Continuum-discretized coupled-channels method for four-body nuclear breakup in $^{12}\text{C} + ^6\text{He}$

T. Matsumoto,\textsuperscript{1} H. Hiyama,\textsuperscript{2} K. Ogata,\textsuperscript{1} Y. Iseri,\textsuperscript{3} M. Kamimura,\textsuperscript{1} S. Chiba,\textsuperscript{4} and M. Yahiro\textsuperscript{1}

\textsuperscript{1}Department of Physics, Kyushu University, Fukuoka 812-8581, Japan
\textsuperscript{2}Department of Physics, Nara Women’s University, Nara 630-8506, Japan
\textsuperscript{3}Department of Physics, Chiba-Keizai College, Todoroki-cho 4-3-30, Inage, Chiba 263-0021, Japan
\textsuperscript{4}Advanced Science Research Center, Japan Atom Energy Research Institute (JAERI), Tokai, Ibaraki 319-1195, Japan

(Dated: November 7, 2018)

PACS numbers: 21.45.+v, 21.60.Gx, 24.10.Eq, 25.60.-t

We propose a fully quantum-mechanical method of treating four-body nuclear breakup processes in scattering of a projectile consisting of three constituents, by extending the continuum-discretized coupled-channels method. The three-body continuum states of the projectile are discretized by diagonalizing the internal Hamiltonian of the projectile with the Gaussian basis functions. For $^{6}\text{He} + ^{12}\text{C}$ scattering at 18 and 229.8 MeV, the validity of the method is tested by convergence of the elastic and breakup cross sections with respect to increasing the number of the basis functions. Effects of the four-body breakup and the Borromean structure of $^{4}\text{He}$ on the elastic and total reaction cross sections are discussed.

The study on neutron-halo nuclei has become one of the central subjects in the unstable nuclear physics since the discovery of such nuclei\textsuperscript{1}. In scattering of a two-neutron-halo nucleus such as $^{8}\text{He}$ and $^{11}\text{Li}$, the projectile easily breaks up into its three constituents ($n+n+\text{core}$), indicating that the scattering should be described as a four-body ($n+n+\text{core}+\text{target}$) reaction. Then an accurate theory for treating such a four-body breakup is highly desirable.

So far the eikonal and adiabatic calculations were proposed and applied to $^{6}\text{He}$ and $^{11}\text{Li}$ scattering around 50 MeV/nucleon\textsuperscript{2,3,4,5}. Since these calculations are based on semi-classical approaches, they work well at higher incident energies. In fact, the elastic cross section of $^{6}\text{He} + ^{12}\text{C}$ scattering at 229.8 MeV has recently been measured\textsuperscript{6} and successfully analyzed by the eikonal calculation with the six-nucleon wave function of $^{6}\text{He}$\textsuperscript{7}. However, these approaches seem not to be applicable for low-energy scattering such as $^{12}\text{C}(^{6}\text{He},^{6}\text{He})^{12}\text{C}$ at 3 MeV/nucleon\textsuperscript{8} measured very recently.

In this rapid communication, we present a fully quantum-mechanical method of treating four-body nuclear breakup. The method is constructed by extending the continuum-discretized coupled-channels method (CDC\textsuperscript{C})\textsuperscript{9} that treats three-body breakup processes in scattering of the two-body projectile. In CDC\textsuperscript{C}, the total scattering wave function is expanded in terms of bound and continuum states of the projectile. The continuum states are classified by the linear ($k$) and angular momenta, and they are truncated by setting an upper limit to each quantum number. The $k$-continuum is then divided into small bins and the continuum states in each bin are averaged into a single state. This procedure of discretization is called the average (Av) method. The $S$-matrix elements calculated with CDC\textsuperscript{C} converge as the modelspace is extended\textsuperscript{10}. The converged CDC\textsuperscript{C} solution is the unperturbed solution of the distorted Faddeev equations, and corrections to the solution are negligible within the region of space in which the reaction takes place\textsuperscript{10}.

