Isobaric yield ratio difference (IBD) and nuclear density determination

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Outline

* 1. Background and Motivation
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Measurement of nuclear density and nuclear symmetry energy (NSE) is an important question in nuclear physics. NSE depends on nuclear density and temperature. Heavy-ion collisions (HIC) can produce nuclear matters from sub-saturation to supra-saturation densities, making HIC be the unique method studying NSE in lab. Nuclear density (and NSE) can not be measured directly. It is still an important task to find new probes to nuclear density and NSE.

- Neutron density
- supra-saturation nuclear matter in compressed zones of HIC.
1. Background and motivation

- An isobaric yield ratio difference (IBD) method is proven to be sensitive to the density difference between nuclei
- Isoabaric yield ratio (IYR) is defined as the ratio between isobars differing two in I=N-Z
- \( R = \frac{y(A, I+2)}{y(A, I)} \)
  - \( y(A, I) = CA^T \exp\{ [F(A, I) + N\mu_n + Z\mu_p] / T \} \)
  - \( R = \exp\{ [F(A, I - 2) - F(A, I) + \mu_n - \mu_p] / T \} \)
- The systematic dependence of \( y \) cancels out in \( R \).

grand-canonical ensembles theory, C. B. Das et al., PRC 64, 044608 (2001).
2. IBD method

* In IYR

* \[ R = \exp\left\{ \left[ F(A, I - 2) - F(A, I) + \mu_n - \mu_p \right] / T \right\} \]

* \[ \ln R = \left[ \Delta F(A, I + 2, I, A) + \Delta \mu_{np} \right] / T \]

* \[ \Delta \mu_{np} = \mu_n - \mu_p \]

* Define the difference between IYRs in 2 reactions, namely IBD,

* \[ \Delta_{21} \ln R = \frac{[(\mu_{np})_2 - (\mu_{np})_1]}{T} \]

* \[ = \frac{[\mu_{n2} - \mu_{n1} - (\mu_{p2} - \mu_{p1})]}{T} = \frac{\Delta \mu_{n21} - \Delta \mu_{p21}}{T} \]

2. IBD method

- Comparing to isoscaling
  - $\alpha = (\mu_{n2} - \mu_{n1})/T = \Delta\mu_{n21}/T$;
  - $\beta = (\mu_{p2} - \mu_{p1})/T = \Delta\mu_{p21}/T$;

- IBD and isoscaling
  - $\Delta_{21}\ln R = \frac{\Delta\mu_{n21} - \Delta\mu_{p21}}{T} = \alpha - \beta$

2. IBD method

Chemical potential and nuclear density

* \( \alpha = \ln \rho_{n2} - \ln \rho_{n1} \),
* \( \beta = \ln \rho_{p2} - \ln \rho_{p1} \),
* Denoting the density difference between the reactions.
* For IBD,
  * \( \Delta_{21} \ln R = \alpha - \beta = \ln \rho_{n2} - \ln \rho_{n1} - (\ln \rho_{p2} - \ln \rho_{p1}) \)
  * \( = \Delta (\ln \rho_n)_{21} - \Delta (\ln \rho_n)_{21} \)
  * \( = \ln \rho_{n2} - \ln \rho_{p1} - (\ln \rho_{n1} - \ln \rho_{p1}) \)
  * \( = \Delta (\ln \rho_{np})_{21} - \Delta (\ln \rho_{np})_{21} \)

3. SAA model

* Statistical abrasion-ablation model
* Abrasion-stage (pre-fragment determination)
* Evaporation-stage (final fragment determination)

- Projectile and target nuclei are divided into independent tubes
- Neutron and proton densities discriminated (Fang et al.)
  * $\rho_n$, $\rho_p$

References:
3. SAA model

* pre-fragment determination
* Nucleons abraded from the overlapping tubes

\[ < \Delta A(b) > = \int d^2 s \rho_n^P(s)[1 - t_n(s - b)] \]
\[ + \int d^2 s \rho_p^P(s)[1 - t_p(s - b)], \]

* \( t_n(s-b), t_p(s-b) \) : transmission probability for neutrons and protons at \( b \),

\[ t_k(s-b) = \exp\{-[\rho_n^T(s-b)\sigma_{nk} + \rho_p^T(s-b)\sigma_{pk}]\}, \]

