Dynamic Isovector Reorientation of Deuteron as a Probe to Nuclear Symmetry Energy

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We present the calculations on a novel reorientation effect of deuteron attributed to isovector interaction in the nuclear field of heavy target nuclei. The correlation angle determined by the relative momentum vector of the proton and the neutron originating from the breakup deuteron, which is experimentally detectable, exhibits significant dependence on the isovector nuclear potential but is robust against the variation of the isoscaler sector. In terms of sensitivity and cleanness, the breakup reactions induced by the polarized deuteron beam at about 100 MeV/u provide a more stringent constraint to the symmetry energy at subsaturation densities.

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Previously, the study of nuclear symmetry energy has drawn intense attention in both nuclear physics and astrophysics because it is an essential input in modeling the neutron stars as well as in understanding the structural properties and the reaction dynamics involving exotic nuclei. Quantitative elucidation of the density dependence of symmetry energy $E_{\mathrm{sym}}(\rho)$ still remains one of the major tasks in nuclear physics although some progress has been made in constraining the $E_{\mathrm{sym}}(\rho)$ at subsaturation densities using both terrestrial nuclear laboratory data and astrophysical observations [1–12]. For further information regarding the symmetry energy issue, see the topical collection [13].

So far, the extraction of the $E_{\mathrm{sym}}(\rho)$ from heavy ion collisions relies unavoidably on the transport model simulations in most cases. Looking into the existing probes in the violent heavy ion collisions, the symmetry energy takes effect via the isospin transport including isospin diffusions and isospin drift characterized by the isospin migration due to the isospin difference and the density gradient, respectively [5]. In reality, these two mechanisms can not be separated and the isospin dependence of in-medium nucleon-nucleon collisions comes into play; complexity then arises in the description of the whole transport process. Model dependent treatment of the collisions as well as the nuclear potential may yield considerable discrepancies in the model outputs even with identical initial conditions. So far, some of the analyses do not contain theoretic uncertainty evaluations. From the experimental point of view, the uncertainty of constraints to the $E_{\mathrm{sym}}(\rho)$, particularly far from saturation density, is still large. Further searches for clean and effective probes of $E_{\mathrm{sym}}(\rho)$ are ongoing [14–17].

On the other hand, some types of the direct reaction, like the elastic or inelastic scattering as well as the direct projectile breakup, involve fewer degrees of freedom in the reaction process and may reduce the difficulties in modeling the collision. As shown in our previous work, due to the isovector potential, there is a significant difference in the scattering angle between proton- and neutron-induced scattering off a heavy target at a large impact parameter [18]. Since it is hard to get a monochromatic neutron beam at around 100 MeV, the experimental test remains a difficult task. Thanks to the availability of a polarized deuteron beam at hundreds of MeV/u at various running accelerators around the world [19–23], the deuteron, with one proton and one neutron bound loosely at large average separation distances, provides an alternative opportunity to probe the isovector interaction. Superimposing to the isoscalar and Coulomb interaction, the isovector force, being attractive to the proton and repulsive to the neutron, leads to a reorientation effect to the deuteron passing the heavy target field, which is detectable in a properly selected range of the impact parameter.

The first evidence of the orientation of a deuteron nucleus in the field of a heavy target was reported by Oppenheimer and Phillips [24] in deuteron induced transmutations [25]. Because of the Coulomb repulsion on the proton, the deuteron is readily polarized in the field, leaving the neutron closer to the heavy nucleus and enhancing the transmutation cross sections. At a higher beam energy, the breakup of the deuteron occurs coupling to the elastic scattering, which has been consistently described by various theoretic calculations including the folding model [26,27], adiabatic approximation [28], and the continuum discretization coupled channel (CDCC) model [29].