Also for four-body breakup processes in scattering of the three-body projectile, CDC\textsuperscript{C} has to prepare three-body bound and discretized-continuum states of the projectile. Because of the difficulty of preparing all the three-body states with the Av method, CDC\textsuperscript{C} so far analyzed $^{6}\text{He}$ scattering within a limited model in which a two-neutron pair is treated as a single particle, di-neutron ($^{7}n$)\textsuperscript{11}. However, the accuracy of the di-neutron model has not been confirmed yet, because of the absence of fully quantum-mechanical method of treating four-body breakup.

In our previous work\textsuperscript{12} on three-body breakup in scattering of the two-body projectile, we proposed a new method of discretization, called the pseudo-state (PS) method. In the method, continuum states of the projectile are replaced by discrete pseudo-states obtained by diagonalizing the internal Hamiltonian of the projectile in a space spanned by the $L^2$-type Gaussian basis functions. The CDC\textsuperscript{C} solution calculated by the PS method agrees with that by the Av method which can be regarded as the exact solution. Thus, a reasonable number of the Gaussian basis functions can form an approximate complete set in a finite configuration space being important for three-body breakup processes. It is very likely that the approximate completeness persists also in the case of four-body breakup processes. Actually, as shown latter, we can see clear convergence of calculated elastic and breakup cross sections with respect to increasing the number of the Gaussian basis functions. It should be noted that the Gaussian basis functions are widely used to solve bound-state problems of few-body systems\textsuperscript{13}, since the use of the basis functions reduces numerical works much. Thus, the four-body breakup processes can be analyzed properly by CDC\textsuperscript{C} with the PS method. We refer to this new method as four-body CDC\textsuperscript{C} and the usual CDC\textsuperscript{C} for three-body breakup as three-body CDC\textsuperscript{C}.

The first application of four-body CDC\textsuperscript{C} thus designed is made for $^{6}\text{He} + ^{12}\text{C}$ scattering at 18 and 229.8 MeV, where the projectile has the Borromean structure and then easily breaks up into two nucleons and $^{4}\text{He}$. In these scattering processes,
the incident energies $E_{\text{in}}$ are much higher than the Coulomb barrier energy ($\sim 3$ MeV), so only nuclear breakup processes become significant. We thus concentrate our application on nuclear breakup. The calculated elastic cross sections well reproduce experimental data at both $E_{\text{in}}$. Moreover, effects of the four-body breakup and the Borromean structure of $^6$He on the elastic and total reaction cross sections are discussed in the case of $E_{\text{in}} = 18$ MeV.

We assume that $^6$He+$^{12}$C scattering is described as a four-body system, $n+n+^4$He+$^{12}$C. Then, the Schrödinger equation can be written as

$$ K_R + \sum_{i \in P} \sum_{j \in T} v_{ij} + V_C(R) + H_0 - E \Psi(\xi, R) = 0, \quad (1) $$

where $R$ and $\xi$ are, respectively, the coordinate of the center-of-mass of $^6$He relative to $^{12}$C and the internal coordinates of $^6$He; $K_R$ is the kinetic energy associated with $R$. Here, $H_0$ is the internuclear Hamiltonian of $^6$He-projectile, and $E$ is the sum of $E_{\text{in}}$ and the ground state energy of $^6$He. The $v_{ij}$ represent two-body nuclear interactions working between $^6$He-projectile (P) and $^{12}$C-target (T). Meanwhile, the Coulomb potential $V_C$ is treated approximately as a function of $R$ only, i.e., we neglect Coulomb breakup processes.

The four-body wave function $\Psi^{JM}$, where $J$ is the total angular momentum of the four-body system and $M$ is its projection on the $z$-axis, is expanded in terms of a finite number of the internal wave functions $\Phi_\gamma$ of $^6$He-projectile:

$$ \Psi^{JM}(\xi, R) = \sum_{nI,L} \chi^{JM}_{nI,L}(P_n I, R)/R \chi^{JM}_{nI,L}, \quad (2) $$

