Isospin dependence of ^{6}He+ p optical potential and the symmetry energy

Dao T. Khoa* and Hoang Sy Than
Institute for Nuclear Science & Technique, VAEC, P.O. Box 5T-160, Nghia Do, Hanoi, Vietnam
(Received 22 September 2004; published 6 April 2005)

A consistent folding analysis of the elastic $p(^6\mathrm{He},^6\mathrm{He})p$ scattering and charge exchange $p(^6\mathrm{He},^6\mathrm{Li}^*)n$ reaction data measured at $E_{\mathrm{lab}} = 41.6A$ MeV has been performed within the coupled channels formalism. We have used the isovector coupling to link the isospin dependence of ^{6}He+p optical potential to the cross section of $p(^6\mathrm{He},^6\mathrm{Li}^*)n$ reaction exciting the 0^+ isobaric analog state (IAS) at 3.563 MeV in ^{6}Li. Based on these results and the Hartree-Fock calculation of asymmetric nuclear matter using the same isospin-dependent effective nucleon-nucleon interaction, we were able to confirm that the most realistic value of the symmetry energy E_{sym} is around 31 MeV. Our analysis has also shown that the measured charge exchange $p(^6\mathrm{He},^6\mathrm{Li}^*)n$ data are quite sensitive to the halo tail of the ^{6}He density used in the folding calculation and the IAS of ^{6}Li is likely to have a halo structure similar to that established for the ground state of ^{6}He.

DOI: 10.1103/PhysRevC.71.044601 PACS number(s): 24.50.+g, 25.60.Bx, 25.60.Lg

The knowledge about the symmetry part of the nuclear equation-of-state (EOS) is vital for the understanding of the dynamics of supernovae explosion and the formation of neutron stars [1,2]. The symmetry part of the nuclear EOS is actually determined by the nuclear matter (NM) symmetry energy $S(\rho)$ defined in terms of a Taylor series expansion of the NM binding energy $B(\rho, \delta)$ as follows:

$$B(\rho, \delta) = B(\rho, 0) + S(\rho)\delta^2 + O(\delta^4) + \cdots \qquad (1)$$

where $\delta = (\rho_n - \rho_p)/\rho$ is the neutron-proton asymmetry parameter. The contribution of $O(\delta^4)$ and higher-order terms in Eq. (1), that is, the deviation from the parabolic law was proven to be negligible [3,4]. The NM symmetry energy determined at the NM saturation density, $E_{\mathrm{sym}} = S(\rho_0)$ with $\rho_0 \approx 0.17$ fm^{-3}, is widely known in the literature as the *symmetry energy* or symmetry coefficient. Although numerous nuclear many-body calculations have predicted E_{sym} to be around 30 MeV (see, e.g., Refs. [3–6,10]), a direct experimental determination of E_{sym} still remains a challenging task. One needs, therefore, to relate E_{sym} to some experimentally inferrable quantity such as the neutron skin in neutron-rich nuclei [7–10] or the fragmentation data of heavy-ion (HI) collisions involving $N \neq Z$ nuclei [11–13]. An accurate estimate of the E_{sym} value is also very important for nuclear astrophysics. For example, a small variation of E_{sym}, used as input for the hydrodynamic simulation of supernovae, significantly affects the electron capture rate in the “prompt” phase of type II supernovae [2]. Another example is a calculation of NM and masses of finite nuclei using Skyrme forces [6], which shows that the neutron-rich NM does not collapse only if the corresponding E_{sym} value is within the range 28–31 MeV. E_{sym} is also an important input for the study of the density dependence $S(\rho)$ based on transport-model simulation of the HI collisions (see Ref. [11] and references therein), and the most recent transport-model results favor $E_{\mathrm{sym}} \approx 31$–32 MeV [13].

