Research Article

Radial Flow in a Multiphase Transport Model at FAIR Energies

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Received 13 October 2017; Revised 15 January 2018; Accepted 6 March 2018; Published 22 April 2018

Academic Editor: Raghunath Sahoo

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Azimuthal distributions of radial velocities of charged hadrons produced in nucleus-nucleus (AB) collisions are compared with the corresponding azimuthal distribution of charged hadron multiplicity in the framework of a multiphase transport (AMPT) model at two different collision energies. The mean radial velocity seems to be a good probe for studying radial expansion. While the anisotropic parts of the distributions indicate a kind of collective nature in the radial expansion of the intermediate “fireball,” their isotropic parts characterize a thermal motion. The present investigation is carried out keeping the upcoming Compressed Baryonic Matter (CBM) experiment to be held at the Facility for Antiproton and Ion Research (FAIR) in mind. As far as high-energy heavy-ion interactions are concerned, CBM will supplement the Relativistic Heavy-Ion Collider (RHIC) and Large Hadron Collider (LHC) experiments. In this context our simulation results at high baryochemical potential would be interesting, when scrutinized from the perspective of an almost baryon-free environment achieved at RHIC and LHC.

1. Introduction

When two heavy nuclei collide with each other at high-energy it is expected that a color deconfined state composed of strongly coupled quarks and gluons is formed. The properties of such a state, formally known as Quark-Gluon Plasma (QGP) [1], are governed by the rules of quantum chromodynamics (QCD). In order to understand the bulk properties of this extended QCD state and to understand the dynamical processes that might be involved in its formation and subsequent decay, over last three decades or so QGP has been widely searched in many high-energy experiments [2]. Of all the efforts in this regard, the study on the emission of final state particles with respect to the reaction plane of an AB collision, a plane spanned by the beam direction and the impact parameter vector, has been a popular technique that can characterize the thermodynamic and hydrodynamic properties of the QGP matter [3, 4]. In this technique the Fourier decomposition of the anisotropic azimuthal distribution has been widely employed to explore the collective behavior of the final state particles. More specifically, the second harmonic coefficient, traditionally known as the elliptic flow parameter (v_2), is of special

interest [5]. The v_2 results obtained from the RHIC and LHC experiments show considerable hydrodynamical behavior of the matter present in the overlapping zone of the colliding nuclei, an intermediate “fireball” that gets thermalized within a very short time interval (<1 fm/c) and subsequently expands almost like a “perfect fluid” having a very small ratio of shear viscosity to entropy density [6–8]. In RHIC [9–13] and LHC [14–17] experiments the v_2 parameter has been widely studied as a function of the centrality of the collision, transverse momentum (p_T), and rapidity (y) or pseudorapidity (η) of the produced particles, for different colliding systems and at varying collision energies. Using the AMPT model, presence of anisotropy in the azimuthal distribution of transverse rapidity (y_T) has been investigated in Au + Au collision at $\sqrt{s_{NN}} = 200$ GeV [18]. Recently, we have reported some simulation results on the anisotropy present in the azimuthal distribution of p_T of the emitted charged hadrons that has relevance to the radial flow of charged hadrons produced at FAIR energies [19]. The CBM experiment is dedicated to explore the deconfined QCD matter at high baryon density and low to moderate temperature. It is a fixed target experiment being designed with incident beam energy range $E_{lab} = 10$ –40 GeV per nucleon, which is expected to produce

partonic matter of density 6 to 12 times the normal nuclear matter density at the central rapidity region [20]. But at the same time it should be kept in mind that our present understanding of the collective flow of hadronic/partonic matter at this energy region is constrained by the availability of only a few experimental results [21]. Therefore, to get an idea about the expected behavior of any variable or parameter that is relevant in this regard, we have to rely mostly upon the event generators and models. In this article we present some basic simulated results on the (an)isotropy of the radial velocity of charged hadrons produced in Au + Au collisions at $E_{\text{lab}} = 10$ A and 40 A GeV using the AMPT model [22, 23]. The paper is organized as follows: a brief description of the methodology used in this analysis is given in Section 2, the AMPT model is summarily described in Section 3, our simulation based results are discussed in Section 4, and finally in Section 5 our observations are listed.

