Origin of the finite nuclear spin and its effect in intermediate energy heavy ion collisions

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Abstract The heavy-ion phase-space exploration (HIPSE) model is used to discuss the origin of the nuclear spin in intermediate energy heavy-ion collision (HIC). The spin of maximal projectile-like fragment is found to depend strongly on impact parameter of a reaction system, while it relates weakly to the collision violence. Some interesting multi-fragmentation phenomena related to the spin are shown. We also found that the excitation energy in the de-excitation stage plays a robust role at the de-excitation stage in HIC.

Key words Nuclear spin, Projectile multifragmentation, Projectile evaporation, Phase transition

1 Introduction

At different temperatures and densities, finite-size nuclear matter can undergo different state and show various properties. Experiments and theories have been developed in recent years[1-8] to explore properties of nuclear matter, especially those concerning phase transition phenomenon during intermediate energy heavy-ion collisions (HIC). Some couples of conjugate variables, i.e. the control parameter and corresponding order parameter, are used to describe dynamical and thermodynamical degrees of freedom in a finite nuclear system. Among them are temperature and entropy[9], pressure and density, symmetry energy and isospin[1]. By adjusting the control parameter, the order parameter distribution of the system can be achieved, which can be severed as an index to see whether the system has undergone phase transition or not.

Lopez proposed a measurable effect of phase transition due to the different spin of projectile fragments, instead of the excited energy, and found that the asymmetry between the largest and the second largest projectile charged fragment showed a bimodality behavior. They also found that at spin around 60−70 $\hbar$ the projectile-like source, or quasi-projectile (QP) source, would suffer evaporation of residue (ER) or multifragmentation (MF), no matter what the excitation energy of the system is. In this case, the spin plays the role of control parameter, which decides the decaying source suffers ER or MF. Ring P *et al.*[13] reported that, such phase transition was not an ordinary first order Liquid-Gas transition, but a specific second order one, which may connect to the so called Jacobi shape transition. Recently, Le Fèvre and Aichelin[15] proposed that the bimodality is also common phenomenon during the fast early HIC, based on QMD model.

In this article, we use the phenomenological heavy-ion phase space exploration (HIPSE) to study the origin of spin and its effect on the production of intermediate fragments (IMF). The role of excitation energy is also investigated as a comparison.

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2 Heavy-ion phase space exploration (HIPSE) model

HIPSE[12] is a dynamical model which followed by a statistical model, SIMON[14], to account for both dynamical and statistical aspects of the HIC. In this model, three steps are addressed to describe the whole nuclear reaction dynamical process and de-excitation process: the entrance channel (approach of the projectile and the target nuclei), building the partition (formation of fragments), and final state interaction and the reaggregation phase (with an in-flight statistical decay). At the beginning of HIC, the projectile and target are away from each other at large distance (larger than the size of projectile and target) and evolve themselves under the macroscopic proximity potential with respecting to classical two-body dynamics. At a small distance, the macroscopic proximity potential becomes sharper and a phenomenological parameter (the hardness parameter α_a) is then adopted to account for this effect. At the minimal distance, nucleons in each nucleus are sampled according to Thomas-Fermi distribution. The participant and spectator regions are then obtained using simple geometrical considerations. Nucleons outside the overlap region define the quasi-projectile and quasi-target spectators. Then two physical effects, namely direct nucleon-nucleon collision and nucleon exchange, are treated in a simple way. When the beam energy increases, the effect of direct nucleon-nucleon collisions becomes increasingly important, while the rate of nucleon exchange between target and projectile decreases. The two effects are modeled by assuming that a fraction, x_{coll}, of the nucleons in the overlap region undergoes in-medium collisions and a fraction, x_{ex}, for the nucleons in the overlap to exchange with the quasi-projectile and quasi-target spectators. They tend to smear the memory of entrance channel and relax the pure participant-spectator picture. After all the above steps, a coalescence procedure, which explores all the nucleons in phase space, is then performed to recognize the primary fragment in HIPSE. The possibility of fusion between fragments is tested to consider the final state interaction (The stage is referred as *before burn*). Finally, fragments propagate according to classical Hamiltonian as the entrance case. Also, the statistical procedure SIMON is attached to deexcite the hot primary fragments (This stage is referred as *after burn*).

