Mass dependence of balance energy: comparison with experimental data

Rajni Bansal[1], Sakshi Gautam[2], and Rajeev K. Puri[1*]
[1] *Department of Physics, Panjab University, Chandigarh - 160 014, India*
[2] *Department of Physics, Dev Samaj College for Women, Sector 45 B, Chandigarh -160 047, India*

Introduction

The collective transverse flow is a novel candidate to gain insight into the properties of nuclear matter at different thermodynamical conditions. The dependence of transverse flow to various entrance channel parameters like incident energy, system size, colliding geometry, mass asymmetry and isospin of the reacting nuclei is well established experimentally as well as theoretically [1–3]. The energy dependence of transverse flow, in particular, is of great importance and it leads to a term known as balance energy (E_{bal}) or energy of vanishing flow (EVF), where attractive and repulsive interaction counterbalance each other. The balance energy is of great significance because experimentally determined balance energy can be easily compared with various theoretical calculations as it is free from any experimental uncertainties. A lot of efforts are being done in this direction and balance energies for more than 15 systems have been measured experimentally [1, 2] for the mass ranging between 24 (^{12}C+^{12}C) to 394 (^{197}Au+^{197}Au) units.

On the other hand, extensive studies have also been carried out regarding the system size effects in the disappearance of flow. The studies revealed power law behavior for the system size dependence of the balance energy. Similar power law dependence has been reported for various phenomenon. From the careful analysis of literature on the system size dependencies of balance energy, it has been found that the power law factor is not unique and varies with the theoretical model used as well as with the mass range. Also most of the theoretical attempts are limited to a much narrower range. One of the author and collaborator have carried out a systematic study of mass dependence of E_{bal} for the reactions ranging from ^{12}C+^{12}C to ^{238}U+^{238}U using isospin-independent quantum molecular dynamics (QMD) model and calculated the balance energy for the reaction of ^{238}U+^{238}U for the first time [4]. At the same time, due to recent interest of nuclear physics community towards neutron rich isotopes, the use of isospin-dependent quantum molecular dynamics (IQMD) model as a theoretical tool is desired due to the implementation of various isospin features in it. A study of mass dependence of balance energy using IQMD model is carried out by Kumar *et al.* [5] recently, but their study was restricted to the mass range between 122 (^{64}Zn+^{58}Ni) to 394 (^{197}Au+^{197}Au) units. Thus, here we aim to present the complete and systematic study of mass dependence of balance energy using IQMD model [6].

Results and discussion

For the present study, we use the isospin-dependent quantum molecular dynamics model which explicitly includes the isospin degree of freedom [7]. We simulated the reactions ranging from ^{12}C+^{12}C to ^{197}Au+^{197}Au whose measured balance energies are available (as stated in introduction) using soft momentum-dependent (SMD) equation of state along with $\sigma = 0.8\sigma_{free}$. The reactions are followed till the transverse in-plane flow saturates. In particular, 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 =

*Electronic address: rkpuri@pu.ac.in

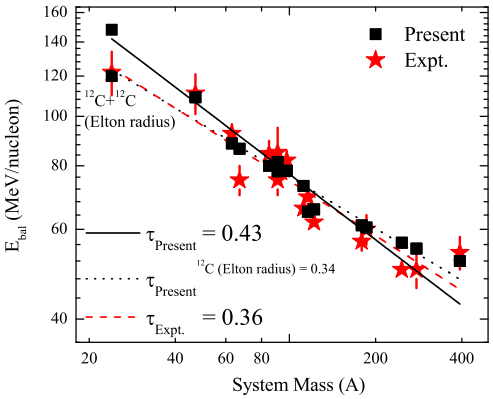

FIG. 1: The balance energy as function of total mass of the system. Lines represent the power law fit $\propto A^{-\tau}$. The stars with error bars represent experimental data whereas squares correspond to present calculations.

1.6 fm), ^{40}Ar+^{45}Sc (b/b_{max} = 0 − 0.28), ^{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 − 0.28), ^{64}Zn+^{58}Ni (b = 0-2.5 fm), ^{86}Kr+^{93}Nb (b/b_{max} = 0 − 0.28), ^{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 above reactions are simulated at incident energies ranging between 40 MeV/nucleon and 150 MeV/nucleon depending upon the mass of the colliding pair. The reactions are simulated at different fixed incident energies and a straight line interpolation is used to calculate the balance energy. For the transverse flow we use the quantity "*directed transverse momentum* $\langle p_x^{dir} \rangle$", which has been defined in Ref. [3].

In Fig. 1, we display the system size dependence of balance energy through out the mass range from ^{12}C+^{12}C to ^{197}Au+^{197}Au. The squares represent our theoretical calculations with soft momentum-dependent EOS and reduced in-medium nucleon-nucleon cross-section ($\sigma = 0.8\sigma_{free}$). From the figure, we see that E_{bal} follows a power law behavior ($\propto A^{-\tau}$) with system size, where power law factor τ (labeled by $\tau_{\rm Present}$) is 0.43, also when we use Elton radius for ^{12}C+^{12}C reaction [8] then power law factor becomes 0.34. The measured balance energies for the corresponding systems are displayed by the stars and the power law factor (labeled by $\tau_{\rm Expt.}$) is 0.36. It is clear that present IQMD calculations reproduces the measured E_{bal} (and its mass dependence) through out the mass range. It is worth mentioning that, previously also, the IQMD calculations with same parameter set of SMD EOS with $\sigma = 0.8\sigma_{free}$ reproduces the measured E_{bal} for the reactions of ^{58}Ni+^{58}Ni and ^{58}Fe+^{58}Fe through out the range of colliding geometry [3] and this was the motivation for taking the same parameter set for the present calculations.

This work is funded by University Grant Commission (UGC) Project No. 42-811/2013(SR).

References

[1] J. P. Sullivan *et al.*, Phys. Lett. B **249**, 8 (1990); C. A. Ogilvie *et al.*, Phys. Rev. C **42**, R10 (1990); D. Krofcheck *et al.*, *ibid.* C **46**, 1416 (1992); A. Buta *et al.*, Nucl. Phys. A **584**, 397 (1995); G. D. Westfall *et al.*, Phys. Rev. Lett. **71**, 1986 (1993); D. Cussol *et al.*, Phys. Rev. C **45**, 044604 (2002).

[2] Z. Y. He *et al.*, Nucl. Phys. A **598**, 248 (1996); D. J. Magestro *et al.*, Phys. Rev. C **62**, 041603(R) (2000).

[3] S. Gautam and A. D. Sood, Phys. Rev. C **82**, 014604 (2010); S. Gautam *et al.*, Phys. Rev. C **83**, 034606 (2011); *ibid.* C **83**, 014603 (2011); *ibid.* C **86**, 034607 (2012).

[4] A. D. Sood, R. K. Puri and J. Aichelin, Phys. Lett. B **594**, 260 (2004); A. D. Sood and R. K. Puri, Phys. Rev. C **69**, 054612 (2004).

[5] S. Kumar *et al.*, Phys. Rev. C **82**, 024610 (2010).

[6] R. Bansal, S. Gautam and R. K. Puri Phys. Rev. C (submitted).

[7] C. Hartnack *et al.*, Eur. Phys. J A **1**, 151 (1998).

[8] R. Bansal, S. Gautam, R. K. Puri and J. Aichelin Phys. Rev. C **87**, 061602(R) (2013).