# Comparison of IQMD results with other N-body molecular dynamics approaches

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## Introduction

The energy of vanishing flow has been a topic of great interest for last four decades. A lot of efforts have been done in this direction experimentally as well as theoretically. Here, we make an attempt to compare our theoretical calculations for the energy of vanishing flow (EVF) carried out using Isospin Quantum Molecular Dynamics (IQMD) model [1] with earlier attempts using many-body approaches like the Quantum Molecular Dynamics (QMD) [2], IQMD [3, 4], Ultra-relativistic Quantum Molecular Dynamics (UrQMD) [5], and Antisymmetrized Molecular Dynamics (AMD) [6] models as well as with optical model [7] to see the model dependencies on this observable.

## Results and discussion

We simulate thousands of events for various reactions ranging from $^{12}$C +$^{12}$C to $^{197}$Au +$^{197}$Au as per earlier attempts using soft momentum-dependent equation of state (EOS) along with reduced cross-section ($0.8\sigma_{free}$) using Isospin-dependent Quantum Molecular Dynamics (IQMD) model [1]. In Fig. 1, we display the energy of vanishing flow as a function of system mass where squares represent our present calculations and circles correspond to earlier calculations using the above mentioned many-body models. Lines represent the power law fit $\propto A^{-\tau}$.

Fig. 1(a) displays the calculations of QMD model done by one of the authors and collaborator [2]. Different circles correspond to the various sets of EOS and cross-sections. From Fig. 1(a), we find that the system size dependence of EVF corresponding to hard momentum-dependent (HMD) EOS with 40 mb cross-section shows better agreement with present calculations. Next, Fig. 1(b) displays the results of IQMD model by Zhang *et al.* [3] for the reactions of $^{12}$C+$^{12}$C and $^{112}$Sn+$^{112}$Sn

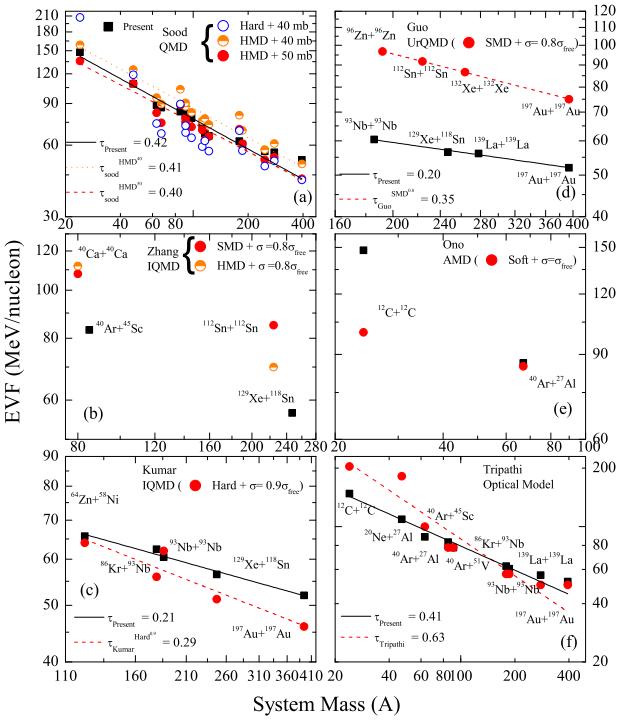


FIG. 1: The energy of vanishing flow (EVF) as function of system mass (A) for various theoretical approaches of many-body type and the corresponding balance energies are represented by circles. Square represent present IQMD calculations. Different panels correspond to different theoretical attempts. Lines represent the power law fit $\propto A^{-\tau}$.

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(circles). From the figure, we see that the results of Zhang *et al.* (for both SMD and HMD EOS with reduced nn cross-section) are higher than that predicted by present calculations. This is due to the difference in the initialization of projectile and target nuclei and the interaction range of nucleons used in both the models. Another attempt to study the mass dependence of EVF using present IQMD model is done by Kumar *et al.* [4](Fig. 1(c)). The study by Kumar *et al.* was conducted using hard EOS with 10% reduced cross-section. From the figure, we see that both the calculations give almost similar power law dependence. The little difference in the EVF of the heavier systems is due to the difference in the EOS and reduction factor of nn cross-section used by Kumar *et al.* compared to the present calculations. Another attempt to study the mass dependence of EVF is done by Guo *et al.* [5] using UrQMD model. Their results are displayed in Fig. 1(d) by circles. From the figure we see that EVF differ by a large amount compared to our present calculations, whereas, the power law factors are relatively same. This is because of different treatment of Pauli blocking in UrQMD model calculations. Also, in UrQMD calculations the cross-section reduction factor corresponding to both density and momentum is employed, which leads to comparatively effective reduction compared to our IQMD calculations (where a constant reduction factor is used). This reduced cross-section also leads to higher energy of vanishing flow in the study of Ref. [5]. Further, Ono *et al.* [6] calculated the energy of vanishing flow for the reactions of $^{12}$C+$^{12}$C and $^{40}$Ar+$^{27}$Al using AMD model. The results are displayed in Fig. 1(e) by circles. From the figure we see that energy of vanishing flow is higher for our calculations compared to that with AMD calculations, though the difference is significant only for the lighter system of $^{12}$C+$^{12}$C. While investigating the details of AMD calculations, we have found that the momentum dependence is taken care of in AMD calculations by using Gogny forces having same compressibility as that of soft EOS in the IQMD calculations. Moreover, the isospin feature through the symmetry potential and nn scattering cross-section have also been incorporated. On the other hand, the reduction factor to the cross-section is not employed and this is one of the reasons that has led to the difference between the two approaches. Due to enhanced cross-section in AMD (compared to that used in IQMD where 20% reduction is done), the energy of vanishing flow gets reduced for the reaction of $^{12}$C+$^{12}$C. It is worth noticing that calculated EVF differ for $^{12}$C+$^{12}$C reaction, whereas for $^{40}$Ar+$^{27}$Al the difference almost vanishes. This is due to the fact that the simulations are carried out at different impact parameters in both the cases. As for the $^{12}$C+$^{12}$C reaction, the impact parameter is 2 fm in both the cases, whereas for the reaction of $^{40}$Ar+$^{27}$Al, the present IQMD calculation are carried out at central geometry (1.6 fm) and corresponding AMD calculations are done at 3 fm. In the last part of the comparison, we have displayed the results of optical model calculations by Tripathi *et al.* [7]. From the figure we see that our calculations under predict the EVF compared to that with the calculations of Tripathi *et al.* for lighter systems, whereas, the calculations do not differ much for the reactions involving heavier masses.

## References

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