3 Role of quasi-projectile spin and excitation energy

3.1 Spin of fragments in HIPSE model

The spin of fragment is performed by the sum over all angular momentum of nucleons inside the fragment. Fig.1 shows the average spins of maximal fragment at different impact parameters at various incident energies, for $^{129}Xe+^{120}Sn$ *before burn*. The average spins increases with the incident energy, and show similar impact parameter dependent trend. They increase rapidly from very central HIC to near central HIC, reach their maximum at the impact parameter range of 3–4 fm. In peripheral HIC, the average spins decreases with increasing impact parameter.

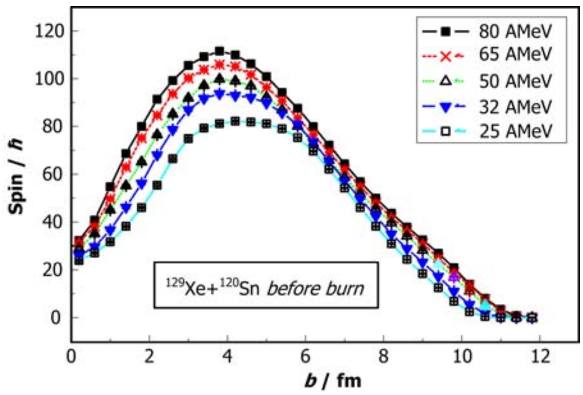

Fig.1 Average spin of the maximal fragment as a function of the impact parameter at various incident energies. The lines are for guiding the eyes.

This trend can be understood classically. The rigid body moment is proportional to both the force imposed upon it and the corresponding moment arm. In an HIC, the two components are corresponding to the incident energy and impact parameter, respectively. The HIC system can acquire higher total moment by increasing either the incident energy or the impact parameter. This moment decides the total angular momentum the system can reach. However, a nucleus is not a perfect rigid body (a nucleus looks like a drop of liquid). In a very peripheral HIC, even at high incident energy, the violence of HIC is not so strong due to small overlap between projectile and target.

Thus, the average spin decreases with increasing impact parameter at the peripheral HIC. Only in near central HIC, when the interaction between projectile and target is strong enough, can the initial angular momentum of the HIC system transfer into the spin of fragment with high efficiency. Then the average spins reach their maximum. In a very central collision, the average spins decrease due to the small moment arm between the projectile and target.

3.2 Maximal projectile-like fragment distribution before and after evaporation

In the present version of HIPSE[12], the statistical code SIMON[14] is used for its deexcitation process. SIMON takes the sequential decay mechanism to consider all possible exit channels from the nucleon evaporation, light charged particle (LCP) emission to two-body fission. Focusing on the maximal projectile-like, namely quasi-projectile source, one can study the effect of spin or excitation energy on the source at the deexcitation stage. The average spins as function of the maximal fragment before (up) and after (bottom) deexcitation stage are given in Fig.2, which shows a contrary trend of *before burn* and *after burn*. It can be seen that heavy fragments *before burn* tends to get higher spin, while those sources with higher spin before deexcitation may disintegrate themselves into smaller pieces[7]. It suggests that spin may be a parameter to control the disintegration process of a specific source. However, one should be care in telling the spin effect from the other factors, such as excitation energy. This will be discussed in Section 3.4.

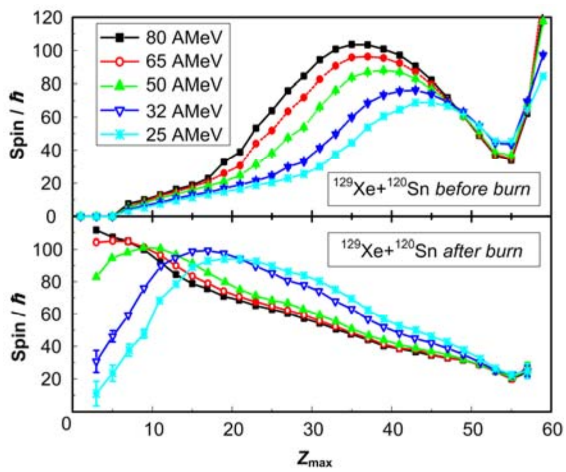

Fig.2 Average spin *vs.* maximal fragment at various incident energies *before burn* and *after burn*. The lines are for guiding the eyes.

