Resonance production and interaction from low to high energy

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1. Probing the properties of hadronic phase

- Resonances have different short lifetimes similar to the **Hadronic phase**
  - allow the study of properties of the hadronic phase in terms of regeneration and re-scattering effects
  - estimate the **duration between chemical and kinetic freeze-out**

### Regeneration
- pseudo-elastic scattering of decay products
  - → **Enhanced** yield

### Re-scattering
- resonance decay products undergo elastic scattering or pseudo-elastic scattering through a different resonance state
  - → Not reconstructed through invariant mass
  - → **Reduced** yield
Motivation

2. Strangeness production
   - Resonances have same quark content as the ground state particles, but different masses
     - help to understand **strangeness production** by factorizing mass and strangeness related effects

3. Spin alignment of vector mesons
Motivation

4. Chiral symmetry restoration

- Calculation from FASTSUM Collaboration shows potential parity doubling - signature of chiral symmetry restoration in heavy-ion collisions

5. In-medium energy loss
### Resonances (particles & decay)

#### Meson

<table>
<thead>
<tr>
<th>Meson</th>
<th>quark content</th>
<th>Decay modes</th>
<th>B.R.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho(770)^0$</td>
<td>$(u\bar{u}+d\bar{d})/2$</td>
<td>$\pi^+\pi^-$</td>
<td>100</td>
</tr>
<tr>
<td>$K^*(892)^0$</td>
<td>$d\bar{s}$</td>
<td>$K^+\pi^-$</td>
<td>66.6</td>
</tr>
<tr>
<td>$K^*(892)\pm$</td>
<td>$u\bar{s}$</td>
<td>$K^0_s\pi^+$</td>
<td>33.3</td>
</tr>
<tr>
<td>$f_0(980)$, $f_2(1270)$</td>
<td>unknown</td>
<td>$\pi^+\pi^-$</td>
<td>46(84)</td>
</tr>
<tr>
<td>$K^*_0,2(1430)^0$</td>
<td>$d\bar{s}$</td>
<td>$K^+\pi^-$</td>
<td>93(49.4)</td>
</tr>
<tr>
<td>$\phi(1020)$</td>
<td>$s\bar{s}$</td>
<td>$K^+K^-$</td>
<td>48.9</td>
</tr>
</tbody>
</table>

#### Baryon

<table>
<thead>
<tr>
<th>Baryon</th>
<th>quark content</th>
<th>Decay modes</th>
<th>B.R.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma(1385)^+$</td>
<td>uus</td>
<td>$\Lambda\pi^+$</td>
<td>87</td>
</tr>
<tr>
<td>$\Sigma(1385)^-$</td>
<td>dds</td>
<td>$\Lambda\pi^-$</td>
<td>87</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>uds</td>
<td>$pK^-$</td>
<td>22.5</td>
</tr>
<tr>
<td>$\Xi(1530)^0$</td>
<td>uss</td>
<td>$\Xi^-\pi^+$</td>
<td>66.7</td>
</tr>
<tr>
<td>$\Xi(1820)^{\pm,0}$</td>
<td>dss (uss)</td>
<td>$\Lambda K^\mp$ ($\Lambda K^0_s$)</td>
<td>unknown</td>
</tr>
<tr>
<td>$\Omega(2012)^\mp$</td>
<td>sss</td>
<td>$\Xi^-K^0_s$</td>
<td>unknown</td>
</tr>
</tbody>
</table>

#### Lifetime (fm/c)

$\rho(1.3) < K^\mp(3.6) < K^0(4.2) < \Sigma^\mp(5.0-5.5) < \Lambda^*(12.6) < \Xi^*(21.7) < \phi(46.2)$
Resonance suppression: $K^{*0}$

- **Suppression** of $K^{*0}$ is observed in different collision systems from various experiments (NA49, NA61/SHINE, STAR)
  - more suppression for larger collision systems
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  - more suppression for larger collision systems

• **Suppression** of $K^{*0}$ w.r.t. the statistical **Hadron Resonance Gas Models (HGM)** is observed for heavier system
• **Suppression** of $K^*$ and $\Lambda^*(1520)$ w.r.t. the statistical Hadron Resonance Gas Models (HGM) while no suppression for $\phi$ w.r.t. the HGM.

• Suppression effect might be related to the lifetime of the resonances.

