The roles of deformation and orientation in heavy-ion collisions induced by light deformed nuclei at intermediate energy

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The reaction dynamics of axisymmetric deformed 24Mg + 24Mg collisions have been investigated systematically by an isospin-dependent quantum molecular dynamics (IDQMD) model. It is found that different deformations and orientations result in apparently different properties of reaction dynamics. We revealed that some observables such as nuclear stopping power (R), multiplicity of fragments, and elliptic flow are very sensitive to the initial deformations and orientations. There exists an eccentricity scaling of elliptic flow in central body-body collisions with different deformations. In addition, the tip-tip and body-body configurations turn out to be two extreme cases in central reaction dynamical process.

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Aligned experiments investigating how deformed 165Ho target affects the total neutron reaction cross section from 2 to 125 MeV [1] and scattering of α particles with 15 ≤ Eα ≤ 23 MeV [2] were carried out about forty years ago. The similar case occurs in nanoscale physics that the initial shape of hot droplets also has significant effects on fragmentation process in the molecular dynamics (MD) framework [3]. It is expected that deformed nuclei induced heavy-ion collisions (HICs) can result in obviously different properties of dynamical processes and final state observables compared with spherical cases. There are some reports about deformed U + U collisions at relativistic and ultrarelativistic energies and it is suggested that deformed U + U collisions are more likely to create quark-gluon plasma (QGP) and may resolve many outstanding problems [4–11]. The deformation effects on reaction cross section [12], elliptic flow [13] and heavy-ion fusion [14, 15] was also discussed recently. On the other hand, polarized target and beam have been widely applied related with spin effects in HICs [16] especially for the total and differential reaction cross section measurement of aligned deformed beams such as 7Li [17] and 23Na [18].

The spin polarized beams have been greatly promoted by projectile-fragmentation reactions recently [19], which brings large angular momentum into fragment spin. Not only the fragmentation process itself produces spin polarized fragments but also the produced spin orientated beam of deformed nuclei can provide valuable information on shape effects during collisions [20]. Therefore, it is very necessary to consider the degree of freedom of initial deformation since so many radioactive nuclei far from β-stability line may have large deformation. However, the knowledge about collisions induced by deformed nuclei is very poor especially at intermediate energy. Due to the distinct differences in overlap region of deformed nuclei collisions, collisions of aligned deformed nuclei may give a clearer and deeper insight into the reaction mechanism such as the process of multifragmentation and the development of collective flow. The different orientational collisions also have the advantage in fixing the uncertain behavior of density dependent symmetry energy, which is an elemental open problem related not only to many problems in nuclear physics but also to a number of important issues in nuclear astrophysics [21]. Besides the advantage in studying reaction mechanism and dynamics, highly deformed nuclei induced reactions may also inspire exotic nuclei research such as halo [22] and cluster phenomena [23].

In this paper, 24Mg + 24Mg collision system is used to investigate the initial deformation and orientation effects by a microscopic transport model: the IDQMD model [24], which was developed from the quantum molecular dynamics (QMD) model [25]. The main advantage of the QMD model is that it can explicitly treat the many body state of collision system. So it contains correlation effects to all orders and can treat the fragmentation and fluctuation of HICs well.

In this calculations, soft and hard nuclear equation of state (EOS) with the incompressibility of K = 200 and 380 MeV, respectively, are used for comparison. Here the strength of symmetry potential C_sym = 32 MeV [26] and experimental parameterized nucleon-nucleon cross section which is energy and isospin dependent are used. 24Mg is approximately treated as a sharp-cutoff ellipsoid with large quadrupole deformation parameter: β2 = 0.416 [26]. For comparison, systematical calculations for tip-tip (body-body) collisions of 24Mg + 24Mg with β2 = 0, 0.05, 0.1, 0.2 (all four cases with the same root mean-square radius) at different energies and impact pa-