Interestingly, as a sort of final state interaction, the Coulomb post acceleration in the breakup of the deuteron (^{11}Li) characterized by the enhanced longitudinal velocity of the proton (^{9}Li core), has been observed and well interpreted using the CDCC calculations [30,31]. In the analog to the polarization of the deuteron, the exotic nucleus ^{17}F, consisting of a ^{16}O core and a loosely bound proton exhibits a polarization effect when scattering off a heavy target, as recently reported in [32]. Because the proton and the neutron experience different interactions with the target, tensor polarization appears after the unpolarized deuteron beam passes through a $S = 0$ target, known as nuclear spin dichroism [33–35].

In this Letter, using an improved quantum molecular dynamics (ImQMD) model, we present the calculation results on a new reorientation effect of the deuteron due to isovector interaction in the nuclear field of a heavy target. Through the correlation angle determined by the relative momentum of the proton and the neutron originating from the breakup of the deuteron, the reorientation effect and its sensitive dependence on $E_{\rm sym}(\rho)$ below the saturation density is demonstrated.

The ImQMD model is an extended version of the quantum molecular dynamics (QMD) model suited for the simulations of the heavy ion collisions at intermediate beam energies [18,36–38]. The QMD model has also been applied in the nucleon-induced reactions and provides consistent description to the data if available [39–43]. In the ImQMD model, the nuclear potential energy density functional including the full Skyrme potential energy density with the spin-orbit term omitted is written as

$$V_{\rm loc} = \frac{\alpha\rho^2}{2\rho_0} + \frac{\beta}{\eta+1}\frac{\rho^{\eta+1}}{\rho_0^{\eta}} + \frac{g_{\rm sur}}{2\rho_0}(\nabla\rho)^2 + \frac{g_{\rm sur,iso}}{\rho_0}[\nabla(\rho_n-\rho_p)]^2 + (A\rho^2 + B\rho^{\eta+1} + C\rho^{8/3})\delta^2 + g_{\rho\tau}\frac{\rho^{8/3}}{\rho_0^{5/3}}, \quad (1)$$

where all coefficients are directly related to the standard Skyrme interaction parameters [18]. To mimic the strong variation of the density dependence of the symmetry potential energy, the (volume) symmetry potential energy term, i.e., the fifth term in Eq. (1), is replaced by $(C_{s,p}/2)(\rho/\rho_0)^{\gamma}\rho\delta^2$, then, the symmetry energy is written as

$$E_{\rm sym}(\rho) = \frac{C_{s,k}}{2}\left(\frac{\rho}{\rho_0}\right)^{2/3} + \frac{C_{s,p}}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma}, \quad (2)$$

where $C_{s,k}$ and $C_{s,p}$ are the kinetic and potential energy parameter, respectively. Unless otherwise indicated, the Skyrme parameter set MSL0 [44], one of Skyrme parameter sets which best satisfies the current understanding of the physics of nuclear matter over a wide range of applications [45], is used in the following calculations. By using various γ one can get various $E_{\rm sym}(\rho)$ and MSL0-like Skyrme interactions. We note that in the current ImQMD framework, the tensor force and the three-nucleon nuclear force, which appear significantly in three body scattering [46,47], are not incorporated even though they may affect $E_{\rm sym}(\rho)$ at high densities [48].

While the initialization of the heavy target nuclei is done as usual as that in [37], the deuteron is initialized semi-classically in a simplified scheme. Similarly, the nucleon in the deuteron is described as a wave package (WP). The line connecting the center of the WP from the neutron to the proton is taken as the long symmetric axis (LSA). The distance between them is set to $3 \pm \Delta r$ fm, where Δr is a random value smaller than 0.25 fm. The direction of the momentum is set to be opposed for n and p on the LSA and the component perpendicular to the LSA is set to zero. The initial magnitude of the momentum is sampled randomly to keep the deuteron stably bound until 100 fm$/c$, namely, the root mean square radius of the deuteron stays in the range 2.1 ± 0.5 fm, where 2.1 fm is the experimental value [49]. By rotating the LSA randomly or onto a certain axis, one can mimic the unpolarized or preoriented deuteron beam as the initial state, respectively. The initial distance between the projectile and the target is 25 fm. For this simplification, we limit our calculations at an adequately high beam energy of 100 MeV/u to avoid the influence of the internal structure of the deuteron.

