Effects of the magnetic field on the spallation reaction implemented by BUU coupled with a phase-space coalescence afterburner

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Abstract – Based on the Boltzmann-Uehling-Uhlenbeck (BUU) transport model coupled with a phase-space coalescence afterburner, the spallation reaction $p+^{197}\text{Au}$ at the incident beam energy $E_{\text{beam}} = 800\text{MeV/nucleon}$ is studied. We find that the number of test particles per nucleon has minor effects on the neutron-to-proton ratio ($n/p$) of the produced heavier fragments while it affects much their yields. The external strong magnetic field affects the production of heavier fragments more than the $n/p$ of produced fragments. The $n/p$ of free nucleons is greatly affected by the strong magnetic field, especially for the nucleons with lower energies.

There has been a renewed interest in the study of spallation reactions induced by either nucleons or light charged nuclei, not only from nuclear physicists but also from astrophysicists and nuclear engineers [1,2]. The spallation reaction is a kind of nuclear reaction in which a particle (e.g., a proton) interacts with a target nucleus. Giving a high energy to the incident proton, the nucleus is then in an excited state and can de-excite by evaporation and/or fission. And then the high number of secondary neutrons are produced. The fragmentation can be used as a source of neutrons, for example, the ADS (accelerator-driven system) [3], which is an external source to drive the sub-critical reactor. The optimum proton energy for the production of neutrons by spallation in a heavy metal target, in terms of costs, target heating, and system efficiency, lies in the range from 600 to 1000 MeV [4]. The spallation reaction is also related to the spallation neutron source (a new generation of pulsed neutron sources based on the proton accelerator, and that can provide high flux pulsed neutron beams for neutron scattering), which is used to probe the structure of the microscopic world [5].

Proton-induced reactions can be described by the semiclassical Boltzmann-Uehling-Uhlenbeck (BUU) transport model [6,7], which is quite successful in characterizing the dynamical evolution of nuclear collision. However, the description of fragment formation is not a trivial task. Because the BUU transport models are incapable of forming dynamically realistic nuclear fragments, certain types of afterburners, such as statistical and coalescence models, can be used as complements. The hybrid model can be usually used to study fragment formation, for instance, BUU + statistical multi-fragmentation model (SMM) [8], BUU + nuclear multi-fragmentation model [9–12]. However, these models all have their own shortcomings, such as the lack of description of the dynamical process of the fragment formation or the fact that they do not give the accurate excitation energies of fragments (which is very important for the de-excitation of a hot fragment [13]).

In this work, we study fragment formation in the proton-induced reaction $p+^{197}\text{Au}$ at the incident beam energy $E_{\text{beam}} = 800\text{MeV/nucleon}$ using the BUU transport model coupled with a phase-space coalescence afterburner [14]. We first deduce a reasonable number of test particles per nucleon by fitting the experimental data. Then we discuss the phenomenon of multi-fragmentation in the external magnetic field and show how the magnetic field affects the spallation reaction.

It is well known that the semiclassical BUU transport model [15] is quite successful in describing the evolution
of nuclear collision. The BUU equation describes time evolution of the single-particle phase-space distribution function $f(r,p,t)$, and the equation is

$$\frac{\partial f}{\partial t} + v \cdot \nabla_r f - \nabla_p U \cdot \nabla_p f = I_{\text{collision}}, \tag{1}$$

where $f(r,p,t)$ can be viewed semi-classically as the probability of finding a single particle at time $t$ with the momentum $p$ at the position $r$. The right-hand side includes the Pauli blocking. Because one has to initialize the nucleon positions to start the cascade model, the nucleon positions imply a certain density. Then we can define the mean-field potential $U$ as a function of density. In our work, where we use the Skyrme parametrization \cite{R15}, it reads

$$U(\rho) = A \left( \frac{\rho}{\rho_0} \right) + B \left( \frac{\rho}{\rho_0} \right)^{\sigma}, \tag{2}$$

where $\sigma = 7/6$, $A = -0.356$ GeV is attractive and $B = 0.303$ GeV is repulsive. With these choices, the ground-state compressibility coefficient of nuclear matter $K = 201$ MeV. $\rho = \rho_n + \rho_p$ is the baryon density and $\rho_n, \rho_p$ are the neutron and proton densities, respectively.

