Mach-like emission from nucleon scattering in proton-nucleus reactions

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Mach-like emission from nucleon scattering in proton-nucleus reaction

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The fast-stage nucleon emission of proton-nucleus (pA) reactions from 300A MeV to 1.8A GeV has been investigated by the quantum molecular dynamics model. It is found that the sideward angular spectrum of nucleon emission presents an interesting Mach-like structure at the early stage of the collision (tens of fm/c). The sideward angular peak value varies from about 45° to near 73°, depending on the bombarding energy. Nucleons emitted from the vicinity of the sideward peak tend to have a fixed momentum value about 0.5 GeV/c, independent of the bombarding energy as well as the impact parameter. Additionally, the sideward angular peak value is almost independent of equation of state, indicating that binary collision at the early fast stage in the intermediate energy pA reaction plays an important role for emergence of Mach-like emission.

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I. INTRODUCTION

Canonical emission is of very interesting phenomenon occurs in different fields in physics. Recently BNL Relativistic Heavy Ion Collider data have shown that a hot and dense quark-gluon plasma (QGP) medium is created in ultrarelativistic heavy-ion collision (HIC). The QGP behaves like an almost perfect fluid and to be opaque to jets created in the initial stage of the collision. The experimental dihadron correlation function [1–4] exhibits an interesting double-peak structure at angles opposite to the trigger jet. It has been suggested [5, 6] that such a structure could be an evidence for Mach cone. However, different theoretical interpretations have been provided, such as Cherenkov-like gluon radiation model [7], shock wave model in hydrodynamic equations [6], jet deflection [8] and strong parton cascade mechanism [9] etc. Since it is still unclear that the main mechanism for the emergence of the double peak structure, many experimental and theoretical works suggest that it should depend on the nature of the hot and dense matter created in the collisions. Very recently, Betz et al. suggested that the conical emission can also arise due to averaging over many jet events in a transversally expanding background in ultrarelativistic heavy-ion collisions. Furthermore, they found that the apparent width of the away-side shoulder correlation is insensitive to the details of the energy momentum deposition mechanism as well as to the system size [10]. Even though much effort on dihadron correlation has been done, the mechanism of such double peak structure is still in debating.

On the other hand, Mach-like structure has been noticed in heavy ion collision at several GeV energy in earlier time. Greiner and collaborators laid the ground work on shock wave induced by heavy-ion more than 30 years ago [11, 12]. Later on, some progresses have been made by various models. For an example, Aichelin et al. had used quantum molecular dynamics (QMD) model to study the asymmetry reaction system ^{20}Ne + ^{197}Au at 1050A MeV in central collisions [13]. A shock wave picture was depicted at the fast stage. While the projectile nucleons punch through the heavy target with a supersonic speed, a strong compression about $2\rho_0$ can be reached and a strong transverse force is put on the projectile surface. Thus, nucleons on the projectile surface will get a transverse velocity and emit in the sideward direction. The picture is very similar to Mach Cone phenomenon. Recently, Rau et al. [14] adopted the hydrodynamic model [15] and UrQMD [16] to simulate the Mach-like wave in the asymmetric system ^{20}Ne + ^{238}U at 1-20A GeV. They got clear Mach cone structure as the picture emerged in hydrodynamic dynamics. While, in the default UrQMD dynamics, they also got similar sideward peak excitation function, although UrQMD has a different mechanism forming the sideward peak and gets a broader width in the sideward angular distribution. Wang et al. studied the dynamical evolution of central collisions induced by GeV light-ion projectiles with two different Boltzmann-Uehling-Uhlenbeck calculations and found the shock wave-like behavior in early stage of reaction [17].