When a deuteron passes by peripherally the heavy target nuclei, as shown by the cartoon in Fig. 1(a), the two nucleons in the deuteron, experience nuclear force and Coulomb force F_c, the latter of which is repulsive only for

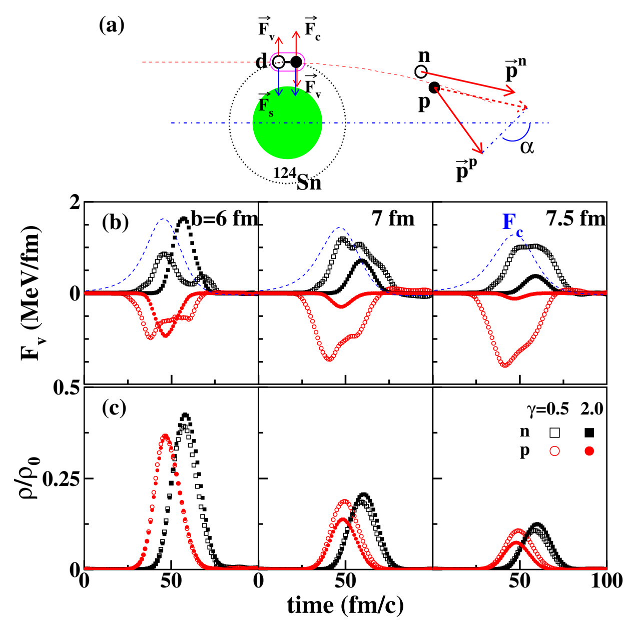

FIG. 1 (color online). (a) The schematic view of a deuteron induced peripheral collision on a heavy target ^{124}Sn. The lower panels show the isovector forces (b) and the local density (c) experienced by n (squares) and p (circles) as a function of time at various impact parameters. The Coulomb force on p is plotted (dashed lines) in panels (b).

the proton and may cause a partial polarization effect characterized by the moving of the proton away from the target or a post acceleration effect after breakup [30]. While the isoscalar nuclear force F_s is attractive to both nucleons and does not lead to an extra polarization effect, the isovector force F_v, being attractive to the proton and repulsive to the neutron, modifies the orientation status of the projectile in addition to the Coulomb polarization. The panels of Fig. 1(b) present the time evolution of F_v acting on the neutron (squares) and the proton (circles) originated from the breakup of the deuteron in 100 MeV/u $d + {}^{124}Sn$ at impact parameter $b = 6$, 7, and 7.5 fm, respectively. For comparison, the Coulomb force F_c (dashed curve) on the proton is also plotted. It is shown that the sign of F_v opposes for proton and neutron, and its magnitude varies with γ. For the deuteron with a certain orientation traversing the target field, the competition between F_v and F_c finally forms a torque which rotates the deuteron and manifests itself as a reorientation effect. Since the difference of F_v between n and p is at the same magnitude of the F_c as shown in the panels of Fig. 1(b), the reorientation effect due to isovector interaction shall be experimentally detectable and, in turn, be very sensitive to the isovector force F_v relevant to $E_{\rm sym}(\rho)$ at $\rho < \rho_0$. Figure 1(c) shows the local density along the trajectories of n and p at corresponding impact parameters. It is clear that the local density preferentially covers the range of $0 \le \rho/\rho_0 \le 0.5$ in the peripheral collisions.