2. Methodology

Before the collision, the nucleons belonging to individual nucleus possess only longitudinal degrees of freedom. Transverse degrees of freedom are excited into them only after an interaction takes place. In mid-central collisions the overlapping area of the colliding nuclei is almond shaped in the transverse plane. This initial asymmetry in the geometrical shape gives rise to different pressure gradients along the long and the short axis of the overlapping zone and correspondingly to a momentum space asymmetry in the final state. As a result, if the matter present in the intermediate “fireball” exhibits a fluid-like behavior, then a collective flow of final state particles is observed, which is reflected in the azimuthal distribution of the particle number as well as in the azimuthal distribution of an appropriate kinematic variable like p_T , y_T and the transverse or radial velocity v_T [24]. The radial velocity has two components, the radial flow velocity and the velocity due to the random thermal motion of the particles constituting the intermediate fireball. For an ideal fluid the radial flow velocity should be isotropic. However, for a nonideal viscous fluid, the shear tension is proportional to the gradient of the radial velocity along the azimuthal direction, which again is related to the anisotropy of radial velocity [18]. An analysis of the v_2 results over the energy range $E_{\text{lab}} \cong 1\text{--}160$ GeV has shown that the observed v_2 values are lower than what is expected from a phenomenology based on the three-fluid dynamics [25]. The difference has been attributed to dissipative effects like viscosity. A single parameter (the Knudsen number) fit of the v_2 results over a wide range of collision energy suggests that the upper limit of the shear viscosity to specific entropy ratio $\eta/s \sim 1\text{--}2$, a value much higher than what is estimated for an almost ideal fluid created at RHIC or LHC energies. However, to understand the exact nature of the flow characteristics or the nature of the fluid created at FAIR energies, we shall have to wait till the CBM results in this regard become available.

We introduce the transverse (radial) velocity as

$$v_T = \frac{p_T}{E} = \frac{p_T}{m_T \cosh y}, \quad (1)$$

where $E = m_T \cosh y$ is the energy of the particle, $m_T = \sqrt{m_0^2 + p_T^2}$ is its transverse mass, m_0 is the particle rest mass, and y is its rapidity. For a large sample of events the total radial velocity $\langle V_T(\phi_m) \rangle$ of all particles falling within the m th azimuthal bin is defined as

$$\langle V_T(\phi_m) \rangle = \frac{1}{N_{\text{ev}}} \sum_{j=1}^{N_{\text{ev}}} \sum_{i=1}^{n_m} v_{T,i}(\phi_m), \quad (2)$$

where $v_{T,i}(\phi_m)$ is the radial velocity of the i th particle, n_m is the total number of particles present in the m th bin, N_{ev} is the number of events under consideration, and $\langle \rangle$ denotes an averaging over events. In this paper we have chosen the transverse velocity as the basic variable in terms of which the azimuthal asymmetry has been studied and compared the results obtained thereof with those of the azimuthal asymmetry associated with the charged particle multiplicity distribution. An azimuthal distribution of $\langle V_T(\phi_m) \rangle$ contains information of the asymmetry in the multiplicity distribution as well as that of the radial expansion. By taking an average over the particle number the mean transverse velocity $\langle \langle v_T(\phi_m) \rangle \rangle$ is introduced as

$$\langle \langle v_T(\phi_m) \rangle \rangle = \frac{1}{N_{\text{ev}}} \sum_{j=1}^{N_{\text{ev}}} \frac{1}{N_m} \sum_{i=1}^{n_m} v_{T,i}(\phi_m), \quad (3)$$

where $\langle \langle \rangle \rangle$ represents first an average over all particles present in the m th azimuthal bin and then over all events present in the sample. This double averaging reduces the multiplicity influences significantly, and the corresponding distribution measures only the radial expansion. In this context we must mention that the mean radial velocity actually consists of contributions coming from three different sources, the average isotropic radial velocity, the average anisotropic radial velocity, and the average velocity associated with thermal motion. It should be noted that both radial and thermal motion contribute to the isotropic velocity of the distribution. Like the azimuthal distribution of charged particle multiplicity $d\langle N_{\text{ch}} \rangle / d\phi$, it is also possible to expand the azimuthal distributions of the total and mean transverse velocities in Fourier series as

$$\begin{aligned} \frac{d\langle V_T \rangle}{d\phi} &\approx v_0 (\langle V_T \rangle) [1 + 2v_2 (\langle V_T \rangle) \cos(2\phi)], \\ \frac{d\langle \langle v_T \rangle \rangle}{d\phi} &\approx v_0 (\langle \langle v_T \rangle \rangle) [1 + 2v_2 (\langle \langle v_T \rangle \rangle) \cos(2\phi)]. \end{aligned} \quad (4)$$

In these expansions only the leading order terms ($n = 0$ and 2) are retained. The anisotropy present in any of the distributions [see (4)] is quantified by the second Fourier coefficient v_2 , whereas v_0 is a measurement of the isotropic flow.