Within the frame of any microscopic model for asymmetric NM, the symmetry energy depends strongly on the isospin dependence of the nucleon-nucleon (NN) interaction used therein [3,4]. Therefore, the E_{sym} value can be indirectly tested in a charge exchange (isospin-flip) reaction, which has been known for decades as a good probe of the isospin dependence of the effective NN interaction [14]. Although the isospin dependence of the optical potential (OP), known by now as Lane potential [15], has been studied since a long time, there has been a considerable interest recently in studying the isospin dependence of the OP in the quasielastic scattering reactions measured with unstable neutron-rich beams. Based on the isospin symmetry, the nucleus-nucleus OP can be written in terms of an isovector coupling [15] as follows:

$$U(R) = U_0(R) + 4U_1(R)\frac{\boldsymbol{t}\cdot\boldsymbol{T}}{aA}, \qquad (2)$$

where $\boldsymbol{t}$ is the isospin of the projectile a and $\boldsymbol{T}$ is that of the target A. For a proton-induced scattering reaction, the second term of Eq. (2) contributes to both the elastic (p, p) scattering and (p, n) charge exchange reaction [16]. Although the relative contribution by the Lane potential U_1 to the elastic (p, p) cross section is small and amounts to only a few percentages for a neutron-rich target [17,18], it determines entirely the (Fermi-type) $\Delta J^\pi = 0^+$ transition strength of the (p, n) reaction, leading to an isobaric analog state (IAS). Therefore, the (p, n) reaction so far has been the main tool in studying the isospin dependence of the proton-nucleus OP. Because this isospin dependence should be better tested in the charge exchange reactions induced by the neutron-rich beams, we consider in the present work the $p(^6\mathrm{He},^6\mathrm{Li}^*)n$ reaction measured by Cortina-Gil *et al.* [19] with the secondary ^{6}He beam at $E_{\mathrm{lab}} = 41.6A$ MeV. Given a large neutron-proton asymmetry ($\delta = 1/3$) of the unstable ^{6}He nucleus, the measured $p(^6\mathrm{He},^6\mathrm{Li}^*)n$ cross section for the transition connecting the ground state (g.s.) of ^{6}He ($T = T_z = 1$) and its isobaric analog partner ($T = 1, T_z = 0, J^\pi = 0^+$ excited state of ^{6}Li at 3.563 MeV) is indeed a good probe of the isovector coupling in the ^{6}He+p system. In the two-channel approximation, the elastic $p(^6\mathrm{He},^6\mathrm{He})p$ scattering and charge

*Electronic address: khoa@vaec.gov.vn.

exchange $p(^6\text{He},^6\text{Li}^*)n$ cross sections can be obtained from the solutions of the following coupled channels (CC) equations [16]:

$$[K_p + U_p(R) - E_p]\chi_p(\boldsymbol{R}) = -\frac{\sqrt{2}}{3}U_1(R)\chi_n(\boldsymbol{R}), \quad (3)$$

$$[K_n + U_n(R) - E_n]\chi_n(\boldsymbol{R}) = -\frac{\sqrt{2}}{3}U_1(R)\chi_p(\boldsymbol{R}). \quad (4)$$

Here $K_{p(n)}$ and $E_{p(n)}$ are the kinetic-energy operators and center-of-mass energies of the $^6\text{He}+p$ and $^6\text{Li}^* + n$ channels, with the energy shift because of the Coulomb energy and Q value of the $p(^6\text{He},^6\text{Li}^*)n$ reaction properly taken into account. $U_p(R)$ is the OP in the $^6\text{He}+p$ channel and $U_n(R)$ is that in the $^6\text{Li}^* + n$ channel. In addition to the charge exchange $p(^6\text{He},^6\text{Li}^*)n$ [19] and elastic $p(^6\text{He},^6\text{He})p$ scattering [20] data measured at 41.6A MeV, a total reaction cross section $\sigma_R = 409 \pm 22$ mb was also measured [21] for the $^6\text{He}+p$ system at a slightly lower energy of 36A MeV. Thus, these data sets are the important constraints for the $^6\text{He}+p$ OP at the considered energy.