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Firstly, we discuss the nuclear stopping power \( R = \frac{1}{2} \sum_i A_i | P_{i \perp} | / \sum_i A_i | P_{i \parallel} |, \) where \( A \) refers to the sum of projectile mass number and target mass number, \( P_{i \perp} = (P_{ix}^2 + P_{iy}^2)^{1/2}, P_{i \parallel} = P_{iz} \) in the c.m. reference system \( [27] \) of different orientational collisions. \( R \) can be used to describe the momentum dissipation and the degree of thermalization. Fig. 2 (a) shows that central body-body collisions lead to larger \( R \) than central tip-tip collisions below 50 MeV/nucleon while the situation reverses when incident energies exceed 75 MeV/nucleon. The more prolate \( ^{24}\text{Mg} \) is, more obvious differences appear. The spherical case lies between tip-tip and body-body collisions at all calculated energies. The larger \( R \) of tip-tip collisions at higher energy is in agreement with the result at 0.52 GeV/nucleon by ART model \( [10] \). However, the inversion of \( R \) between tip-tip and body-body collisions is first observed. It reflects the different roles of the initial space configurations vs. energies.

It is known that the reaction mechanism at intermedi-
at lower energies, where one-body scattering is predominant. Whereas two-body collisions become more important in tip-tip configurations at higher energies.

Since the IDQMD model can treat fragmentation of hot nuclei \[23, 29\] well. It is appropriate to investigate the fragmentation observables. As shown in Fig. 4, the fragment multiplicity has strong correlation with stopping power. Body-body collisions have minimal multiplicity at all impact parameters at higher energies while tip-tip collisions have the maximal one. So this behavior is consistent with that of stopping power at higher energies. It can also be seen from charge distributions in Fig. 5 that the tip-tip and body-body collisions are two extreme cases and the sphere-sphere collisions lie between them. Therefore, the fragment observables also confirm the similar picture indicated by \( R \).

The Body-body collisions with \( b = 0 \) \( \text{fm} \) will produce large collective motions due to the different initial geometry from spherical nuclei. Anisotropic flow method has been developed to measure the anisotropy of particle momentum space which related to the EOS and nuclear reaction dynamics \[30, 32\]. The azimuthal distribution of fragments can be expressed by Fourier expansion \[23 \]
\[
\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n\phi),
\]
where \( \phi \) is azimuthal angle between the transverse momentum of the particle and the reaction plane. The coefficient \( v_n \) is defined as anisotropic flow parameter, among which \( v_2 \) denotes elliptic flow.

It can be calculated in terms of single-particle averages: \( v_2 = \langle \cos(2\phi) \rangle = \frac{<p_x^2 - p_y^2>}{<p_x^2 + p_y^2>} \). Nucleon’s \( v_2 \) induced by deformed U + U collisions has been studied by ART model \[3 \] and optical Glauber model \[13 \] at relativistic energies recently. It seems that the most central body-body collisions give rise to largest \( v_2 \) because of the strongest shadowing effect in the reaction plane \[3 \]. Thus \( v_2 \) of central body-body collisions are most appropriate for investigating the EOS. However, \( v_2 \) developed from deformed nuclei collisions is unknown at intermediate energy and it’s interesting to study their deformation and orientation effects.

\( v_2 \) of light fragments are shown in Fig. 6 in which the eccentricity (\( \epsilon \)) is calculated by maximal geometry overlap region: \( \epsilon = \frac{\sum_i (x_i^2 - y_i^2)}{\sum_i (x_i^2 + y_i^2)} \). Cental tip-tip and sphere-sphere collisions do not have obvious \( v_2 \) because of the transverse symmetry of overlap region while the \( v_2 \) of central body-body collisions has non-zero value.

The negative sign of \( v_2 \) at higher energies is in agreement with deformed U + U collisions by ART model \[3, 10\]. The positive \( v_2 \) at lower energies and the alteration of sign for \( v_2 \) are first observed in central body-body collisions. At higher energies the violent two-body collisions in overlap region build the anisotropy pressure and it prompts fragments emission from in-plane preferential to out-of-plane preferential. The heavier fragments have larger \( v_2 \), which is consistent with ref. \[34 \]. \( v_2 \) of central body-body collisions (\( \beta_2 = 0.05, 0.1, 0.2, 0.416 \)) can be scaled together by \( \epsilon \) from low energies to high energies.

While scaled by the same \( \epsilon \) amplitude as the deformed \( 24\text{Mg} \) collisions, \( v_2 \) for mid-central spherical \( 24\text{Mg} \) collisions shows different behaviors especially for higher energies. Therefore, the scaling of \( v_2 \) indicates that the geometric shapes of participants play an essential role in collective flow of central body-body collisions.

