# Nuclear stopping in asymmetric colliding nuclei

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## Introduction

In recent years, the study of heavy-ion collisions from low to relativistic energies have focused on the variety of phenomena which includes multi-fragmentation [1], anisotropy in the momentum distribution [2], and global stopping of the nuclear matter [3]. As we know, nuclear stopping is one of the essential observables which are necessary to understand the basic reaction dynamics. It is closely related to the question, whether the thermalization (equilibrium) can be reached in a reaction or not for a colliding system. This problem has been studied extensively both theoretically and experimentally [4]. In many cases, nuclear stopping has been studied by baryon rapidity distributions at various beam energies [5]. However, for a meaningful investigation, we study the variation of nuclear stopping by taking into account the asymmetry of the colliding pairs. The asymmetry of a reaction can be defined by the asymmetry parameter [6] $\eta = \mid (A_T - A_P)/(A_T + A_P) \mid$ ; $A_T$ and $A_P$ are, respectively the masses of target and projectile.

Nuclear stopping in HIC was studied with the help of different variables. A direct measure of the nuclear stopping is the rapidity distribution. The rapidity distribution can be defined as

$$Y(i) = \frac{1}{2} ln \frac{E(i) + p_z(i)}{E(i) - p_z(i)}, \tag{1}$$

where $E(i)$ and $p_z(i)$ are respectively, the energy and longitudinal momentum of the $i^{th}$ particle. For a complete stopping, one expect a single Gaussian shape.

The following two quantities can be can be used to describe nuclear stopping in heavy-ion collisions. The first quantity is the anisotropy ratio (R) which is defined as

$$R = \frac{2}{\pi} \frac{[\sum_i \mid p_\perp(i) \mid]}{[\sum_i \mid p_\parallel(i) \mid]} \tag{2}$$

where the summation runs over all nucleons. The transverse and longitudnal momenta are $p_\perp(i) = \sqrt{p_x^2(i) + p_y^2(i)}$ and $p_\parallel(i) = p_z(i)$, respectively. Naturally, for a complete stopping R should be close to unity. Another quantity, which is an indicator of nuclear stopping is the quadrupole moment $Q_{zz}$, defined as

$$Q_{zz} = \sum_i [2p_z^2(i) - p_x^2(i) - p_y^2(i)] \tag{3}$$

Naturally, for a complete stopping, $Q_{zz}$ should be close to zero.

## The Model

Semi classical microscopic improved version of QMD model [7] which includes Skyrme forces, isospin-dependent Coulomb potential, Yukawa potential, symmetry potential, and NN cross-section. The details about the elastic and inelastic cross sections for proton-proton and neutron-neutron collisions can be found in Refs.[7]. Thus, the total interaction potential is given as:

$$V^{ij}(\vec{r'} - \vec{r}) = V^{ij}_{Skyrme} + V^{ij}_{Yukawa} + V^{ij}_{Coul} + + V^{ij}_{sym} \tag{4}$$

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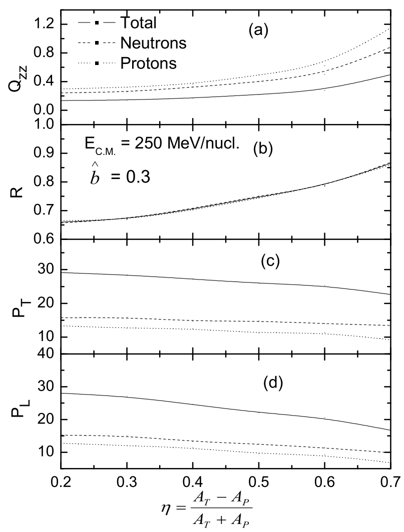


FIG. 1: The quadrupole moment $1/Q_{zz}$ and anisotropy ratio R as a function of asymmetry $\eta$ at a center of mass energy $E_{C.M.}$ = 250 MeV/nucleon. The third and fourth panels show the variation of transverse and longitudnal momentum with asymmetry, respectively. Different curves correspond to the contribution of neutrons and protons along with total contribution.

## Results and Discussion

In the present study, projectile mass is varied between 16 and 56 units and targets are chosen as different isotopes of $Xe$, $Sn$, $Ru$ in such a way that total mass of the reaction remains constant (= 152) for all channels. For example, we take the reactions of ${}_8O^{16} +_{54} Xe^{136}$, ${}_{14}Si^{28} +_{54} Xe^{124}$, ${}_{16}S^{32} +_{50} Sn^{120}$, ${}_{20}Ca^{40} +_{50} Sn^{112}$, ${}_{24}Cr^{50} +_{44} Ru^{102}$, and ${}_{26}Fe^{56} +_{44} Ru^{96}$ etc. Although, the total mass remains constant, the asymmetry of the reaction keeps varying between 0.2 and 0.7. The stopping at any time during the collision can be divided into the contributions emerging from the protons and neutrons. Here, at each time step during the collision, stopping due to neutrons and protons is analyzed separately.

Fig.1(a) shows the final state quadrupole moment $1/Q_{zz}$ decomposed into contributions due to neutrons and protons which increases with the asymmetry $\eta$. Fig.1(b) shows the final state anisotropy ratio $< R >$ as a function of the asymmetry of the system. We see no difference between the contributions due to neutrons and protons. This is due to the fact that $< R >$ is the ratio of the mean transverse momentum $p_\perp(i)$ to the mean longitudnal momentum $p_\parallel(i) = p_z(i)$. To see the clear contribution of neutrons and protons, one has to look into the contributions of transverse and longitudnal momenta as shown in Fig.1(c) and 1(d), respectively. A linear enhancement in the transverse and longitudnal momentum can be seen with asymmetry $\eta$. Further the contribution of neutrons exceeds the corresponding contributions due to protons.

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