The variations of the nucleonic momentum are generally due to momentum and spatial location dependence of its mean-field potential $U$, decided by the gradient force $\nabla r U$ in eq. (1). Besides the gradient and Coulomb forces added on the charged particles, the Lorentz force can also change the momentum of the charged particle. For the external magnetic-field force of the charged nucleon felt, we employ the Lorentz force equation \cite{R16}. According to Hamilton’s equations, the propagations of the nucleon are

$$\frac{dp_i}{dt} = -\nabla U(r_i) + F_{\text{Coulomb}} + F_{\text{Lorentz}},$$

$$\frac{dr_i}{dt} = p_i \sqrt{m^2 + p_i^2}. \tag{3}$$

The test particle method was first applied to the nuclear Vlasov equation by Wong \cite{R17}. In the practical BUU calculations, to analyze fragment formation in proton-induced spallation reactions, we have used different numbers of test particles per nucleon. From them we choose 5 and 10 test particles per nucleon as reasonable values by comparing with experimental data. And in the next calculations to analyze fragmentation in the reactions with strong magnetic field, we use 8 test particles per nucleon as the reasonable value. The number of test particles per nucleon cannot be too small as statistical fluctuations, which are inherent in any Monte Carlo calculation, become apparent. Also the number cannot be too large since we need to sample the phase-space distribution of nucleons \cite{R15}. Usually we use 200–500 test particles per nucleon to do BUU simulations, such as nucleonic emission or meson production. Different numbers of test particles per nucleon really less affect BUU results. However, in the studies here, the number of test particles per nucleon affects much the heavier fragment production. This is because a small number of test particles per nucleon get more statistical fluctuations back when implemented by the BUU transport model. While a large number of test particles per nucleon smooth out statistical fluctuations (which cause fragment production). In fact, the number of produced heavier fragments is often very small compared with free nucleons.

Because most BUU-type transport models are not able to form dynamically realistic fragments, some types of afterburners, such as statistical and coalescence models, are naturally used as a supplement to describe nuclear multi-fragmentation. Such kind of hybrid models can be used well to study fragment formation, for example, in the studies of collective flows of light fragments \cite{R14, R18–20} and fragment formation in proton-induced reactions \cite{R8}. There are also some interesting works available on exerting advanced coalescence models \cite{R21–24}. But these methods have difficulties in predicting heavier fragments. For the purpose of our investigation, we take the simplest phase-space coalescence model \cite{R14, R19, R20}, i.e., a physical fragment is formed mainly when nucleons’ relative momenta are smaller than $P_0$ and relative distances are smaller than $R_0$. The results presented in the following discussions are obtained with $P_0 = 263$ MeV/$c$ and $R_0 = 3$ fm. We have changed the two parameters properly and find that they do not affect our studies here evidently.

For the spallation reactions, the mass distribution of fragments is important for practical applications. Figure 1 shows the mass distribution of fragments in the $p + {197}Au$ reaction at the incident beam energy of 800 MeV/nucleon. The numbers of test particles per nucleon used in the calculations are 5 and 10, respectively. It is clearly shown from fig. 1 that both results are roughly in agreement with the shape of the experimental data, especially in the zone of large-mass-number fragments ($A \geq 130$). In the
mediated range (40 < A < 130), our results are not well in agreement with the experimental data. The results with 5 test particles per nucleon overestimate the production of fragments while the results with 10 test particles per nucleon underestimate the production of fragments. From the physical point of view, a small number of test particles per nucleon get more statistical fluctuations back when implemented by the BUU transport model [15]. Thus, more fragments are produced.

As discussed above, different numbers of test particles per nucleon really less affect the BUU results. In the studies here, however, the number of test particles per nucleon affects much the fragment production (especially for 20 < A < 150). A small number of test particles per nucleon get more statistical fluctuations back when implemented by the BUU transport model [15] while a large number of test particles per nucleon smooth out statistical fluctuations. In fact, the number of produced fragments of 20 < A < 150 is very small compared with free nucleons. The present studies are the first attempts to describe the produced heavier fragments. Further improvements of our method are in progress. Because the experimental data are almost in the range of our simulations, in the next studies we take 8 test particles per nucleon as our model parameter.

Figure 2 shows the neutron-to-proton ratio of nuclear fragments with, respectively, 5 and 10 test particles per nucleon. We can see that the number of test particles per nucleon has a minor effect on the neutron-to-proton ratio of nuclear fragments. The effects of the number of test particles per nucleon (with 5 and 10 test particles per nucleon, respectively) on the neutron-to-proton ratio of nuclear fragments are not more than 5%.