The reorientation effect is detectable if the breakup of the deuteron follows. As marked in Fig. 1(a), we define the correlation angle α as the angle of the relative momentum from n to p with respect to the beam direction by

$$\cos\alpha = \frac{p_z^p - p_z^n}{|\vec{p}^p - \vec{p}^n|}, \quad (3)$$

where the subscript z denotes the beam direction. Figure 2(a) presents the ImQMD calculations of the distribution of α for 100 MeV/u $\vec{d} + {}^{124}Sn$ at $b = 7$ fm. Again, results with $\gamma = 0.5$ and 2.0 are presented. The curves denote the results for the unpolarized deuteron induced reaction. Despite the visible difference between $\gamma = 0.5$ (dashed line) and 2.0 (solid line), the distribution is approximately symmetric with respect to $\alpha = 90°$. The effect of $E_{\rm sym}(\rho)$ is largely smeared by the random initial orientation of the incident deuteron. However, if the deuteron is preorientated parallel to the beam axis (denoted by circle), for instance, the neutron-to-proton vector $\vec{r}^{np}$ is fixed to the beam direction, the distribution of α discriminates, clearly, the two parametrizations of $E_{\rm sym}(\rho)$. With $\gamma = 2$, F_v is much smaller than F_c, the Coulomb force dominates the orientation effect. As a result, the α distributions peak at a forward angle, qualitatively consistent with the Coulomb post acceleration [30]. While, with a soft $E_{\rm sym}(\rho)$ ($\gamma = 0.5$), F_v is large and forms a large isovector

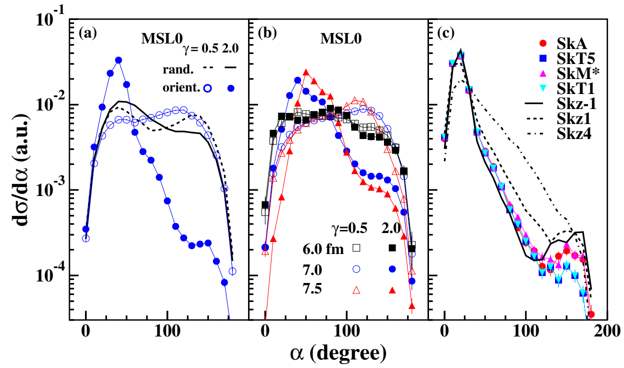

FIG. 2 (color online). The distribution of the correlation angle α in 100 MeV/u $\vec{d} + {}^{124}Sn$. (a) Calculations using MSL0-like Skyrme interactions with $\gamma = 0.5$ and 2.0 for the randomly oriented (curves) and pre-oriented (symbols) deuteron beams. (b) Calculations using MSL0-like Skyrme interactions at impact parameters $b = 6.0$, 7.0 and 7.5 fm. (c) Calculations using 7 real Skyrme interactions. See text for detailed discussion.

torque which counteracts the Coulomb effect, thus, the α distribution tends to be symmetric with respect to $\alpha = 90°$ or even exhibits enhancement at $\alpha > 90°$. The significant difference between the two γ parameters indicates that α is, indeed, a highly sensitive probe to $E_{\rm sym}(\rho)$, and the initial orientation of the incident deuteron is essentially requested for this purpose.

To be more realistic, the simulations shall be applied to actual beam conditions. The deuteron is a spin-1 nucleus. The spatial distribution of the deuteron wave function depends on the total spin projection m_z on the quantization axis, which is chosen as the direction of the particle wave vector $\vec{k}$. With $m_z = \pm 1$, the squared module for the deuteron ground state wave functions possesses a "dummy bell" shape with the relative vector from the neutron to the proton $\vec{r}^{np}$ being parallel with the LSA. It is experimentally achievable to have a nearly full tensor and vector polarization deuteron beam, for which the longitudinal symmetric axis is on the beam direction, but the wave function is symmetric under the exchange of n and p. To predict the reorientation effect of the isovector nuclear potential in an actual experiment, the simulations is done by mimicking a fully tensor and vector polarized deuteron beam with 50% possibility for $\vec{r}^{np} \| \vec{k}$ and 50% possibility for $-\vec{r}^{np} \| \vec{k}$. The results for $b = 7$ fm (circles) are shown in Fig. 2(b). It is shown, now, that the distribution is much less stiff compared with Fig. 2(a). But the discrimination between $\gamma = 0.5$ (open circles) and 2.0 (solid circles) is equally significant in the vicinity of 90°, although the distributions at very forward and backward angles are modified. To investigate the impact parameter dependence, the results for $b = 6$ (squares) and 7.5 fm (triangles) are also presented in Fig. 2(b). As expected, the effect of $E_{\rm sym}(\rho)$ is reduced with decreasing b because the isospin asymmetry in the inner region of the target is reduced, and both the isoscalar and the Coulomb potentials become stronger, the effect of $E_{\rm sym}(\rho)$ is, then, diminished.