To link the Lane potential U_1 to the isospin dependence of the NN interaction, we have used the folding model [17,18] to calculate U_0 and U_1 using the explicit proton and neutron g.s. densities of ^{6}He and the CDM3Y6 density- and isospin-dependent NN interaction [22]. This interaction is based on the M3Y interaction $v_{0(1)}(s)$ deduced from the G-matrix calculation [23] using the Paris NN potential, with the energy and density dependences included explicitly as follows:

$$v_{0(1)}(E, \rho, s) = (1 - 0.0026E)F_{0(1)}(\rho)v_{0(1)}(s), \quad (5)$$

where E is the bombarding energy (per projectile nucleon),

$$F_{0(1)}(\rho) = C_{0(1)}[1 + \alpha \exp(-\beta\rho) - \gamma\rho], \quad (6)$$

and the explicit expression of the finite-range $v_{0(1)}(s)$ interactions is given in Ref. [3]. Parameters of the *isoscalar* part $F_0(\rho)$ of the density dependence (6) were chosen [22] to reproduce saturation properties of the symmetric NM in the Hartree-Fock (HF) approximation and tested in the folding analyses [22,24] of the elastic *refractive* nucleus-nucleus and α-nucleus scattering to infer realistic estimate for the nuclear incompressibility [$K(\rho_0) \approx 250$ MeV]. In a similar manner, we try now to probe the *isovector* part $F_1(\rho)$ in the CC analysis of the charge exchange $p(^6\text{He},^6\text{Li}^*)n$ reaction and, using the HF method of Ref. [3], to accurately estimate the symmetry energy E_{sym}. Because the CDM3Y6 interaction is real, the folding model is used to calculate the real parts of the OP, $V_{0(1)} = \text{Re}\, U_{0(1)}$, which is further scaled by a complex factor to obtained $U_{0(1)}$. By taking isospin coupling explicitly into account, one obtains from Eq. (2) the following:

$$U_p(R) = \left[V_0(R) - \frac{V_1(R)}{3}\right](N_R + iN_I), \quad (7)$$

$$U_n(R) = V_0(R)(N_R + iN_I). \quad (8)$$

In the CC calculation, $U_{p(n)}$ are each added by a spin-orbital potential whose parameters were fixed as taken from the systematics by Becchetti and Greenless [25], and U_p is added further by a Coulomb potential between a point charge and a uniform charge distribution of radius $R_C = 1.35A^{1/3}$ fm. The form factor (FF) of the $p(^6\text{He},^6\text{Li}^*)n$ reaction, to be used in the right-hand sides of Eqs. (3) and (4), is given by Eq. (2) as follows:

$$U_{pn}(R) = \frac{2\sqrt{N-Z}}{A}U_1(R) = \frac{\sqrt{2}}{3}V_1(R)[1 + i(N_I/N_R)]. \quad (9)$$

Thus, the scaling factors $N_{R(I)}$ of the real and imaginary parts of the OP are the main parameters to be determined from the CC description of the charge exchange $p(^6\text{He},^6\text{Li}^*)n$ and elastic scattering $p(^6\text{He},^6\text{He})p$ data, which should also be *constrained* by a total reaction cross section $\sigma_R \approx 400$ mb (an empirical value expected at the considered energy [21]). To have as few free parameters as possible, we have used a simple assumption (9) to scale the real folded (p, n) FF by the same *relative* complex strength as that used in the elastic channel [26]. Our only nuclear structure input is the $^6\text{He}_{\text{g.s.}}$ density and we have considered in this work two different choices: the microscopic density given by the cluster-orbital shell model approximation (COSMA) [27,28] and that obtained recently [29] based on the independent particle model (IPM). The CC calculation was done with the nonrelativistic code FRESCO [30] using the inputs for mass numbers and incident energies given by the relativistically corrected kinematics [31]. For a checking purpose, the CC results plotted in Fig. 1 were also compared with those given by the code ECIS97 [32] (which takes exactly into account the relativistic kinematics) and the two sets of calculated $p(^6\text{He},^6\text{Li}^*)n$ cross sections turned out to be nearly identical.