The condition of strong magnetic field may exist in the Universe, such as white dwarfs, neutron stars, and accretion disks around black holes, and the maximum value of magnetic fields in the Universe may reach $10^{20} - 10^{42}$ G [25]. And with the rapid development of laser technology [26,27], obtaining a strong magnetic field greater than $10^{10}$ tesla artificially in a terrestrial laboratory is possible. Also a strong magnetic field greater than $5 \times 10^{14}$ tesla can be provided via energetic heavy-ion collisions technically [28–31]. In the following, we set the strength of the external magnetic field added to be $10^{15}$ tesla with the direction perpendicular to the reaction plane.

To see the effects of the external strong magnetic field on multi-fragmentation, we plot fig. 3, the mass distribution of the fragments in the $p + ^{197}$Au reaction at the incident energy $E_{\text{beam}} = 800$ MeV/nucleon with and without magnetic field. We use 8 test particles per nucleon in our simulations. From fig. 3, we can see that the magnetic field decreases most of the formations of fragment. Fragments are formed through statistical fluctuation in a nuclear collision, the external magnetic field prevents protons to form a cluster with other nucleons due to the Lorentz force added. However, as shown in fig. 4,
we can see that the effects of the external magnetic field on the n/p of the produced fragments are not very evident.

The energy spectrum of a free neutron is important for ADS and spallation neutron source. We thus studied the effects of the magnetic field on the free-neutron production. Figure 5 shows the energy spectrum of the free neutron in the nuclear spallation reaction $p + ^{197}\text{Au}$ at the incident energy $E_{\text{beam}} = 800\text{MeV/nucleon}$ with and without magnetic field. From fig. 5 we can see that cross-section of the free (especially energetic) neutrons produced in the spallation reaction with magnetic field is smaller than that without magnetic field. From fig. 6, we can see that the neutron-to-proton ratio of free nucleons with magnetic field is evidently larger than that without magnetic field. Free nucleons of the spallation reaction $p + ^{197}\text{Au}$ at $E_{\text{beam}} = 800\text{MeV/nucleon}$ are mainly from the initial de-excitation of hot matter (executed by BUU through nuclear evolution). Because the magnetic field holds protons to shoot out, the initial de-excitation of hot matter is partly prevented. We thus see a small number of free neutrons and protons in the spallation reaction $p + ^{197}\text{Au}$ and large n/p of emitted free nucleons with external magnetic field.

Our present coalescence method does not include fragment de-excitation processes, the fragments are all pre-fragments (their binding energies may not equal their ground-state energies). These pre-fragments may have de-excitation although we construct these fragments at the “final stage” of the nuclear reaction. As shown in ref. [32], fragment de-excitations really affect the n/p of nuclear fragments. The effects of fragment de-excitations on n/p ratios are evidently larger than the effects of the magnetic field on fragments’ n/p ratios (shown in fig. 4). However, we can see that the effects of the magnetic field on free nucleons’ n/p (shown in fig. 6) are much larger than the effects of fragment de-excitations on n/p ratios. Since our studies here concern just the effects of the magnetic field on the fragment production and the effects of the external magnetic field on fragment de-excitation processes are also less known, we thus neglect fragment de-excitation processes. As discussed above, the de-excitation processes of nuclear fragments do not affect our physical results here.

As shown in ref. [30], in heavy-ion collisions there is practically no electromagnetic-field effect on observables. This is due to the mutual dynamical compensation of transverse components as clearly demonstrated in ref. [31]. Such compensation should be absent in a pure magnetic field and negligible in proton-nucleus collisions. Thus, the n/p ratio is expected to be unchanged in heavy-ion collisions but its change for proton-induced collisions in the external magnetic field should emerge.

In conclusion, based on the transport model BUU coupled with a phase-space coalescence afterburner, the p + Au spallation reaction at the incident energy $E_{\text{beam}} = 800\text{MeV/nucleon}$ is studied. The external strong magnetic field added may affect the formation of fragments and the n/p of emitted free nucleons. The effects of the Lorentz force on the n/p of heavier fragments are less evident. These studies may be useful for nuclear physics, astrophysics and nuclear engineering.

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