It is worth mentioning that the scenario using the ansatz (2) with different γ offers an approximate way to survey the effect of $E_{\rm sym}(\rho)$. A stricter way is to calculate the α distribution using the whole parameter set of selected standard Skyrme potentials. Figure 2(c) presents the α distribution with seven sets of Skyrme forces, i.e., SkA [50], SkT5, SkT1 [51], SkM* [52], Skz-1, Skz1, and Skz4 [53]. The first four (later three) sets of parameters yield similar isovector (isoscalar) potential but differ in isoscalar (isovector) sector. It is evident that the correlation angle distribution is clearly discriminated if one counts from Skz-1 to Skz1 and Skz4 with increasing the stiffness of $E_{\rm sym}(\rho)$, but shows insignificant dependence on the variation of isoscalar potentials, indicating that the isovector reorientation effect of the polarized deuteron scattering off the heavy target field offers a clean probe to isovector potential.

To quantify the distribution of α in connection with the stiffness of $E_{\rm sym}(\rho)$ in a simplified scheme, we fit the logarithmic intensity $\ln[d\sigma/d(\cos\alpha)]$ with a linear function of $\cos\alpha$ as

$$\ln[d\sigma/d(\cos\alpha)] = a_0 + a_1\cos\alpha, \qquad (4)$$

near $\cos\alpha = 0$. The coefficient a_1 characterizes the decreasing rate of the $\cos\alpha$ distribution. As an example, Fig. 3(a) presents the logarithmic intensity as a function of $\cos\alpha$ with different γ for the breakup of a tensor- and vector-polarized deuteron in $\vec{\rm d} + {}^{124}$Sn with $b = 7$ fm at 100 MeV/u. The linear fit in $|\cos\alpha| \leq 0.2$ is superimposed. The error bars on the data points are of statistical origin. For simplicity at the beginning, the nucleons from the projectile breakup were tagged in the analysis. It is shown that the slope near $\cos\alpha = 0$ varies dramatically with γ. The solid symbols in Fig. 3(b) show the extracted coefficient a_1 as a function of γ at both $b = 7$ (triangles) and 7.5 fm (squares). The corresponding slope of $E_{\rm sym}(\rho)$ at ρ_0 is plotted on the upper axis. It is shown that a_1 increases significantly with γ, manifesting itself as a sensitive observable to constrain $E_{\rm sym}(\rho)$ at low densities.

Finally, an essential question remains regarding whether the nucleons from the deuteron breakup due to the nuclear mean field in peripheral reactions can be identified experimentally. To solve this question, we calculate the multiplicity and the kinetic quantities of the emitted nucleons from the reaction. Figure 4(a) presents the correlation between the outgoing angle θ and the kinetic energy E_k of the nucleons in the laboratory reference for 100 MeV/u $\vec{\rm d} + {}^{124}$Sn with $b = 7$ fm. Two components are evidently separated, the one originating from the projectile situates at a very forward angle with E_k peaking at beam energy, the other, originating from the target, covers a broad angular range, but the kinetic energy is much lower. Correspondingly, Fig. 4(b1) shows the multiplicity of emitted nucleons with (solid histogram) and without (open histogram) a kinetic energy cut $E_k \geq 50$ MeV. For reference, the multiplicity of protons M_p [Fig. 4(b2)] and neutrons M_n [Fig. 4(b3)] are also plotted. It is shown that more than 90% of the events are characterized by $M_n = M_p = 1$ if the cut on E_k is applied. The two-body collision changes the energies of the colliding nucleon significantly, so the breakup events due to collision are mostly filtered out by this selection criteria. With this cut, the spectrum of $\cos\alpha$ is reanalyzed using the same fitting procedure, as represented in Fig. 3(b) by the open symbols for both $b = 7$ and 7.5 fm. The dependence of a_1 on γ is not changed. Finally, since, experimentally, it is difficult to achieve a fine subdivision of b in peripheral collisions, the results at both impact parameters are mixed and analyzed using the same E_k cut, as shown by the open circles in Fig. 3(b). It is evident that, with the E_k cut, the sensitivity of a_1 on the symmetry energy is maintained. This sensitivity, compared with the existing probes of $E_{\rm sym}(\rho)$, is significantly