Considering that proton-nucleus reaction (pA) is relative simple in reaction mechanism in comparison with the heavy ion reactions, there is a potential advantage to give some hints to understand the mechanism of Mach-like phenomenon in HIC by investigating the fast-stage nucleon emission. In past several decades, the intermediate energy proton-induced reactions (pA) play important roles in the wide applications and fundamental research fields [18–20]. However, the mechanism of pA collision is still not well understood, especially on how to form the sideward peak angular distributions of intermediate mass fragments (IMF) and light charged particles (LCP) [21–25]. In early 1970s, Remsberg and Perry [21] showed

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that the angular distribution of IMF dominates 60° to 70° which is coincided with the angular distribution of Mach Shock conical emission predicted by hydrodynamics models. Hirata et al. [22] used a newly developed non-equilibrium percolation (NEP) model and concluded that a doughnut shape structure results in the IMF sideward peak angular distribution. Hsi et al. [23–25] performed exclusive experimental studies on pA reactions and claimed that the sideward peak of IMF originates in kinematic-focusing effects associated with statistical and thermal multifragmentation of an expanding residue. They argued that the sideward peak was not likely to be the result of shock wave, based on their experimental inclusive angular distribution without sideward peak for LCPs. Using angular correlation analysis, they also denied the sideward peak of IMF angular distribution could come from the breakup of exotic geometric shapes.

Although different physical hypotheses are employed, Quantum Molecular Dynamics model could demonstrate similar phenomenon that hydrodynamical model predicts. In this Letter, we adopt quantum molecular dynamics model to investigate pA reactions. The reaction system p + ^{208}Pb is taken as an example. Various energies and impact parameters, as well as hard or soft EOS, are scanned systematically. The focus is concentrated on nucleon emission at the fast stage of the collision, including the kinetic energy distribution and polar angular distribution.

II. QUANTUM MOLECULAR DYNAMICS MODEL

Quantum Molecular Dynamics model bases on an n-body theory, which simulates heavy ion reactions at intermediate energies on an event by event basis [26, 27]. The Isospin Dependent QMD (IDQMD) is an extension version of QMD, which is suitable to describe from Fermi energy up to $2A$ GeV with the isospin effects considered: different density distribution for neutron and proton, the asymmetry potential term in mean field, different experimental cross-section for neutron-proton (np) and proton-proton (pp,nn), Pauli blocking for neutron and proton separately [28, 29]. Each nucleon is presented in a Wigner distribution function with a width $\sqrt{L}$ (here $L = 2.16$ fm^2) centered around the mean position $\vec{r_i}(t)$ and the mean momentum $\vec{p_i}(t)$, $\phi_i(\vec{r},t) = \frac{1}{(2\pi L)^{3/4}} exp[-\frac{(\vec{r}-\vec{r_i}(t))^2}{4L}] exp[-\frac{i\vec{r}\cdot\vec{p_i}(t)}{\hbar}]$. The mean field in IDQMD model is: $U(\rho) = U^{\rm Sky} + U^{\rm Coul} + U^{\rm Yuk} + U^{\rm sym}$, where $U^{\rm Sky}$, $U^{\rm Coul}$, $U^{\rm Yuk}$, and $U^{\rm sym}$ represents the Skyrme potential, the Coulomb potential, the Yukawa potential and the symmetry potential interaction, respectively [27]. The Skyrme potential is: $U^{\rm Sky} = \alpha(\rho/\rho_0) + \beta(\rho/\rho_0)^\gamma$, where $\rho_0 = 0.16$ fm^{-3} and ρ is the nuclear density. The parameters $\alpha = -356$ MeV, $\beta = 303$ MeV, and $\gamma = 7/6$, correspond to a soft EOS, and $\alpha = -124$ MeV, $\beta = 70.5$ MeV, and $\gamma = 2$, correspond to a hard EOS. $U^{\rm Yuk}$ is a long-range interaction (surface) potential, and takes the following form: $U^{Yuk} = (V_y/2)\sum_{i\neq j} exp(Lm^2)/r_{ij} \cdot [exp(mr_{ij})erfc(\sqrt{L}m - r_{ij}/\sqrt{4L}) - exp(mr_{ij})erfc(\sqrt{L}m + r_{ij}/\sqrt{4L})]$ with $V_y = 0.0074$GeV, $m = 1.25 fm^{-1}$, $L = 2.16$ fm^2, and r_{ij} is the relative distance between two nucleons. The strength of symmetry potential is $C_{sym} = 32$ MeV.