3. AMPT Model

Transport models are best suited to study AB collisions at the energy range under our consideration. Since transport models treat chemical and thermal freeze-out dynamically,

they have the ability to describe the space-time evolution of the hot and dense “fireballs” created in collision between two heavy nuclei at relativistic energy. As mentioned before, in this simulation study we use the AMPT model with partonic degrees of freedom, the so-called string melting version, with the expectation that under the FAIR conditions transitions from the initial nuclear matter to the QGP state (if any) and then from the QGP state to the final hadronic state will take place at high baryon density and low to moderate temperature. Previous calculations have shown that flow parameters consistent with experiment can be developed through AMPT and the model can successfully describe different aspects of the collective behavior of hadronic/partonic matter produced in AB interactions [26–32]. The string melting version of AMPT should be even more appropriate to model particle emission data, where a transition from nuclear matter to deconfined QCD state is expected. AMPT is a hybrid model where the primary particle distribution and other initial conditions are taken from the heavy-ion jet interaction generator (HIJING) [33], and Zhang’s parton cascade (ZPC) formalism [34] is used in subsequent stages. Note that the ZPC model includes only parton-parton elastic scattering with an in-medium cross section derived from pQCD, the effective gluon screening mass being taken as an adjustable parameter. In the string melting version of the AMPT model, all hadrons are produced from string fragmentation like that in the HIJING model. The strings are converted into valence quarks and antiquarks. They are subsequently allowed to interact through the ZPC formalism and propagate according to a relativistic transport model [23]. Finally, the quarks and antiquarks are converted to hadrons via a quark coalescence formalism.

4. Results and Discussion

In this section we describe our results obtained from the Au + Au minimum bias events simulated by the AMPT model (string melting version) at $E_{\text{lab}} = 10$ A and 40 A GeV. A representative value of the parton scattering cross section ($\sigma = 3$ mb) is used in this analysis. The σ value is chosen so as to match with a previously studied collective behavior at FAIR energies [31]. We have indeed compared the NA49 results [21] on the p_T dependence of elliptic flow parameter v_2 by varying σ over a range of 0.1 to 6 mb. We have seen that even though the σ values differ almost by two orders of magnitude, the corresponding differences in the simulated v_2 values are not that significant [35]. The size of each sample of Au + Au events used in this analysis is one million. We begin with the multiplicity distribution of charged hadrons, represented schematically in Figure 1. The nature of the distributions is more or less similar at both energies considered. However, the average and the highest multiplicities are naturally quite larger at $E_{\text{lab}} = 40$ A GeV. In Figure 2 we plot the p_T distributions of charged hadrons. As expected, with increasing p_T we observe an approximately exponential fall in the particle number density. It is interesting to note that, at low p_T values, up to $p_T \approx 1.5$ GeV/c, the slopes of the distributions at both energies hardly differ, but at high p_T , beyond $p_T = 2.0$ GeV/c, the slope values are considerably

FIGURE 1: Charged hadron multiplicity distribution in Au + Au collisions at $E_{\text{lab}} = 10$ A and 40 A GeV.