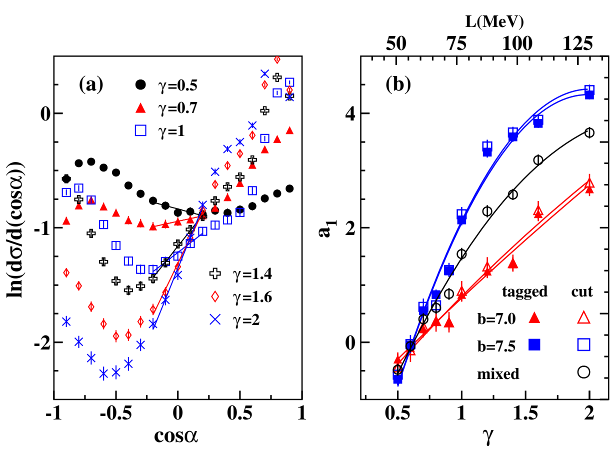

FIG. 3 (color online). (a) The logarithmic spectra of $\cos\alpha$ in $\vec{\rm d} + {}^{124}$Sn with $b = 7$ fm at 100 MeV/u for various γ and corresponding fitted quadratic functions, (b) the linear coefficient a_1 as a function of γ. See text for detailed discussions.

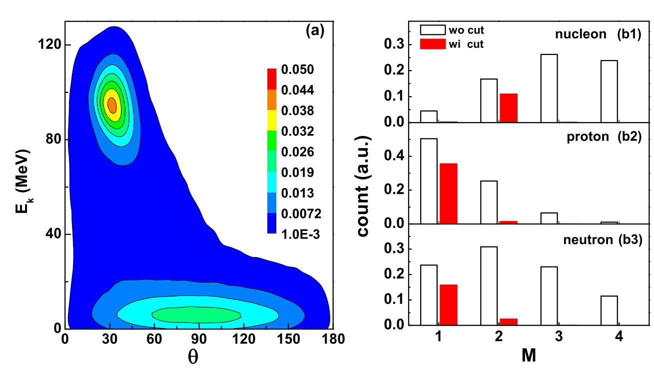

FIG. 4 (color online). (a) The correlation plot of the kinetic energy and the outgoing polar angle of the produced nucleons, (b) the multiplicity spectra of total nucleons (b1), protons (b2), and neutrons (b3) with (solid bars) and without (open bars) the kinetic energy cut.

enhanced and allows a stringent constraint on $E_{\rm sym}(\rho)$ at subsaturation densities.

To summarize, using the ImQMD transport model, the reorientation effect of the deuteron attributed to isovector interaction in the nuclear field of heavy target nuclei has been investigated for the first time. The isovector force forms a torque acting on the proton and the neutron and modifies the orientation of the incident deuteron. It is demonstrated that the correlation angle α, newly defined as a detectable quantity in the breakup of a polarized deuteron projectile, depends sensitively on the isovector potential but shows insignificant influence by the variation of the isoscalar nuclear potential. In terms of the sensitivity and the cleanness, the breakup reactions induced by the polarized deuteron at about 100 MeV/u provides a novel and more quantitative constraint to $E_{\rm sym}(\rho)$ at $\rho < 0.5\rho_0$. Calculations with coupled channel models are called for. If equipped with experiments being able to measure charged particles as well as neutrons at intermediately high energies, the accelerators available for a polarized deuteron beam offer feasible opportunities for this study.

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