3.3 The intermediate mass fragment (IMF) from projectile-like source after evaporation

The multiplicity of the intermediate mass fragment (IMF), is a key to see whether the HIC system suffers the process of phase transition or not[2,6,10]. Here, the fragments of Z=2–20 are defined as IMFs. Fig.3 shows the average IMF multiplicity as function of the spin of the projectile source at different incident energies. The IMF multiplicity increases with the spin at incident energies of below 50 AMeV. At higher than 50 AMeV, where the spin reaches 90 $\hbar$, the multiplicity tends to decrease, indicating that the projectile source suffers a transition from multifragmentation to fission in such a spin of source. From Fig.1, the source with an average spin of 90 $\hbar$ corresponds to the near central collision. This means at near central HIC, the spin of projectile-like source has strong effects on the IMF multiplicity.

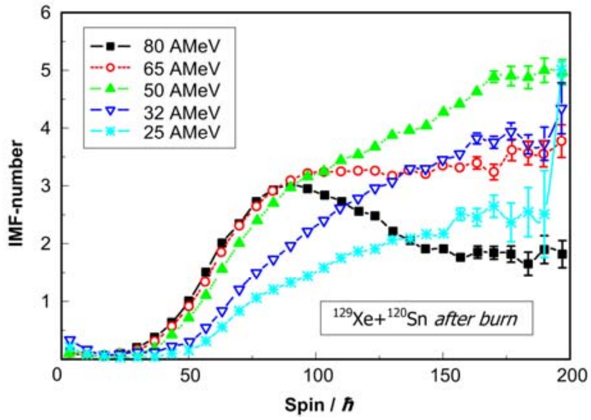

Fig.3 Average intermediate fragment number of projectile-like *vs.* the spin at various incident energies.

3.4 Excitation of fragments in HIPSE model

In HIPSE, the excitation energy of the HIC is realized with respect to the energy conversation law, so it is calculated after considering the total energy, potential energy, kinetic energy, rotation energy and mass *before burn*. Then all fragments get their corresponding fraction of excitation energy, which are proportional to their mass, and deexcite themselves in the following stage. Fig.4 shows the total multiplicity of projectile-like fragments as function of excitation energy of the HIC system at various incident energies. A new scaling law between the total multiplicity and the excitation energy of the HIC is revealed. The total multiplicity at different incident energies increases with the excitation energy. In other words, the total multiplicity of the HIC system is totally determined by the excitation energy. Thus, it is reasonable to take the excitation energy of the system as a control parameter to study the phase transition[2,6,10,11]. However, there dose not exist such scaling between the multiplicity and spin. This reflects the important role of the excitation energy at the deexcitation stage. As a consequence, only after the spin effect is told from those of excitation energy, the Jacobi phase transition can be determined then.

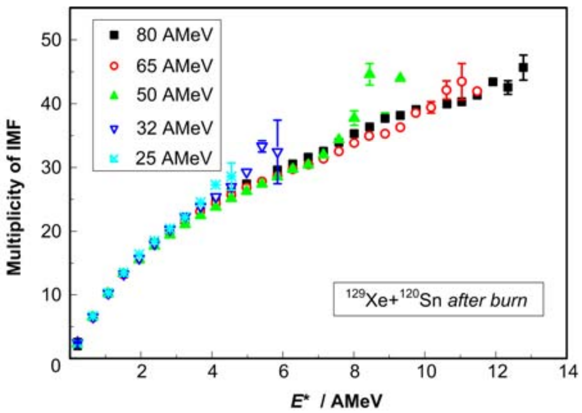

Fig. 4 The average multiplicity of IMF from QP as a function of the spin at various incident energies.

4 Conclusion

Nulcear spin plays an important role both in quantum statistical physics and in nuclear structure, while in HIC, because of the small fraction of energy it occupies, the importance of spin has always been neglected. The discovery of the bimodality induced by the spin opens a new way to study the HIC. In this article, we use HIPSE to study the spin origin and its effect on the deexcitation stage in intermediate HIC energy. The spin of projectile-like source mainly depends on the incident energy and the impact parameter of HIC. The assumption of taking the spin as a parameter to control the source to suffer fission or multifragmentation has been tested. However, the excitation energy plays more importance role than spin in the deexcitation stage. A scaling between the total multiplicity and excitation energy of the HIC is found at the deexcitation stage. This means it should be very careful to tell the effects of spin from those of excitation energy. It would be very interesting to get a further step to study the mechanism of spin in HIC, which will help to understand the whole dynamical process in detail.

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