We found that $N_R \approx 0.85$, and $N_I \approx 0.55$, which were mainly determined by the fit to the elastic scattering data

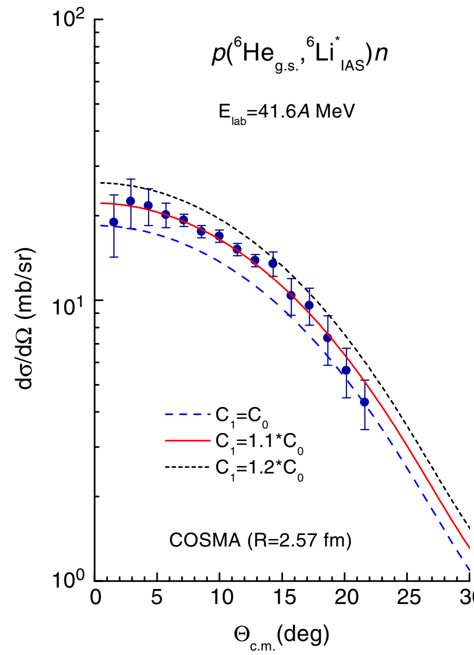

FIG. 1. (Color online) CC results for the charge exchange $p(^6\text{He},^6\text{Li}^*)n$ cross section at $E_{\text{lab}} = 41.6A$ MeV in comparison with the data measured by Cortina-Gil *et al.* [19].

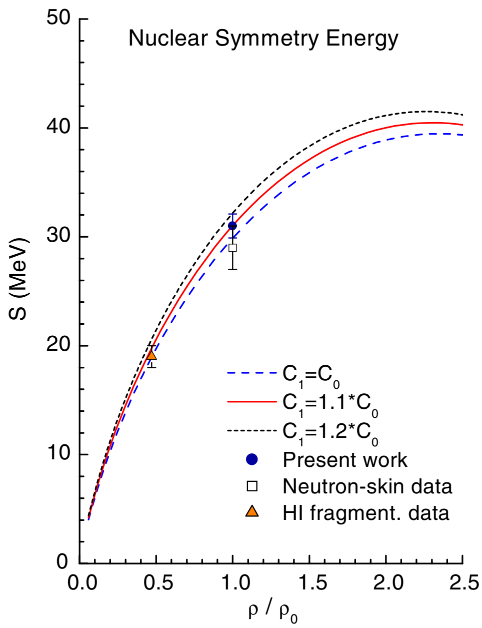

FIG. 2. (Color online) Density dependence of the NM symmetry energy $S(\rho)$ predicted by the HF formalism of Ref. [3] using the same isovector strengths C_1 as those used in Fig. 1, in comparison with the empirical points deduced from the neutron-skin [9] and HI fragmentation [12] data.

and by a constraint that the calculated σ_R is around 400 mb. It is noteworthy that a continuum-discretized coupled channels (CDCC) calculation of the elastic ^{6}He+p scattering at about the same energy by Mackintosh and Rusek [33] has shown that the real dynamic polarization potential due to ^{6}He breakup is repulsive in the center and at the surface, so that a renormalization factor $N_R < 1$ of the real folded OP is well expected. The relative strength $N_I/N_R \approx 0.65$ [used further to calculate FF for the $p(^{6}\text{He},^{6}\text{Li}^*)n$ reaction] also agrees reasonably with the CDCC results [33], which give the ratio of volume integrals of the imaginary and real parts of the ^{6}He+p OP around 0.6.