FIGURE 2: Charged hadron p_T distribution in Au + Au collisions at $E_{\text{lab}} = 10$ A and 40 A GeV.

different, this being stiffer at $E_{\text{lab}} = 10$ A GeV. The inverse slope can be related to the temperature of the intermediate “fireball” as and when it achieves a thermal equilibrium. With varying collision energies, the particles produced in soft processes, therefore, correspond to almost same source temperature, irrespective of the collision energy. A Monte Carlo Glauber (MCG) model [36] is employed to characterize the geometry of an AB collision. Using the MCG model the average transverse momentum $\langle p_T \rangle$ of particles produced in AB collisions belonging to a particular centrality can be determined. In Figure 3 such a plot of $\langle p_T \rangle$ against the number of participating nucleons (N_{part}), a measure of the centrality of the collision, is graphically shown. At both the collision energies considered in this analysis, at low N_{part} the $\langle p_T \rangle$ values are significantly different, $\langle p_T \rangle$

FIGURE 3: Average transverse momentum of charged hadrons as a function of N_{part} in Au + Au collisions at $E_{\text{lab}} = 10$ A and 40 A GeV.

increases almost linearly with increasing centrality, and each distribution saturates at similar value, $\langle p_T \rangle \approx 0.365$ GeV/c. The fact that at the highest centrality the saturation value of $\langle p_T \rangle$ of produced particles is almost independent of the incident beam energy is perhaps due to kinematic reasons. The transverse degree of freedom that was absent before the collision took place is excited into the interacting AB system due to multiple nucleon-nucleon (NN) scattering and rescattering. Our results indicate that the degree of such excitations, which predominantly depends on the number of binary collisions N_{coll} , appears to remain almost same for the most central collisions of the Au + Au system in the FAIR energy region. In Figure 4 we present the azimuthal distributions of (a) the total radial velocity $\langle V_T \rangle$, (b) the multiplicity (N_{ch}), and (c) the mean radial velocity $\langle \langle v_T \rangle \rangle$ of charged hadrons produced at $E_{\text{lab}} = 40$ A GeV in the mid-rapidity region, within $\Delta y = \pm 1.0$ symmetric about the central value y_0 and within the 0–80% centrality range. Presence of anisotropy in all three distributions is clearly visible. It is also observed that while all three distributions exhibit same periodicity, their amplitudes are quite different. In order to show that all three distributions can analytically be described by a single function like $N[1 + \alpha \cos(2\phi)]$ without significant contributions coming from other harmonics, we fit the distributions with exactly the same relative vertical axis range with respect to the value of the parameter α centred around the same value of the other parameter N (here $N = 1.0$) and plot them together in Figure 4(d) along with the respective fitted lines. When appropriately scaled, we find that the elliptic anisotropy present in the distribution of total radial velocity is almost equal in magnitude to that coming from the anisotropy in multiplicity distribution. In comparison, corresponding anisotropy in the mean radial velocity is quite small. The results at $E_{\text{lab}} = 10$ A and 40 A GeV are qualitatively similar.

FIGURE 4: Azimuthal distribution of (a) total radial velocity, (b) multiplicity, (c) mean radial velocity, and (d) all the aforesaid quantities properly normalized for charged hadrons produced in Au + Au collisions at $E_{\text{lab}} = 40$ A GeV.

4.1. Centrality Dependence of v_2 and v_0 . Elliptic flow results from interactions between particles comprising the intermediate “fireball,” and hence it is a useful probe for the identification of local thermodynamic equilibrium. The v_2 values are smaller for the extreme central and peripheral collisions, which can be explained in terms of the initial geometric effects and the pressure gradient produced thereof [37]. In the hydrodynamical limit v_2 is proportional to the elliptic eccentricity (ϵ_2) of the overlapping region of the colliding nuclei, whereas in the low density limit v_2/ϵ_2 is proportional to the product of the rapidity density of charged particles $d\langle N_{\text{ch}} \rangle/dy$ and inverse of the overlapping area of the colliding nuclei. It is believed that the centrality dependence of elliptic flow provides valuable information regarding the degree of equilibration achieved by the intermediate “fireball” and also regarding the characteristics of (re)scattering effects present therein [38]. Some model based results at FAIR energies can be found in [19, 31, 35].