* Cross sections of a prefragment with \( N \) neutrons and \( Z \) protons abraded,

\[ \sigma(\Delta N, \Delta Z) = \int d^2 b P(\Delta N, b) P(\Delta Z, b), \]

Cross section of prefragment is mainly determined by density and nucleus-nucleus reaction cross sections.
3. SAA model

* Fermi-type density distributions of nucleus

\[ \rho_k(r) = \frac{\rho_k^0}{1 + \exp\left(\frac{r-C_k}{t_kf_k/4.4}\right)}, \quad k = n, p \]

* \( t_k \) diffuseness, \( f_k \) introduced to adjust \( t_k \). The increase of \( f_k \) will push nucleons from core to surface of nucleus.

A. Fermi-type density distribution, Ozawa, T. Suzuki, I. Tanihata, Nucl. Phys. A 693, 32 (2001);
3. SAA model

* Evaporation process—decay of hot prefragment
* Excitation energy \( E^* \) of prefragment
  \[ E^* = 13.3 \ < A(b) \ > \text{MeV} \]
  * Excitation energy for per abraded nucleon 13.3 MeV.
  * \( <A(b)> \) abraded nucleons from projectile at \( b \).
* Prefragment \( (N,Z) \) decays by emitting \( n, p \) or \( \alpha \), until the residue is stable.
* The emitting particle is selected according to \( \min(s_n, s_p, s_\alpha) \) of prefragment \( (N,Z) \).

Comparing with GEMINI and SMM, the decay method of SAA is an simple way to determine the final fragment.
3. SAA model

- SAA (lines) can well reproduce the measured data (symbols)
4. Results and discussion

* The calculated $80\text{A MeV } \text{Ca} + ^{12}\text{C}$ reactions by using a modified statistical abrasion ablation model
* $38, 40, 42, 44, 46, 48, 50, 52\text{ Ca as projectiles}$
* Neutron density difference
* $\Delta_{21}\ln R = \Delta(\ln \rho_n)_{21}$
4. Results and discussion

- prefragments
- IBD-plateaus
- Height increases with n/z of projectile
- $\Delta_{21} \ln R = \Delta (\ln \rho_n)_{21} - \Delta (\ln \rho_n)_{21}$
- Assuming the proton density distributions of $^{x}Ca$ are the same
- $\Delta_{21} \ln R = \Delta (\ln \rho_n)_{21}$
- H of Plateau sensitive to $\Delta (\ln \rho_n)_{21}$

Similar trends of $\Delta \mu_{n21}/T$ and $\Delta \ln \rho_n \ r<6fm$
4. Results and discussion

* Averaged values of plateaus $\langle \Delta \mu_{n21}/T \rangle$ vs. I of fragments
* $\langle \Delta \mu_{n21}/T \rangle$ changes little with I
4. Results and discussion

- Final fragments
- IBD-plateaus
- Height also increases with n/z of projectile
- H of Plateau less sensitive to $\Delta (\ln \rho_n)_{21}$
- Plateau disappears in neutron-rich fragments
4. Results and discussion

- Decay effects in IBD
- H of final fragments is suppressed, make H less sensitive to the density changes of Ca isotopes
- Prefrags. IBD
- SAA ~1.75
  - Final frags. IBD
  - SAA ~0.5, exp. ~2
4. Results and discussion

- SAA well reproduces yields of frag. in $^{40}$Ca reaction, but overestimates yields of frags with small A in the I=-1, 0 and 1 chains in the $^{48}$Ca+C reaction.
- SAA underestimate IYR for I=-1 frags in the $^{48}$Ca+C reaction.
- The decay calculations should account for the difference between IYRs for reactions of neutron-rich projectile nucleus.
5. Conclusions

- Experimentally, IBD is sensitive to density difference between projectiles.
- IBD from SAA prefags is sensitive to the density difference between projectiles. While IBD from SAA final frags is suppressed and is less sensitive to the density difference between projectiles.
- The decay calculation for small A fragments should be modified.
- More works should be carried out on the IBD probes both theoretically and experimentally.

More discussion on the IBD method, please refer to:
Group members

Wang Shan-Shan, Zhang Yan-Li, Qiao Chun-Yuan, Zhang Hui-Ping, Bai Xiao-Man, Yu Jiao

Thanks for your attention!