Recent results from the NA61/SHINE experiment

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Outline

- NA61/SHINE experiment
- Selected results from p+p energy scan (20, 31, 40, 80, 158 GeV/c):
  - Inverse slope parameter $T$ — “Step”
  - $\pi^+$ mid-rapidity multiplicity calculation
  - $K/\pi$ ratio — “Horn”
  - Comparison with Monte–Carlo models
- Selected results from $^7$Be+$^9$Be energy scan (20A, 30A, 40A, 75A, 150A GeV/c):
  - Forward Energy ($FE, E_F$) event selection (centrality)
  - Width of the $\pi^-$ rapidity distribution — “Dale”
  - Collectivity in $^7$Be+$^9$Be
NA61/SHINE detector system

Beam → Target → VTPC-1 → GAP TPC → VTPC-2 → Vertex magnets → MTPC-L, MTPC-R → ToF-L, ToF-F, ToF-R → PSD

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NA61/SHINE 2D scan goals

Statistical Model of the Early Stage (SMES)

\( p + p \)
Identified particle spectra in $p+p$ collisions

- Large acceptance for all particle types
- $p_T < 1 \text{ GeV/c}$
- $y_{\text{Beam}}(158 \text{ GeV/c}) = 2.8$
- $y_{\pi} \lesssim 3$
- $y_{K} \lesssim 2$
- $y_p \lesssim y_{\text{Beam}}$
- Lack of mid-rapidity pions, but they are possible
Mid–rapidity spectra of Kaons

- Spectra fitted by:

\[ \frac{d^2n}{dp_T dy} = \frac{S p_T}{T^2 + m_K^2} \exp \left( -\frac{\sqrt{p_T^2 + m_K^2} - m_K}{T} \right) \]

- Fit allows to calculate:
  - The inverse slope parameter $T$
  - Kaon multiplicity in $p_T$ range not accessible by data

PhD thesis of S. Pulawski
• Energy dependence of the inverse slope parameter $T$ of kaon spectra exhibits rapid changes in both $p+p$ and $Pb+Pb$ interactions.

PhD thesis of S. Pulawski
The energy dependence of $K^+/\pi^+$ ratio in $p+p$ changes at the energy where horn structure is visible in Pb+Pb.
\( \frac{K}{\pi} \) ratio in p+p interactions — comparison to models

- High precision NA61/SHINE data allows to impose rigorous constraints for Monte-Carlo models.

Vovchenko et al., PRC 90, 024916 (2014), and private communication. Gavin Salam private communication


PhD thesis of S. Pulawski

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Proton mean transverse mass

- $\langle m_T \rangle$ was calculated using fitted function:
  \[
  \frac{d^2n}{dp_T^2} dy = \frac{S}{T^2 + m_p T} \exp \left( - \frac{\sqrt{p_T^2 + m_p^2}}{T} \right).
  \]

- $\langle m_T \rangle$ of protons produced in p+p interactions around mid-rapidity increase slowly with collision energy.

- Neither UrQMD nor HSD describe this behavior.

Vovchenko et al., PRC 90, 024916 (2014), arXiv:1408:5493, and private communication;
PhD thesis of S. Pulawski
$^7\text{Be} + ^9\text{Be}$
The results depend (< 5%) on the definition of forward energy.

By calculating $E_F$ in a larger PSD acceptance, we include more spectators but also more produced particles.
The “h−” analysis method

- ≈ 90% of the negatively charged hadrons produced in $^7\text{Be}+^9\text{Be}$ interactions are $\pi^-$

- In the h− method a small contribution of other particles ($K^-$, $\bar{p}$, and decays from $\Lambda$ and $K^0_S$) is subtracted based on EPOS model predictions

- In p+p interactions the $dE/dx$ and tof identification methods cover much narrower region of the phase-space than the h− method

![Graph showing K/π ratio vs. √s_{NN} (GeV)]

![Graph showing π− distribution vs. y]
Double differential spectra of $\pi^-$

- Analysis done in four FE event classes: 0–5%, 5–10%, 10–15%, 15–20%
- All quantities were derived from double differential spectra

$$\frac{d^2n}{dydp_T} \text{ or } \frac{d^2n}{dydm_T}$$

corrected for detector effects and feed–down from weak decays
Rapidity spectra \((^7\text{Be}+^9\text{Be}, \text{p}+\text{p})\)
5 energies, 4 FE event classes
Asymmetry in rapidity spectra

Two opposite effects influence asymmetry of the spectra:

- asymmetric system — $^7$Be projectile on $^9$Be target (small effect),
- centrality selection based on projectile spectators (large effect).