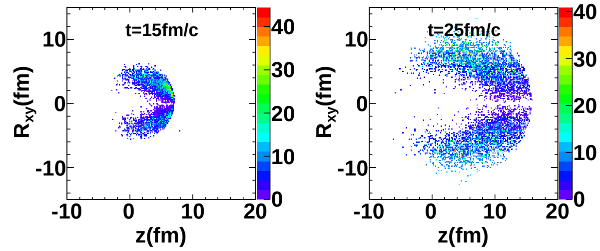

FIG. 1: (Color online) Position correlation 2D histogram R_{xy} versus z in a cylindrical coordinate system. The reaction system is $1A$ GeV p+ ^{208}Pb at $b = 1$ fm with the hard EOS. Left: Evolution time is 15 fm/c. Right: Evolution time is 25 fm/c. A linear scale plot is used.

IDQMD treats the many body state explicitly, and contains correlation effects to all orders and deals with fragmentation and fluctuation of HICs. To recognize fragments produced in HICs, a simple coalescence rule is used with the criteria Δr = 3.5 fm and Δp = 300 MeV/c between two considered nucleons. Thus, nucleons dominated in Fermi motion will be limited in the target.

III. RESULTS AND DISCUSSIONS

Conical emission structure at the early stage of pA reaction has been observed in our IDQMD calculation. As Fig.1 presents for p + Pb at $1A$ GeV, Mach-like structure develops at 15 fm/c, while the head of the conical structure disappears at 25 fm/c.

Fig.2 shows that the yield of nucleons and the average kinetic energy of nucleons evolve with time. The yield shows a stable increase for both protons and neutrons. However, at 15 fm/c, including the protons emitted from projectile, there are only 2.5 nucleons at each event on average. This means that at each event, there exists no Mach-like structure, because, at least, three nucleons are required to form such structure. In addition, the average kinetic energy of nucleons presents a dropping situation. This, therefore, gives a hint that fast nucleons emit at the early stage and slow nucleons emit at the latter stage. The trend that neutron yields faster than proton, is consistent with the phenomenon which Ma et al. has found [28].

To show the dynamics process in detail, we select several time points during the reaction evolution to see the kinetic energy (E_k) spectra (Fig. 3) and polar angular distribution (Fig. 4). For all nucleons, a roughly fixed E_k peak near 140 MeV can be found before 20 fm/c,

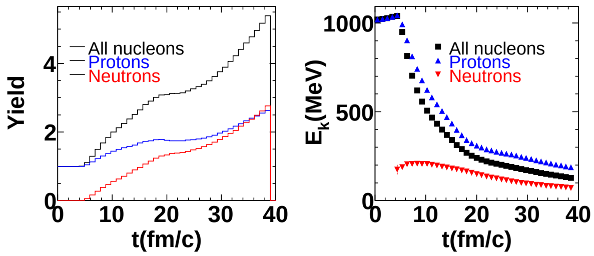

FIG. 2: (Color online)Left: The yield of nucleons at different time. Right: The average kinetic energy at different time for all nucleons (black square), protons (blue up triangle) and neutrons (red down triangle). The same reaction system and condition as Fig. 1.

