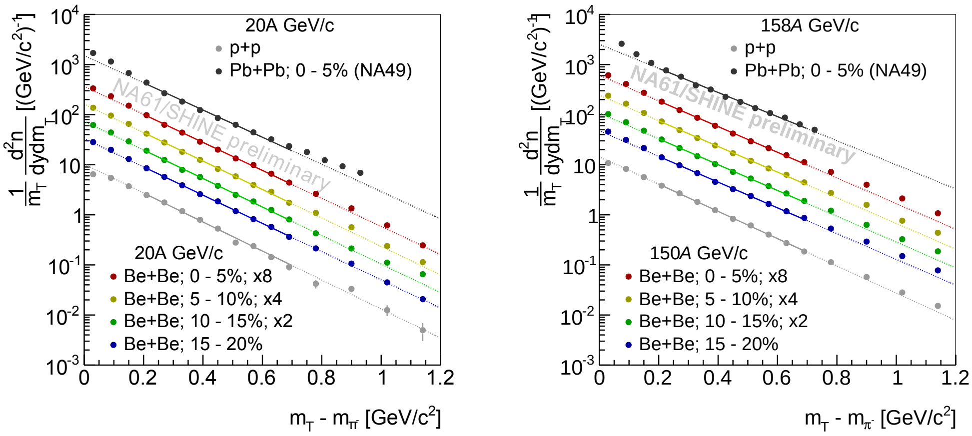

Figure 10: Transverse mass spectra of π^- mesons for ^{7}Be+^{9}Be , p+p and Pb+Pb interactions at 20*A* GeV/c *(left)* and 150*A* GeV/c *(right)*.

To compare shape of transverse mass spectra of negatively charged pions for various system sizes the ratio of normalized transverse mass spectra for ^{7}Be+^{9}Be/p+p and Pb+Pb/p+p was calculated (Fig. 11). Both ratios, ^{7}Be+^{9}Be/p+p and Pb+Pb/p+p, have the same structure.

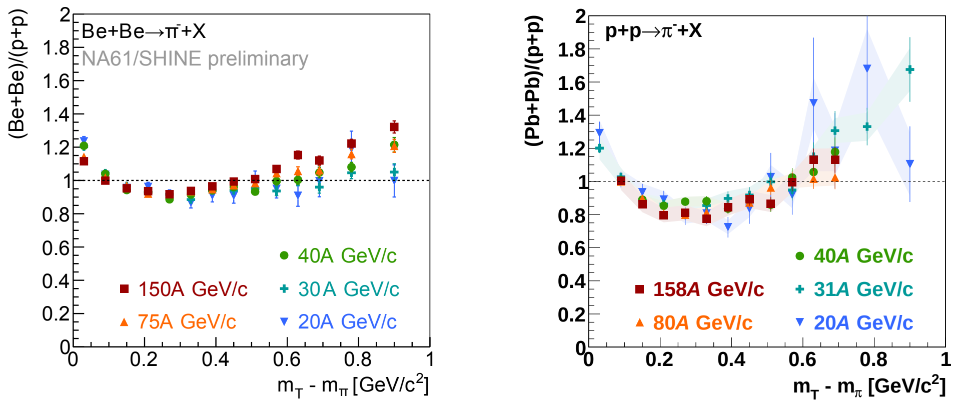

Figure 11: Ratio of normalized transverse mass spectra for different system sizes. *Left*: ^{7}Be+^{9}Be/p+p; *Right*: Pb+Pb/p+p.

At the high transverse mass region increase of the ratio is visible in both cases. This increase, and the corresponding decrease at intermediate transverse masses, are usually attributed to the collective flow. The effect is less pronounced in ^{7}Be+^{9}Be/p+p ratio. Furthermore, in the Pb+Pb data no beam momentum dependence is visible, while in the Be+Be data, the increase of the ratio at the high m_T seems to be larger for higher beam momenta, which is visible in Fig. 12. Such effect might suggest dependence of the magnitude of collective effects on the increasing beam momentum in ^{7}Be+^{9}Be collisions.

The detailed explanation of the observed structures requires further analysis.

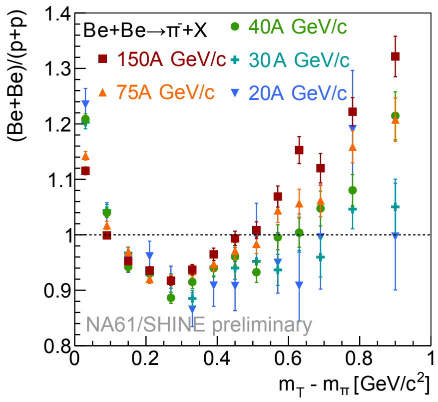

Figure 12: Ratio of normalized transverse mass spectra for ^{7}Be+^{9}Be/p+p. Note the rainbow-like systematics at the high m_T suggesting increase of collective effects with beam momentum.

4. Conclusions

The inelastic cross section of ^{7}Be+^{9}Be interactions were measured at three beam momenta in the SPS energy range. The results, together with the earlier measurement at 1.45*A* GeV/c, allowed to establish energy dependence of inelastic cross section for ^{7}Be+^{9}Be interactions.

The spectra of negatively charged pions in ^{7}Be+^{9}Be collisions were presented at five beam momenta, in four centrality classes. The width of the rapidity distribution in analyzed system sizes (p+p, ^{7}Be+^{9}Be, Pb+Pb) exhibits monotonic behaviour as the function of beam energy. The non-monotonic behaviour as the function of the system size revealed importance of the isospin asymmetry in p+p data. The transverse momentum spectra of negatively charged pions exhibit interesting structures. The increase at the high transverse mass region in ^{7}Be+^{9}Be interactions can be attributed to the collective behaviour of the created matter.

Acknowledgments

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