The $p(^{6}\text{He},^{6}\text{Li}^*)n$ cross section given by the COSMA density [28] was found to have a shape very close to that of the measured angular distribution (see Fig. 1). Because the strength N_I/N_R was fixed at 0.65, the CC description of the $p(^{6}\text{He},^{6}\text{Li}^*)n$ data could be improved only by fine tuning the strength C_1 of the isovector part of the density-dependence (6) of the CDM3Y6 interaction. One can see that the best fit is achieved when C_1 is about 10% stronger than the isoscalar strength C_0. We have further performed the HF calculation of asymmetric NM with the same isospin- and density-dependent CDM3Y6 interaction using the method described in Ref. [3]. The density dependence of the NM symmetry energy $S(\rho)$ obtained with the same isovector strengths C_1 as those used in Fig. 1 is shown in Fig. 2, and one can deduce easily $E_{\text{sym}} \approx 31 \pm 1$ MeV from our HF results. This result should be complementary to the nuclear structure studies that relate the slope of the EOS of asymmetric NM and the associated E_{sym} value to the neutron skin, a method first suggested by Alex Brown [7]. If one adopts, for example, a neutron-skin $\Delta R \approx 0.1$–0.2 fm for ^{208}Pb, then a systematics based on the mean-field calculations (see Fig. 7 of Ref. [9]) gives $E_{\text{sym}} \approx 27$–$31$ MeV (this value is compared with our HF result in Fig. 2). The main methods to determine the neutron skin are either the analyses of elastic (p, p) scattering on stable $N \neq Z$ targets [34,35] or studies of asymmetric NM and structure of finite nuclei [10,36]. However, the uncertainty still remains rather high and ΔR for ^{208}Pb nucleus was found to range from 0.083–0.11 fm [35] to 0.13 ± 0.03 fm [10] or around 0.17 fm [34] and up to about 0.22 fm [36]. A more accurate determination of ΔR is expected from the measurement of parity-violating electron scattering [37] and it might be used for a more precise determination of E_{sym}. Our result is also complementary to the nuclear reaction studies based on the transport-model simulations [11,12]. For example, a recent antisymmetrized molecular dynamics (AMD) analysis of the HI fragmentation data [12] obtained $S(\rho \approx 0.08\ \text{fm}^{-3}) \approx 18-20$ MeV (see Fig. 2), which gives useful information on the low-density part of $S(\rho)$. Because the charge exchange $p(^{6}\text{He},^{6}\text{Li}^*)n$ cross section is peaked at the most forward angles (see Fig. 1), our CC analysis has probed mainly the surface part of the FF, which, in turn, is determined by the low-density part of $v_1(E, \rho, s)$. The fact that our HF calculation reproduces quite well the empirical half-density point of $S(\rho)$ [12] shows the reliability of the isospin dependence of the CDM3Y6 interaction. Note that the Gogny-AS effective NN interaction used in the AMD calculation of Ref. [12] also gives $E_{\text{sym}} \approx 31$ MeV at ρ_0 (see Fig. 1 of Ref. [38]), in a very close agreement with our HF result. Thus, the HF result shown in Fig. 2 should provide a realistic description of the EOS of asymmetric NM for densities up to about 2 ρ_0.

In addition to the conclusion on the symmetry energy, we have found further that the measured $p(^{6}\text{He},^{6}\text{Li}^*)n$ data are also sensitive to the halo tail of the ^{6}He nucleus. Because the IAS of ^{6}Li is just an isobaric analog partner of $^{6}\text{He}_{\text{g.s.}}$, the isospin symmetry implies [39] that this IAS of ^{6}Li should have about the same halo structure as that of $^{6}\text{He}_{\text{g.s.}}$, and the central OP's in the entrance and exit channels should be well described by Eqs. (7) and (8). To study this effect, we have used in the folding calculation two versions of the COSMA density [28] that have RMS radii of 2.57 and 2.48 fm as well as the IPM density [29], which has the RMS radius of 2.46 fm. Although the IPM density was shown [29] to give a good description of the interaction cross section measured with ^{6}He beam at high energies, it was calculated in the independent particle model that does not account for the dineutron correlation in ^{6}He. In this sense, the COSMA densities are more accurate and should give a better description of the $p(^{6}\text{He},^{6}\text{Li}^*)n$ data if the IAS of ^{6}Li has the same halo structure as $^{6}\text{He}_{\text{g.s.}}$. The CC results obtained with three different choices of the $^{6}\text{He}_{\text{g.s.}}$ density are shown in Fig. 3 and one can see that the COSMA density is indeed more appropriate than the IPM density and gives a consistently good description of both the elastic scattering and charge exchange data. With the same $N_{R(I)}$ factors used throughout these calculations, the COSMA densities with RMS = 2.57 and 2.48 fm give $\sigma_R = 408$ and 399 mb, respectively, quite close to the empirical value of about 400 mb. The IPM density gives $\sigma_R = 382$ mb, which