Selection of 5% of most central collisions:

- introduce sharp cut on projectile spectators ($N_{\text{proj}}^{S} \leq 2$),
- fluctuations of target spectators are not explicitly restricted ($N_{\text{targ}}^{S} \approx \text{Gaussian}(x_0 = 3.7; \sigma = 1.4)$).
Width of the rapidity distribution

- $\sigma_y$ calculated from fitted function (two symmetrically displaced Gaussians)
- $\sigma_y$ related to speed of sound $c_s^2$ — “Dale”
- Smooth, monotonic behaviour with energy
- Non-monotonic behaviour with the system size:

$$\frac{\sigma_y(p+p)}{y_{beam}} \lesssim \frac{\sigma_y(Pb+Pb)}{y_{beam}} \lesssim \frac{\sigma_y(7\text{Be}+9\text{Be})}{y_{beam}}$$

Effect of isospin asymmetry on $\sigma_y/y_{beam}$

- The isospin asymmetry affects width of the $\pi^-$ rapidity distribution in $p+p$ and $Pb+Pb$
- $^7Be+^9Be$ is almost isospin symmetric
- In $p+p$ collisions rapidity width of $\pi^+$ is larger than width of $\pi^-$ distribution
- The width of the sum of $\pi^+$ and $\pi^-$ distributions is in between

Transverse mass spectra ($p+p$, $^7\text{Be}+^9\text{Be}$, $\text{Pb}+\text{Pb}$)
Comparison of transverse mass spectra (energy and system size)

Ratio of normalized $m_T$ spectra at different energies allows to compare shape of the spectra

$^7\text{Be}+^9\text{Be}$ data for 0-15% FE event class
$\text{Pb}+\text{Pb}$ data for 5% or 7.5% most central interactions
Comparison of transverse mass spectra

- From $m_T - m_{\pi^-} > 0.3 \text{ GeV/c}^2$ the ratio increases with beam momentum.
- Up to $m_T - m_{\pi^-} < 0.3 \text{ GeV/c}^2$ the ratio decreases with beam momentum.
- The beam momentum dependence of the ratio observed in $^7\text{Be}+^9\text{Be}$ is not visible in Pb+Pb collisions (previous slide).
- The shape of the ratio indicates the presence of radial collective flow in $^7\text{Be}+^9\text{Be}$.
- The energy dependence of the ratio suggests that the radial flow increases with the collision energy.
Summary

The data on pion, kaon and proton production properties in p+p was presented, as well as negative pion spectra from $^7\text{Be}+^9\text{Be}$ at five beam momenta (20A, 30A, 40A, 75A, 150A GeV/c).

- p+p data is unexpectedly interesting.
- Even in p+p the energy dependence of $K^+/\pi^+$ and inverse slope parameter $T$ exhibits rapid changes in the SPS energy range.
- High precision NA61/SHINE data present a challenge for models and should allow their improvement.
- The isospin effects play a large role in p+p data, the effects will be studied in detail to compare p+p with $^7\text{Be}+^9\text{Be}$ data.
- The shape of transverse mass spectra shows energy dependence that is different in $^7\text{Be}+^9\text{Be}$ and p+p.
- The radial flow in $^7\text{Be}+^9\text{Be}$ might increase with collision energy.
Additional Slides
Inverse slope parameter system size and energy dependence

- \( \sqrt{s_{NN}} \) [GeV]

- T [MeV]

- Pb + Pb; central (NA49)
- Be + Be; central
- p + p

- \( \) Pb+Pb much higher than p+p
- Effect of radial flow
- \( ^7\text{Be} + ^9\text{Be} \) points in between Pb+Pb and p+p
- Note: Inverse slope parameter in A+A collisions is very sensitive to fit range and size of the rapidity bin.