In Figure 5 we compare the centrality dependence of the v_2 parameter obtained from distributions of all three variables under consideration. The overall centrality dependence is

FIGURE 5: Centrality dependence of anisotropy parameter v_2 obtained from the azimuthal distributions of total radial velocity, multiplicity, and mean radial velocity in Au + Au collision at $E_{\text{lab}} = 10$ A and 40 A GeV.

found to be similar for $v_2(\langle V_T \rangle)$ and $v_2(\langle N_{\text{ch}} \rangle)$. However, $v_2(\langle \langle v_T \rangle \rangle)$, which in magnitude is quite small in comparison with the v_2 values obtained from the other two variables, behaves quite differently. All three variations are consistent with our observations of Figure 4(d). It is to be noted that the anisotropy in mean radial velocity, which describes the radial expansion, is significantly smaller than that of the corresponding multiplicity distribution in the mid-central region. In this regard we also intend to scrutinize the effects of the collision energy involved. It is observed that $v_2(\langle V_T \rangle)$ and $v_2(\langle N_{\text{ch}} \rangle)$ at $E_{\text{lab}} = 40$ A GeV are marginally higher than those obtained at $E_{\text{lab}} = 10$ A GeV, a general feature of any v_2 result, which has been confirmed over a wide energy range. The $v_2(\langle \langle v_T \rangle \rangle)$ values are not significantly different at the two collision energies involved either. We expect that the isotropy parameter (v_0) of all aforesaid distributions is also of certain importance and we graphically plot the results in Figure 6. The v_0 values associated with $\langle V_T \rangle$ and $\langle N_{\text{ch}} \rangle$ distributions show a linear dependence with increasing N_{part} , being highest in the most central events. This feature of v_0 can be ascribed to the fact that the azimuthally integrated magnitude of transverse flow increases with increasing centrality of the collisions. On the contrary, an increasing trend in the $v_0(\langle \langle v_T \rangle \rangle)$ values with increasing N_{part} is restricted only to the peripheral collisions, and beyond $N_{\text{part}} \approx 80$ the $v_0(\langle \langle v_T \rangle \rangle)$ values achieve a saturation, being nearly independent of the centrality of the collisions. A significant energy dependence of v_0 is also observed for all three variables considered in this analysis. We do not see any significant energy dependence in the variation of $v_0(\langle \langle V_T \rangle \rangle)$

with N_{part} . The $v_0(\langle N_{\text{ch}} \rangle)$ values are however consistently higher at $E_{\text{lab}} = 40$ A GeV than those at $E_{\text{lab}} = 10$ A GeV, the difference becoming larger with increasing N_{part} . Once again $v_0(\langle \langle v_T \rangle \rangle)$ behaves quite differently in this regard. The values at $E_{\text{lab}} = 10$ A GeV are consistently higher than those at $E_{\text{lab}} = 40$ A GeV. We may recall that the mean radial velocity has been defined in a way such that the multiplicity effects are removed. Therefore, we conclude that the particle multiplicity plays a dominant role to determine the total transverse flow, and a higher energy input results in a lower amount of azimuthally integrated transverse flow.

4.2. Transverse Momentum Dependence of v_2 and v_0 . It is well known that the anisotropy coefficient v_2 depends on p_T of charged hadrons. Hydrodynamics as well as resonance decay are expected to dominate at low p_T , whereas high p_T particles are expected to stem out from the fragmentation of jets modified in the hot and dense medium of the intermediate “fireball” [15]. At FAIR energies the production of high p_T hadrons would be rare, and owing to statistical reasons we restrict our analysis up to $p_T = 2.0$ GeV/c. v_2 arising from multiplicity distributions of the produced hadrons has been studied widely as a function of p_T using the data available from the experiments held at RHIC [39] and LHC [40]. Simulation results under FAIR-CBM conditions utilizing the UrQMD, AMPT (default), and AMPT (string melting) models can be found in [19, 31]. Figure 7 depicts that the anisotropies present in $\langle N_{\text{ch}} \rangle$, $\langle V_T \rangle$, and $\langle \langle v_T \rangle \rangle$ distributions rise monotonically with increasing p_T . At $E_{\text{lab}} = 40$ A GeV, beyond $p_T = 1.5$ GeV/c, there is a trend of saturation in

FIGURE 6: Centrality dependence of isotropic flow coefficient v_0 obtained from the azimuthal distributions of total radial velocity, multiplicity, and mean radial velocity in Au + Au collision at $E_{\text{lab}} = 10$ A and 40 A GeV.

