Effect of width of the Gaussian wave packet on the energy of vanishing flow in heavy-ion collisions

Rajni Bansal*
M.C.M. D. A. V. College for Women, Sector 36 A, Chandigarh -160 036, INDIA

Introduction

A good progress has been made on the evolution of various simulation models, which are being used to study various observables, but the stability of ground state nuclei is still a serious issue for many dynamical models. This problem is more pronounced when momentum-dependent interactions are included in the calculations. Many attempts reported in the literature [1] tried to solve this problem by controlling various technical parameters like using (i) covariant treatment of two-body interaction and scattering (ii) cooling procedure via Pauli blocking and (iii) implementation of different ground-state initializations. One of the other technical parameters that effects the stability of the nucleus is width of the Gaussian wave packet (L), used to represent each nucleon in various dynamical models. The choice of the correct Gaussian width is must to ensure the proper building of the nucleus as it determines the interaction range of nucleons and hence influences the interaction density of finite system. The very small value of L is excluded as it leads to pre-emission of the nucleons, on the other hand, very large L value leads to smearing of the fluctuations. Also, width of the Gaussian wave packet is found to have significant role on the variables such as collective flow, multifragmentation, pions and kaon production etc. [2–4]. Recently, Gautam *et al.* [4] showed the sensitivity of the energy of vanishing flow (EVF) towards the interaction range of nucleons for isobaric reactions over whole colliding geometry. Here, we aim to study the role of stability of the nucleus via interaction range of the nucleons on the mass dependence of energy of vanishing flow (EVF) over the entire periodic table. We use "*directed transverse momentum* $\langle p_x^{dir} \rangle$" to calculate EVF, which is defined as [5],

$$\langle p_x^{dir} \rangle = \frac{1}{A} \sum_{i=1}^{A} sign\{y(i)\} p_x(i), \qquad (1)$$

where $y(i)$ is the rapidity and $p_x(i)$ is the momentum of i^{th} particle. The rapidity is defined as

$$y(i) = \frac{1}{2} \ln \frac{\mathbf{E}(i) + \mathbf{p}_z(i)}{\mathbf{E}(i) - \mathbf{p}_z(i)}, \qquad (2)$$

where $\mathbf{E}(i)$ and $\mathbf{p}_z(i)$ are, respectively, the energy and longitudinal momentum of i^{th} particle. In this definition, all the rapidity bins are taken into account. We performed the simulations at different fixed incident energies and a straight line interpolation is used to calculate the EVF. The present analysis is carried out using Isospin Quantum Molecular Dynamics Model [4].

The Model

The IQMD model has been used extensively for studying the isospin effects on large number of observables. The IQMD model is a N-body theory which simulates heavy-ion reaction on event by event basis and hence preserves correlations and fluctuations of the reaction. The isospin degree of freedom enters into the calculations via symmetry potential, cross-sections, and Coulomb interaction. In this model, nucleons are represented by Gaussian wave packets given by,

$$\psi_i(\mathbf{r}, \mathbf{p}_i(t), \mathbf{r}_i(t)) = \frac{1}{(2\pi L)^{\frac{3}{4}}} exp[\frac{i}{\hbar}\mathbf{p}_i(t).\mathbf{r} - \frac{(\mathbf{r} - \mathbf{r_i(t)})^2}{4L}], \qquad (3)$$

*Electronic address: `rajnibansal.pu@gmail.com`

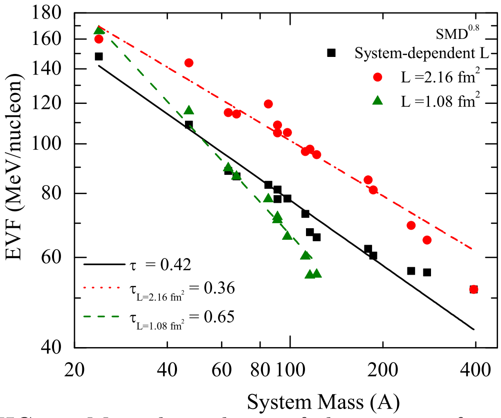

FIG. 1: Mass dependence of the energy of vanishing flow for different choice of Gaussian wave packet width. Lines represent the power law fit $\propto$ $A^{-\tau}$.