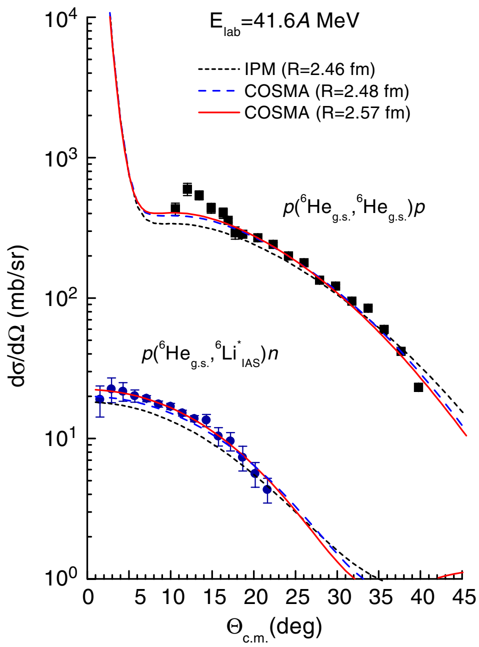

FIG. 3. (Color online) CC results for the elastic scattering $p(^6\mathrm{He},^6\mathrm{He})p$ and charge exchange $p(^6\mathrm{He},^6\mathrm{Li}^*)n$ cross sections at $E_{\mathrm{lab}} = 41.6A$ MeV, given by the OP and FF obtained with three choices of the $^6\mathrm{He}_{\mathrm{g.s.}}$ density (see text) in comparison with the data measured by Cortina-Gil *et al.* [19,20].

is slightly smaller than 400 mb. The description of the elastic scattering and charge exchange data by the IPM density can only be improved by further reducing the N_I factor, but then σ_R becomes significantly smaller than the empirical value. One can see in Fig. 3 that from two versions of the COSMA density the $p(^6\mathrm{He},^6\mathrm{Li}^*)n$ data seem to favor that with RMS $= 2.57$ fm. Such a RMS radius agrees with that predicted earlier by the three-body calculation of ^{6}He, which takes into account the dynamic correlation between the α-core and dineutron [40].

In addition to the elastic $p(^6\mathrm{He},^6\mathrm{He})p$ scattering and charge exchange $p(^6\mathrm{He},^6\mathrm{Li}^*)n$ reaction, inelastic $p(^6\mathrm{He},^6\mathrm{He}^*)p'$, scattering to the 1.87-MeV 2^+ state of ^{6}He has also been measured [41] at a nearby energy of $40.9A$ MeV. This (unbound) excitation of ^{6}He has been a subject of extensive analyses of the elastic and inelastic $^6\mathrm{He}+p$ scattering either in the distorted-wave Born approximation (DWBA) or CC formalism. In particular, the halo effect has been shown to be significant in the 2^+ inelastic scattering channel (see Fig. 3 of Ref. [41]). Therefore, a folding analysis of the 2^+ inelastic scattering data using the same $^6\mathrm{He}+p$ OPs as those used in Fig. 3 would be quite complementary to the results discussed above for the charge exchange reaction. The real 2^+ inelastic FF was calculated by the folding model [17,18] using a simple ansatz for the transition density, where the proton and neutron parts of the ($^6\mathrm{He}_{\mathrm{g.s.}} \to {}^6\mathrm{He}^*_{2^+}$) transition density are given by deforming proton and neutron parts of the $^6\mathrm{He}_{\mathrm{g.s.}}$ density with the deformation lengths $\delta^{(p)}_{2^+}$ and $\delta^{(n)}_{2^+}$ determined recently in a CC analysis of the $^4\mathrm{He}(^6\mathrm{He},^6\mathrm{He})^4\mathrm{He}$ reaction [42]. The folded 2^+ inelastic FF was further scaled by the same complex factor $(1 + iN_I/N_R)$ as that used to obtain the charge exchange FF in Eq. (9). The DWBA results obtained with three choices of the $^6\mathrm{He}_{\mathrm{g.s.}}$ density are plotted in Fig. 4 and one can see that the best description of the $p(^6\mathrm{He},^6\mathrm{He}^*)p'$ data are again given by the COSMA density. The deficiency of the IPM density is about the same as that shown above in the calculated $p(^6\mathrm{He},^6\mathrm{Li}^*)n$ cross sections.