where $\chi^{JM}_{nI,L} = [\Phi_{nI}(\xi) \otimes i^L Y_L(\Omega_R)]^{JM}$. The $\gamma$ stands for the set of $(n, I, m)$, where $I$ is the total spin of $^6$He and $m$ is its projection on the $z$-axis, and $n$ stands for the $n$ th eigenstate with positive energy. The ground state of $^6$He, which is the only bound state of $^6$He, is denoted by $\gamma_0 \equiv (0, I_0, m_0)$. The $\Phi_\gamma$ satisfies $H_0 \Phi_\gamma = \epsilon_\gamma \Phi_\gamma$ and the expansion-coefficient $\chi^{JM}_{nI,L}$ in Eq. (1) represents the relative motion between the projectile and the target; $L$ is the orbital angular momentum regarding $R$. The relative moment $P_n I$ is determined by the conservation of the total energy: $E = P_n^2 / 2\mu + \epsilon_n I$, with $\mu$ the reduced mass between the projectile and the target. Multiplying Eq. (1) by $\chi^{JM}_{nI,L}$ from left, one can obtain a set of coupled differential equations for $\chi^{JM}_{nI,L}$, called CDCC equation; it should be noted that the CDCC equation for the four-body system is formally equal to that for the three-body system. Solving the CDCC equation under the appropriate asymptotic boundary condition [6, 14], we can obtain the elastic and discrete breakup $S$-matrix elements. Details of the formalism of CDCC are shown in Ref. [9].

In the Gaussian expansion method (GEM) [13], each $\Phi_\gamma$ is given by

$$ \Phi_\gamma(\xi) = \sum_{c=1}^3 \psi^{(c)}_\gamma(\xi), \quad (3) $$

where $c$ denotes the set of Jacobian coordinates shown in Fig. 1. We here take the angular-momentum coupling scheme as $I = A + S$, where $A$ and $S$ are the total orbital-angular-momentum and the total intrinsic spin of $^4$He, respectively. Then $\psi^{(c)}_\gamma$ has the following form:

$$ \psi^{(c)}_\gamma(\xi) = \varphi^{(\alpha)}_c \sum_{\Lambda, S} \left[ \eta^{(n_1)}_\gamma \otimes \eta^{(n_2)}_\gamma \right]_{A,S} \xi, \quad (4) $$

where $n_{1/2}$ is the spin wave function of each valence neutron ($n_1$ or $n_2$) and $^4$He has been treated as an inert core with the $(0s)^4$ internal configuration, $\varphi^{(\alpha)}$. The definition of $(y_c, r_c)$ is given in Fig. 1. The amplitude-function $\psi^{(c)}_{nAM\Lambda}$ with $M\Lambda$ the projection of $\Lambda$ on the $z$-axis, is expanded in terms of the Gaussian basis functions:

$$ \psi^{(c)}_{nAM\Lambda}(y_c, r_c) = \sum_{\Lambda, S} \sum_{i=1}^{i_{\text{max}}} \sum_{j=1}^{j_{\text{max}}} A^{(c)}_{n,\bar{i}\Lambda j\ell \Lambda} \lambda_{\epsilon c} e^{-\epsilon_{c}(y_c - \bar{y}_{c})^2} x_{\bar{r}_{c}} \epsilon(\epsilon_{c}/\epsilon) \sum_{\Lambda, S} \eta^{(n_1)}_\gamma \otimes \eta^{(n_2)}_\gamma \left[ A^{(c)}_{n,\bar{i}\Lambda j\ell \Lambda} \right]_{A,S} \quad (5) $$

where $\lambda$ is the angular momentum regarding $y_c$ ($r_c$). The Gaussian range parameters are taken to be a geometric progression:

$$ \bar{y}_i = (\bar{y}_i (\epsilon_{\text{max}}/\bar{y}_i))^{(i-1)/(i_{\text{max}}-1)}, \quad (6) $$

$$ \bar{r}_j = (\bar{r}_j (\epsilon_{\text{max}}/\bar{r}_i))^{(j-1)/(j_{\text{max}}-1)}. \quad (7) $$

The $\Phi_\gamma$ is antisymmetrized for the exchange between $n_1$ and $n_2$; we then have $A^{(2)}_{n,\bar{i}\Lambda j\ell \Lambda} = (-)^S A^{(1)}_{n,\bar{i}\Lambda j\ell \Lambda}$, and $(-)^{A+S}$ must be 1 for $c = 3$. Meanwhile, the exchange between each valence neutron and each nucleon in $^4$He is treated approximately by the orthogonality condition model [15]. The eigenenergies $\epsilon_n I$ of $^6$He and the corresponding expansion-coefficients $A^{(c)}_{n,\bar{i}\Lambda j\ell \Lambda}$ are determined by diagonalizing $H_0$ [16, 17].