FIGURE 7: Transverse momentum dependence of anisotropy parameter v_2 obtained from the azimuthal distributions of total radial velocity, multiplicity, and mean radial velocity in Au + Au collision at $E_{\text{lab}} = 10$ A and 40 A GeV.

the v_2 values extracted from all three variables. Once again we conclude that the multiplicity dominates over the radial velocity at a particular p_T bin, and $v_2(\langle N_{\text{ch}} \rangle)$ and $v_2(\langle V_T \rangle)$ are found to be almost equal in the $0 \leq p_T \leq 2.0$ GeV/c

range. Once we get rid of the multiplicity effects, the actual anisotropy present in the radial velocity comes out, which we can see in the plot of $v_2(\langle \langle v_T \rangle \rangle)$ against p_T shown in the same diagram. As a result, within $0.25 \leq p_T \leq 1.25$ GeV/c the

FIGURE 8: Transverse momentum dependence of isotropic coefficient v_0 obtained from the azimuthal distributions of total radial velocity, multiplicity, and mean radial velocity in Au + Au collision at $E_{lab} = 10$ A and 40 A GeV.

$v_2(\langle \langle v_T \rangle \rangle)$ values are slightly lower at higher E_{lab} . At FAIR energies, however, we do not find any noticeable deviation in the trend of this p_T dependence of v_2 from its nature observed at RHIC energies [24]. Comparing Figure 7(a) with Figure 7(b), we see a very weak (almost insignificant) energy dependence of v_2 in terms of all three variables concerned. We may reckon that FAIR-CBM energy range may not provide us with a proper platform to study the energy dependence of anisotropy, but it may be suitable for studying the issues related to the isotropy measure v_0 . The p_T dependence of v_0 has been shown in Figure 8. It is observed that the v_0 coefficients associated with $\langle N_{ch} \rangle$, $\langle V_T \rangle$, and $\langle \langle v_T \rangle \rangle$ while being plotted against p_T exhibit similar nature. In the low p_T region, the v_0 values extracted from each variable rise with increasing p_T , attain a maximum, and then fall off to a very small saturation value (almost zero) at both incident energies beyond $p_T = 1.25$ GeV/c. Once again, while $v_0(\langle V_T \rangle)$ values at $E_{lab} = 10$ A and 40 A GeV are almost identical, the $v_0(\langle N_{ch} \rangle)$ values at $E_{lab} = 40$ A GeV are higher in the low

p_T region ($p_T \lesssim 0.7$ GeV/c) than those at 10 A GeV. On the contrary, the $v_0(\langle \langle v_T \rangle \rangle)$ values obtained at $E_{lab} = 40$ A GeV are lower in the low p_T region ($p_T \lesssim 0.5$ GeV/c) than those at 10 A GeV. At FAIR energy the random thermal motion of particles perhaps dominates over their collective behavior, which at high p_T leads to a very small amount of azimuthally integrated magnitude of net flow.

5. Conclusion

In this paper we present some basic results on the elliptic and radial flow of charged hadrons. The study is based on the azimuthal distributions of total transverse velocity, mean transverse velocity, and multiplicity of charged hadrons produced in Au + Au collisions at $E_{lab} = 10$ A GeV and 40 A GeV. We have used the AMPT model (string melting version) to generate the events. We observe that azimuthal asymmetries are indeed present in all three distributions. However, we also note that in our simulation results the azimuthal anisotropy of the final state particles is predominantly due to the asymmetry of particle multiplicity distribution, and only a small fraction of this asymmetry is due to kinematic reasons. The overall nature of the dependence of the elliptic anisotropy parameter on the centrality of the collision and transverse momentum of produced particles are similar for the three variables considered in the present analysis. The elliptic flow parameter is highest in the mid-central collisions, and within the interval $0 \leq p_T \leq 2.0$ GeV/c it is highest at the highest p_T . From our simulated results in the FAIR energy range we find a very small energy dependence of the elliptic flow parameter. On the other hand, the azimuthally integrated magnitude of the radial flow is maximum for most central collisions and its values are high in the low p_T region. From this analysis we see that the contribution to v_0 from the asymmetry in multiplicity distribution and that coming from the asymmetry in kinematic variable v_T exhibit an opposite incident beam energy dependence. While the former is higher at higher E_{lab} , the latter is higher at lower E_{lab} . Our simulated results are consistent with those obtained from RHIC and LHC energies and do not require any new dynamics to interpret. However, in future there is enough scope to appropriately model these results in terms of relevant thermodynamic and hydrodynamic parameters associated with the intermediate “fireball” produced in AB collisions.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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