where L represents width of the Gaussian wave packet. The baryons propagate using the classical equations of motion under the baryon potential V^{ij} given by:

$$\begin{aligned}
V^{ij}(\vec{r}\,' - \vec{r}) &= V^{ij}_{Sky} + V^{ij}_{Yuk} + V^{ij}_{Coul} \\
&\quad + V^{ij}_{mdi} + V^{ij}_{sym} \\
&= [t_1\delta(\vec{r}\,' - \vec{r}) + t_2\delta(\vec{r}\,' - \vec{r})\rho^{\gamma-1} \\
&\quad (\frac{\vec{r}\,' + \vec{r}}{2})] \\
&\quad + t_3\frac{\exp(-|(\vec{r}\,' - \vec{r})|/\mu)}{(|(\vec{r}\,' - \vec{r})|/\mu)} \\
&\quad + \frac{Z_iZ_je^2}{|(\vec{r}\,' - \vec{r})|} \\
&\quad + t_4\ln^2(t_5(\vec{p}\,' - \vec{p})^2 + 1)\delta(\vec{r}\,' - \vec{r}) \\
&\quad + t_6\frac{1}{\rho_0}T_{3i}T_{3j}\delta(\vec{r}\,' - \vec{r}). \qquad (4)
\end{aligned}$$

Here Z_i and Z_j denote the charges of i^{th} and j^{th} baryon, and T_{3i} and T_{3j} are their respective T_3 components (i.e., 1/2 for protons and $-1/2$ for neutrons). The parameters $t_1, \ldots,$ t_5 are adjusted to the real part of the nucleonic optical potential.

Results and discussion

For the present mass-dependent analysis, we simulated the reactions of ^{12}C+^{12}C (b/b_{max} = 0.4), ^{20}Ne+^{27}Al (b/b_{max} = 0.4), ^{36}Ar+^{27}Al (b = 0-2.5 fm), ^{40}Ar+^{27}Al (b = 1.6 fm), ^{40}Ar+^{45}Sc (b/b_{max} = 0.4), ^{40}Ar+^{51}V (b/b_{max} = 0.3), ^{64}Zn+^{27}Al (b = 0-2 fm), ^{40}Ar+^{58}Ni (b = 0-3 fm), ^{64}Zn+^{48}Ti (b = 0-2.5 fm), ^{58}Ni+^{58}Ni (b/b_{max} = 0.28), ^{64}Zn+^{58}Ni (b = 0-2.5 fm), ^{86}Kr+^{93}Nb (b/b_{max} = 0.4), ^{93}Nb+^{93}Nb (b/b_{max} = 0.3), ^{129}Xe+^{118}Sn (b = 0-3 fm), ^{139}La+^{139}La (b/b_{max} = 0.3), and ^{197}Au+^{197}Au (b = 0-4 fm). The choice of reactions and the colliding geometry is guided by the experimental findings. The most reliable soft momentum-dependent equation of state along with reduced isospin- and energy-dependent nucleon-nucleon (nn) cross-section (σ = 0.8 $\sigma_{NN}{}^{free}$) is used to simulate the above mentioned reactions. In Fig. 1, squares, triangles and circles represent the calculations using system-dependent Gaussian width, fixed value of L= 1.08 fm^2 and L= 2.16 fm^2, respectively. From the figure it is clear that with increase in the value of L, EVF increases (see circles and triangles) because of the smearing of density profile for larger interaction range and this results in the reduction of flow, and hence, pushes the EVF to higher values. Also, when one uses L= 1.08 fm^2 then heavy nuclei could not be build up due to the pre-emission of the nucleons, and hence we can not extract their corresponding energy of vanishing flow.

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