Resonance suppression: energy dependence ($K^{*0}/K$)

- $K^{*0}/K$ and $\phi/K$ ratios have been measured at different energies
  - $K^{*0}/K$: decreasing with increasing multiplicity
  - $\phi/K$: independent of multiplicity

- $K^{*0}/K$ ratios in central collisions are smaller than the ratios from pp & ee collisions
  (ratios for AA collisions are results from most central collisions. e.g. 0-10% or 0-20%)
  - no clear energy dependence from 7.7 GeV/c to 5.02 TeV
Resonance suppression: energy dependence ($\phi/K$)

- Flat behavior in a wide range of energy ($\sim 10-10^4$ GeV) and different collision systems

PHYSICAL REVIEW C 102, 024912 (2020)
• Increase for low energies due to canonical suppression
  - reproduced by statistical model calculation with strangeness correlation radius parameter $R_c = 2.2\text{fm}$ (purple dashed curve)


PHYSICAL REVIEW C 102, 024912 (2020)
Resonance suppression: energy dependence ($\phi/K$)

- GCE underestimates data at low energy

- Thermal model with CE gives a good description of data at $\sqrt{s_{NN}}=3$ GeV

- SMASH&UrQMD$^2$ calculations reproduce $\phi/K$ at $\sqrt{s_{NN}}=3$ GeV
Resonance to long-lived particle ratios

- **suppression** of the ratios of short-lived resonances in central Pb-Pb collisions - indicates dominance of rescattering over regeneration

- no significant centrality dependence for long-lived resonances e.g. Ξ*, φ

- no energy dependence from RHIC to LHC

- smooth trend: pp→pA→AA
Probing the hadronic phase

- Estimate the **time duration between chemical and kinetic freeze-out** from the measurement of $K^0/K$ ratios in Pb-Pb and pp collisions
- lifetime of hadronic phase smoothly increases with multiplicity
- found to be $\sim 4$-7 fm/c for central collisions

$$[K^0/K]_{\text{kinetic}(\text{Pb-Pb})} = [K^0/K]_{\text{chemical}(\text{pp})} \times e^{-\tau/\tau_{K^0}}$$
Probing the hadronic phase

- There seems no energy dependence from 39 GeV to 200 GeV at RHIC
- Hadronic lifetime (\(\Delta t\)) at RHIC seems to be smaller than at LHC
- \(\Delta t\) measured from NA61/SHINE is comparable with RHIC
  - \(K^0/K^+\): 3.7\(\pm\)1.2 fm/c
  - \(K^0/K^-\): 3.2\(\pm\)1.2 fm/c
Probing the hadronic phase

Summary of estimation of the lower limit of hadronic phase for $\rho^0/\pi$, $K^*/K$, $K^{*\pm}/K$, and $\Lambda^*/\Lambda$

Estimated time duration measured in $\sqrt{s_{NN}}=5.02$ TeV energy seems larger than those from $\sqrt{s_{NN}}=2.76$ TeV - But within the systematic error

Need theory input to have better understanding
Strangeness enhancement in small system

What causes the enhancement? mass vs. strangeness

Ground state
s=1: Λ(1116)
s=2: Ξ(1320)
s=3: Ω(1670)

Resonances
s=1: Σ*(1385)±, Λ*(1520)
s=2: Ξ*(1530)0
s=3: Ω(2012)±
Strangeness enhancement in small system

\[ \langle \frac{dN_{\text{ch}}}{d\eta_{\text{lab}}} \rangle_{\eta_{\text{lab}} < 0.5} \times 10^{-3} \]

\( \Sigma(1385)^\pm, \Lambda(1520): \)
- Same strangeness content as \( \Lambda \)
- Mass is similar (grater) to \( \Xi \)
- \( \Sigma^*/\pi \) and \( \Lambda^*/\pi \) are compatible with \( \Lambda/\pi \)

\( \Xi(1530)^0: \)
- Same strangeness content as \( \Xi \)
- Mass is between \( \Xi \) & \( \Omega \)
- \( \Xi^*/\pi \) is compatible with \( \Xi/\pi \)

- Relative strangeness production increases with the multiplicity
- Enhancement of hyperons is due to their strangeness content (not a mass effect)

Spin alignment

• Deviation of $\rho_{00}$ from $\frac{1}{3}$ indicates spin alignment.