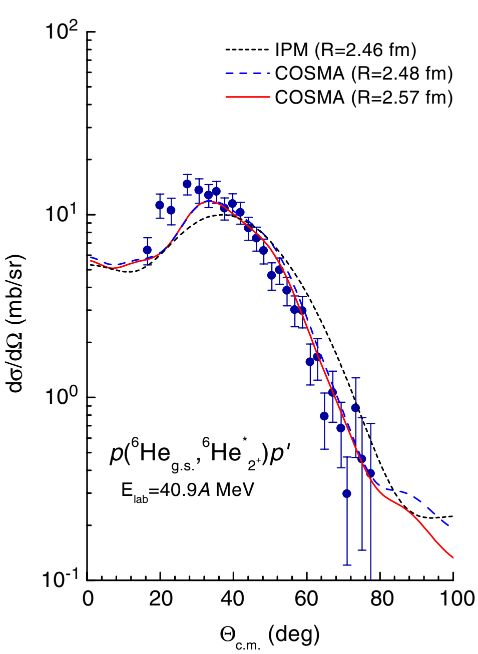

FIG. 4. (Color online) DWBA results for the inelastic $p(^6\mathrm{He},^6\mathrm{He}^*)p'$, scattering to the 1.87-MeV 2^+ state of ^{6}He at $E_{\mathrm{lab}} = 40.9A$ MeV, given by the OP and FF obtained with three choices of the $^6\mathrm{He}_{\mathrm{g.s.}}$ density (see text) in comparison with the data measured by Lagoyannis *et al.* [41].

Finally, we note that a folding analysis of the present charge exchange $p(^6\mathrm{He},^6\mathrm{Li}^*)n$ data has been done earlier [19,21] using the famous JLM (complex) G-matrix interaction. Although the real, imaginary, and isovector strengths of the JLM interaction were adjusted to the best fit of the elastic scattering and charge exchange data, these analyses seem to be unable to give a good description of the last data points of the measured $p(^6\mathrm{He},^6\mathrm{Li}^*)n$ cross section no matter what density distribution of ^{6}He is used in the folding calculation (see, e.g., Fig. 2 of Ref. [21]). Our CC results represent, therefore, an accurate alternative description that also provides important input for the description of the equation-of-state of asymmetric NM. The future measurements of the charge exchange reactions induced by the neutron-rich beams would be very valuable in studying the isospin dependence of the nucleus-nucleus interaction and making a more reliable conclusion on the symmetry energy.

The authors thank Nicolas Alamanos and Valerie Lapoux for making the measured cross sections available in tabulated form. The research was supported, in part, by the Natural Science Council of Vietnam and Vietnam Atomic Energy Commission.