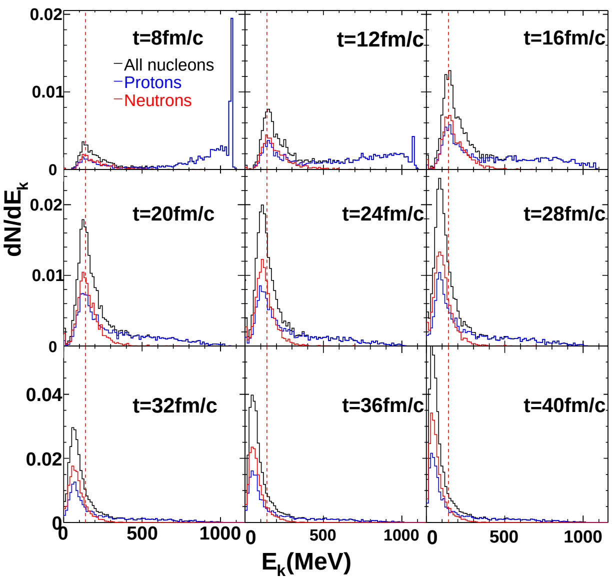

FIG. 3: (Color online): Evolution of the kinetic energy distribution of nucleons with time. A fixed peak can be found near $E_k = 140$ MeV before 20 fm/c, then the low energy part comes out and the former 140 MeV peak is submerged. The same reaction system and condition as Fig. 1.

then E_k smears to lower energy. For protons, there exists a high energy peak at the early stage, and later on it turns into a high energy tail which stems from those induced protons, distorted only a little by the mean field.

Hsi et al.[24] had measured the polar angular distribution for "gray proton"(100MeV $< Ep <$400MeV) and found no sideward peak. Basing on this consideration, they denied the possibility of shock-wave-like effects in pA reaction. However, it is not so easy to select suitable kinetic energy cut to separate the nucleons emitting at the early fast stage from the ones evaporating at the latter stage. In addition, the efficiency for detecting high energy nucleons should be carefully considered.

In pA reaction, the maximal density is just a little more than normal nuclear matter density ρ_0. Therefore it is hard to explain the transverse emission by the way the Ref. [13] does, which needs high compression gradi-

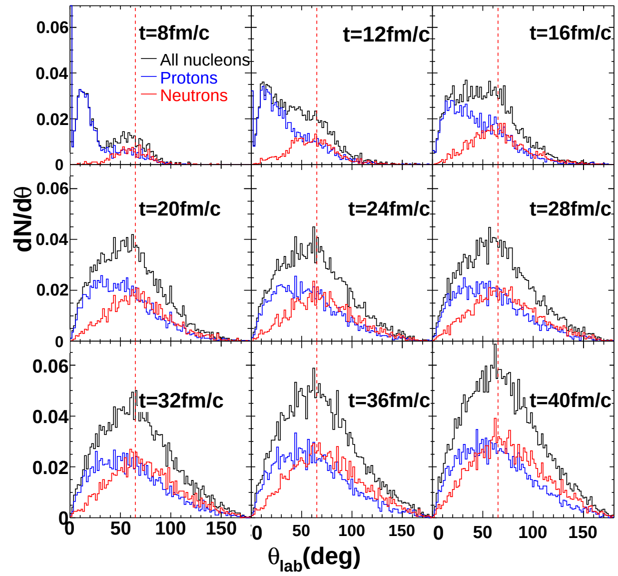

FIG. 4: (Color online): Evolution of the polar angle distribution of nucleons with time. A fixed sideward peak can be found near 65° in laboratory system. The same reaction system and condition as Fig. 1.

ent. In IDQMD, with the reaction process going on, the small value of angular peak, composed by mostly high energy induced protons, gets more and more feeble, while a fixed sideward peak shows up at about 65° for all nucleons, then a thermal part comes out with a peak at ∼90°, which will dominate at the latter isotropic stage (see Fig.4). The incident protons would also get the chance of collision with other nucleons in the target. The chance of collision is determined by experimental proton-proton and proton-neutron cross-section, including the elastic and the inelastic channels. After the binary collision, the projectile proton shares its kinetic energy and momentum with its collision partner, which results in the sideward angular distribution peak at the early stage of pA reaction.

The correlation between the momentum and polar angular of nucleons is also studied. Nucleons coming from the the vicinity of the angular peak tend to get a fixed momentum value 0.53GeV (140MeV) at the early stage (15fm/c). At the following stage (25fm/c), the sideward emission nucleons move their momentum peak to lower value and extend their angular distribution width at the same time (Figure 5). The situation is very similar to Mach shock structure that ideal hydrodynamical models have predicted.