  Measured from the angular distribution of the daughter particle in parent’s rest frame:

  $\rho_{00}$: Element of spin density matrix
  if $\rho_{00} = \frac{1}{3}$, No spin alignment

  $\frac{dN}{d(\cos\theta^*)} \propto (1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta^*$

• Large angular momentum [1] and intense magnetic field [2] is expected in initial stage of heavy-ion collisions
  - spin alignment of vector meson could occur

Spin alignment: $\rho_{00}$ vs. $\rho_T$

- spin alignment ($\rho_{00}<1/3$) of vector meson in heavy-ion collisions at low $\rho_T$
- no spin alignment for vector meson in pp collisions
- no spin alignment for spin 0 meson ($K^0_s$)
- Measurements with Random Event Plane consistent with 1/3 (a small deviation at lowest $\rho_T$ bin: residual effect of event plane)
Spin alignment: $\rho_{00}$ vs. $\langle N_{\text{part}} \rangle$

- Spin alignment ($\rho_{00} < 1/3$) of vector meson in heavy-ion collisions at low $p_T$.
- $\rho_{00} \sim 1/3$ at high-$p_T$.
- $\rho_{00} \sim 1/3$ in central and peripheral collisions.
Conclusion

• Hadronic resonances are valuable probes to study the properties of hadronic phase and strangeness production, spin alignment (+chiral symmetry restoration, in medium energy loss, etc.)

• K*0/K and φ/K ratios are observed in different collision systems from various experiments
  - more suppression of K*0/K for the larger system
  - no energy dependence of K*0/K and φ/K ratios in a wide range (10-10⁴ GeV)

• Suppression of short-lived resonances in large collision systems
  - dominance of re-scattering over regeneration
  - no suppression observed for the longer-lived resonances

• Enhancement of strange baryon with multiplicity is due to strangeness content
  - confirmed by comparing ground state particle & resonances

• Spin alignment (ρ00<1/3) of vector meson is found in heavy-ion collisions at low pT in mid-central Pb-Pb collisions
Backup
**Intermediate-\(p_T\) (2 < \(p_T\) < 8 GeV/c)**
- baryon-meson splitting
- hint of **mass ordering** among mesons
- higher \(R_{AA}\) values for proton (might be due to baryon-meson effect)

**High-\(p_T\) (>8 GeV/c)**
- similar **suppression** for different light flavor hadrons
- No flavor (u,d,s) dependence
**Intermediate-\( p_T \) (2 < \( p_T < 8 \text{ GeV/c} \))**
- **mass dependent** for strange baryons

**High-\( p_T \) (>8 GeV/c)**
- **no suppression** for different light flavor hadrons
- No flavor (u,d,s) dependence
Strangeness enhancement: $\phi$

- $\phi/K (|S|=0)/(|S|=1)$
  - flat or slightly increasing at lowest multiplicities
  - suggest $\phi$ behaves like a $S \geq 1$ particle

- $\Xi/\phi (|S|=2)/(|S|=0)$
  - increase for low multiplicity collisions
  - fairly flat across wide multiplicity range

- The $\phi$ has “effective strangeness” of 1-2 units
Resonance to long-lived particle ratios

Antonina Rosano, Prottay Das (QM2022)

K$^\pm$/K$^0$ ratio in Pb-Pb collisions at ALICE:
- Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV, $|y| < 0.5$
- pp $\sqrt{s} = 13$ TeV, $|y| < 0.5$

Models:
- K*/K
- PYTHIA6 Perugia 2011
- PYTHIA8 Monash 2013
- PYTHIA8 Without CR
- EPOS-LHC no UrQMD
- DIPSY
- gammaS-CSM
- HRG
- MUSIC + SMASH
- MUSIC + SMASH res. dec.

ALICE Preliminary

Uncertainties:
- stat. (bar), total sys. (open box)
- uncorr. sys. (shaded box)

Neelima Agrawal, Sonali Padhan (QM2022)

$\Lambda(1520)/\Lambda$ ratio:
- pp, $\sqrt{s} = 7$ TeV
- p-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- pp, $\sqrt{s} = 13$ TeV
- pp, $\sqrt{s} = 5.02$ TeV
- Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
- Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- STAR, $\sqrt{s_{NN}} = 200$ GeV

Models:
- MUSIC+SMASH
- MUSIC (SMASH off)
- $\gamma_s$-CSM
- PCE

$T_{ch} = 156$ MeV
- THERMUS
- GSI-Heidelberg
- SHARE3

$T_{ch} = 138$ MeV, $\gamma_q = 1.63$, $\gamma_s = 2.08$
- SHARE3