[1] H. A. Bethe, Rev. Mod. Phys. **62**, 801 (1990).
[2] F. D. Swesty, J. M. Lattimer, and E. S. Myra, Astrophys. J. **425**, 195 (1994).
[3] D. T. Khoa, W. von Oertzen, and A. A. Ogloblin, Nucl. Phys. **A602**, 98 (1996).
[4] W. Zuo, I. Bombaci, and U. Lombardo, Phys. Rev. C **60**, 024605 (1999).
[5] M. Brack, C. Guet, and H. B. Håkansson, Phys. Rep. **123**, 276 (1985).
[6] J. M. Pearson and R. C. Nayak, Nucl. Phys. **A668**, 163 (2000).
[7] B. A. Brown, Phys. Rev. Lett. **85**, 5296 (2000).
[8] C. J. Horowitz and J. Piekarewicz, Phys. Rev. Lett. **86**, 5647 (2001).
[9] R. J. Furnstahl, Nucl. Phys. **A706**, 85 (2002).
[10] A. E. L. Dieperink, Y. Dewulf, D. Van Neck, M. Waroquier, and V. Rodin, Phys. Rev. C **68**, 064307 (2003).
[11] B. A. Li, Phys. Rev. Lett. **88**, 192701 (2002); Nucl. Phys. **A708**, 365 (2002).
[12] D. V. Shetty, S. J. Yennello, A. S. Botvina, G. A. Souliotis, M. Jandel, E. Bell, A. Keksis, S. Soisson, B. Stein, and J. Iglio, Phys. Rev. C **70**, 011601(R) (2004).
[13] L. W. Chen, C. M. Ko, and B. A. Li, Phys. Rev. Lett. **94**, 032701 (2005).
[14] R. R. Doering, D. M. Patterson, and A. Galonsky, Phys. Rev. C **12**, 378 (1975).
[15] A. M. Lane, Phys. Rev. Lett. **8**, 171 (1962).
[16] G. R. Satchler, *Direct Nuclear Reactions* (Clarendon Press, Oxford, 1983).
[17] D. T. Khoa, E. Khan, G. Colò, and N. Van Giai, Nucl. Phys. **A706**, 61 (2002).
[18] D. T. Khoa, Phys. Rev. C **68**, 011601(R) (2003).
[19] M. D. Cortina-Gil *et al*., Nucl. Phys. **A641**, 263 (1998).
[20] M. D. Cortina-Gil *et al*., Phys. Lett. **B401**, 9 (1997).
[21] A. de Vismes *et al*., Phys. Lett. **B505**, 15 (2001).
[22] D. T. Khoa, G. R. Satchler, and W. von Oertzen, Phys. Rev. C **56**, 954 (1997).
[23] N. Anantaraman, H. Toki, and G. F. Bertsch, Nucl. Phys. **A398**, 269 (1983).
[24] D. T. Khoa and W. von Oertzen, Phys. Lett. **B342**, 6 (1995); D. T. Khoa *et al*., Phys. Rev. Lett. **74**, 34 (1995).
[25] F. D. Becchetti and G. W. Greenlees, Phys. Rev. **182**, 1190 (1969).
[26] G. R. Satchler and W. G. Love, Phys. Rep. **55**, 183 (1979).
[27] M. V. Zhukov, B. V. Danilin, D. V. Fedorov, J. M. Bang, I. J. Thompson, and J. S. Vaagen, Phys. Rep. **231**, 151 (1993).
[28] A. A. Korsheninnikov *et al*., Nucl. Phys. **A617**, 45 (1997).
[29] D. T. Khoa, H. S. Than, T. H. Nam, M. Grasso, and N. Van Giai, Phys. Rev. C **69**, 044605 (2004).
[30] I. J. Thompson, Comp. Phys. Rep. **7**, 167 (1988).
[31] M. E. Farid and G. R. Satchler, Phys. Lett. **B146**, 389 (1984).
[32] J. Raynal, *Computing as a Language of Physics* (IAEA, Vienna, 1972), p. 75; J. Raynal, coupled-channel code ECIS97 (unpublished).
[33] R. S. Mackintosh and K. Rusek, Phys. Rev. C **67**, 034607 (2003).
[34] S. Karataglidis, K. Amos, B. A. Brown, and P. K. Deb, Phys. Rev. C **65**, 044306 (2002).
[35] B. C. Clark, L. J. Kerr, and S. Hama, Phys. Rev. C **67**, 054605 (2003).
[36] J. Piekarewicz, Phys. Rev. C **69**, 041301(R) (2004).
[37] C. J. Horowitz, S. J. Pollock, P. A. Souder, and R. Michaels, Phys. Rev. C **63**, 025501 (2001).
[38] A. Ono, P. Danielewicz, W. A. Friedman, W. G. Lynch, and M. B. Tsang, Phys. Rev. C **68**, 051601(R) (2003).
[39] K. Arai, Y. Suzuki, and K. Varga, Phys. Rev. C **51**, 2488 (1995).
[40] J. S. Al-Khalili, J. A. Tostevin, and I. J. Thompson, Phys. Rev. C **54**, 1843 (1996).
[41] A. Lagoyannis *et al*., Phys. Lett. **B518**, 27 (2001).
[42] D. T. Khoa and W. von Oertzen, Phys. Lett. **B595**, 193 (2004).