Additionally, different impact parameters, energies and EOS are investigated systematically. Nucleons emitting within momentum range 0.3GeV/c $<$ P $<$ 0.6GeV/c are selected in the following study. After the head of projectile protons punches through the center of ^{208}Pb target, five angular peak values are sampled continuously, with a time step 1 fm/c. The average angular peak value is then calculated from these five peak values as the final

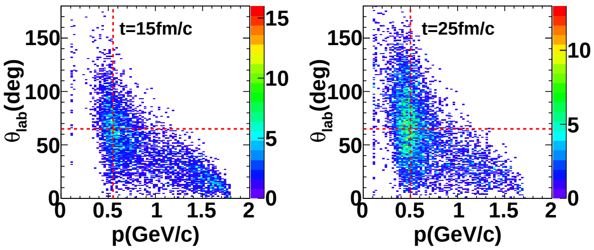

FIG. 5: (Color online): Correlation between the momentum and polar angular of nucleons at 15fm/c (left) and 25fm/c (right). Nucleons near 65° sideward peak have a fixed momentum value about 0.53 GeV/c (140MeV) in Laboratory system. The same reaction system and condition as Fig. 1.

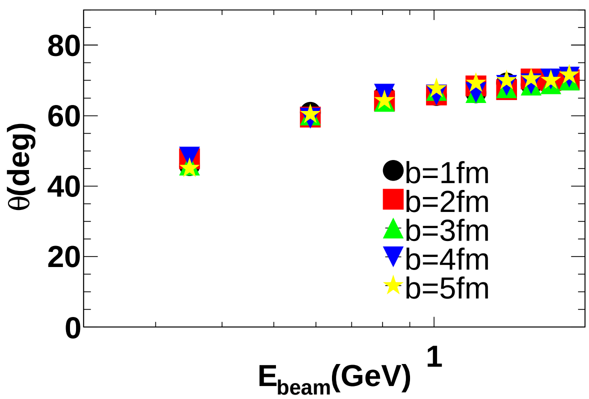

FIG. 6: (Color online): Excitation function of the sideward angular peak value of nucleons. The system is p + ^{208}Pb from energy 330A MeV to 1.81A GeV with impact parameter from b = 1 fm to b = 5 fm and hard EOS. The error bars are smaller than the marker-size.

result. Excitation function of the sideward angular peak value for p + ^{208}Pb is presented for the hard EOS (Fig. 6). The sideward angular peak values increase with the beam energy from about 45° at 330MeV up to and a limited 73° at 1.81GeV. Soft EOS gives the same values of angular peak values and bombarding energy dependence as the hard EOS case, and also shows insensitivity to impact parameter (not shown here due to the limited space). Overall, the results are independent of the impact parameter and EOS.

IV. SUMMARY

In summary, we apply quantum molecular dynamics model to revisit the early stage nucleon emission in pA reaction. It is found, for the first time, that the peak of sideward angular distribution for the early emitting nucleons is energy dependent. With the increasing of beam energy, the sideward angular peak value increases to a limit value 73°, while the momentum of the emitting protons tend to get a fixed value 0.53 GeV/c (140 MeV). However, the peak of sideward angular distributions are independent of impact parameters and EOS. This Mach-like phenomenon is similar to the result that hydrodynamical models have predicted, although different physical interpretation are employed. The binary nucleon collision plays the essential role, which results in the sideward angular emission. In event-level, there are only 2-3 nucleons emitting at the early stage (before 20 fm/c), so there exists no Mach-like structure in the event basis. In this case, we are unable to apply the angular correlation method to extract the Mach-like structure information event by event. In the present model, the Mach-like structure can be regarded as the scattering effect mostly by the bombarding proton with the target nucleons summing over each event, which is very different from bulk collective hydrodynamical behavior. This mechanism may also give some hints to the Mach-like cone structure in ultra-relativistic energy [5, 6, 8–10, 30]. As far as the experiment is concerned, the key is to separate the nucleons emitting at the early stage from those coming from the later stage and to improve the detecting efficiency of the forward and sideward emitting nucleons, especially for those “grey nucleons”[24].

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