The energy excitation function of \( v_2 \) at mid-central sphere-sphere collisions varies from positive (in-plane, rotational-like emission) to negative (out-of-plane, “squeeze-out” pattern) \[31, 35\]. This energy point is so-called transition energy, which is near 100MeV/nucleon.

FIG. 4: (Color online) Energy dependence of fragment multiplicity of tip-tip, body-body and sphere-sphere collisions at different reduced impact parameters (\( b_{red} = b/b_{max} \), where \( b_{max} \) refers to the maximal impact parameter for different cases).

FIG. 5: (Color online) Charge distributions of tip-tip, body-body and sphere-sphere collisions at different \( b_{red} \) and incident energies.
central collisions with
tip collisions. The dashed lines are drawn to guide the eye. Left: \( v_2 \) in central collisions with \( b = 0 \) fm; Right: scaled \( v_2 \) with eccentricity \( \epsilon \) in central body-body collisions and non-central spherical \( ^{24}\text{Mg} \) collisions. The spherical \( ^{24}\text{Mg} \) collisions with \( b = 1.45 \) fm and 2.85 fm have the same absolute value of \( \epsilon \) as the deformed central \( ^{24}\text{Mg} \) collisions with \( \beta_2 = 0.2 \) and 0.416 , respectively.

![FIG. 6:](image)

**FIG. 6:** (Color online) \( v_2 \) excitation function of light fragments at mid-rapidity \((-0.5 < Y < 0.5)\) of deformed and spherical collisions. The dashed lines are drawn to guide the eye. Left: \( v_2 \) in central collisions with \( b = 0 \) fm; Right: scaled \( v_2 \) with eccentricity \( \epsilon \) in central body-body collisions and non-central spherical \( ^{24}\text{Mg} \) collisions. The spherical \( ^{24}\text{Mg} \) collisions with \( b = 1.45 \) fm and 2.85 fm have the same absolute value of \( \epsilon \) as the deformed central \( ^{24}\text{Mg} \) collisions with \( \beta_2 = 0.2 \) and 0.416 , respectively.

![FIG. 7:](image)

**FIG. 7:** (Color online) Average \( v_2 \) excitation function of light fragments at mid-rapidity \((-0.5 < Y < 0.5)\) for deformed and spherical collisions with soft and hard EOS. \( v_2 \) is averaged with \( b \) from 0 to \( b_{\text{max}} \) for body-body and sphere-sphere collisions.

For spherical collision system, there exist three competing components affecting the transition energy: (1) rotation of the compound system, (2) expansion of the hot and compressed participant zone, and (3) shadowing of the colder spectator region. Only the expansion survives in central spherical collisions, which merely generates azimuthal symmetric flow. However, both body-body collisions have bulk transverse asymmetry overlap region and there is no rotation effect. Also the shadowing is different from mid-central collisions of spherical nuclei. Therefore, it provides an ideal tool to understand how the azimuthal pressure, expansion and flow development from the almond-shape overlap, which are all related with the extraction of the EOS. Average \( v_2 \) is shown in Fig. 7 with soft and hard EOS. Hard EOS enhances \( v_2 \) for both spherical and deformed collisions. Deformed configuration gives rise to larger \( v_2 \) than sphere-sphere configuration for both soft and hard EOS.

In summary, deformed \( ^{24}\text{Mg} + ^{24}\text{Mg} \) collisions have been studied systematically by IDQMD model. The inversion of \( R \) vs. energies between tip-tip and body-body collisions reflects the two different configurations play different roles on reaction dynamics. The fragment observables also show different behaviors for the two configurations. The sphere-sphere collisions lie between tip-tip and body-body collisions in nuclear stopping and fragmentation. Moreover, the excitation functions of \( v_2 \) for different deformed central body-body collisions can be scaled on a similar curve by eccentricity. \( v_2 \) averaged by impact parameter (collision configuration is represented by Fig. 1) in deformed collisions is stronger than that of spherical collisions for both soft and hard EOS. The large \( v_2 \) developed from central body-body collisions have advantages in studying the EOS and transition energy. Tip-tip collisions can be used to study the liquid-gas phase transition in finite nuclear systems due to the longer collision time. In addition, deformed nuclei may have some implications on halo and cluster structure research. Therefore, the merits of collisions of deformed nuclei can shed light on the studies of both the nuclear structure and the reaction dynamics from low energies to relativistic energies.

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