In the four-body CDCC calculation shown below, we take $I^\pi = 0^+$ and $2^+$ states for $^6$He; $\pi$ is the parity of $^6$He. We
show in Table II the maximum values of the internal angular momenta, \( \alpha_{\text{max}}, \ell_{\text{max}}, \text{ and } \lambda_{\text{max}} \), and the Gaussian range parameters, \( y_1, y_{\text{max}}, r_1 \), and \( r_{\text{max}} \), used in the calculation of \( \Phi_n \). It should be noted that most of them depend on \( I^T \) and \( c \), while in Eqs. (6–7) the dependence has been omitted for simplicity. In order to demonstrate the convergence of the four-body CDCC solution with respect to increasing the number of the Gaussian basis functions, we prepare three sets of the basis functions, i.e., sets I, II and III. Each set is specified by \( i^T_{\text{max}} \) and \( j^T_{\text{max}} \); again, the \( I^T \) and \( c \)-dependence of them has been omitted in Eqs. (6–7). One can calculate the total number of the eigenenergies of \( H_6, N^T_{\text{max}} \) by using Eqs. (6–7) and the input parameters shown in Table II. The values of \( i^T_{\text{max}}, j^T_{\text{max}} \) and \( N^T_{\text{max}} \) for each set are shown in Table II. In the actual CDCC calculation for \(^6\text{He}+^{12}\text{C} \) scattering at 18 MeV (229.8 MeV), high-lying states with \( E_{nl} > 25 \text{ MeV} \) are found to give no effect on the elastic and breakup S-matrix elements. Thus, the effective number of the eigenstates of \(^6\text{He}, N^T_{\text{max}} \) is reduced much for each of sets I–III, as shown in Table II.

As for the coupling potentials in the CDCC equation, we adopt the double folding model (8) as follows:

\[
U_f^{(n)}(R) = (N_R + iN_I)V_f^{(n)}(R),
\]

\[
V_f^{(n)}(R) \equiv \sum_{i \in I, j \in T} v_{ij} \Phi_{g_s}^{(T)}(r)\Phi_{g_s}^{(n)}(r) - \sum_{i \in I, j \in T} \int \rho_{\Phi}^{(n)M}(r) \Phi_{g_s}^{(n)}(r) dR \delta(r - r_i),
\]

where \( \Phi_{g_s}^{(T)}(r) \) is the coordinate of a nucleon in the projectile (target) relative to the center-of-mass of the particle, and \( R = R + r_T - r_P \). The quantum number \( \zeta \) represents \( n, I \) and \( L \) together, and the elastic channel, which has the incident wave, is denoted by \( \zeta \equiv (0, I_0, L_0) \). The ground state density \( \rho_{\Phi}^{(n)M}(r) \) is the wave function of the ground state, is calculated by the microscopic 3\( \alpha \) cluster model (9). We in this study define the transition densities of \(^6\text{He}, \rho_{\Phi}^{(n)M}(r) \), as

\[
\rho_{\Phi}^{(n)M}(r) = \sum_{i \in I, j \in T} v_{ij} \Phi_{g_s}^{(T)}(r)\Phi_{g_s}^{(n)M}(r) - \sum_{i \in I, j \in T} \int \rho_{\Phi}^{(n)M}(r) \Phi_{g_s}^{(n)M}(r) dR \delta(r - r_i),
\]

As for the nucleon-nucleon effective interaction \( v_{\text{NN}} \), we use the realistic energy- and density-dependent M3Y (DDM3Y) interaction (10). Since the DDM3Y interaction is real, \( V_{f^{(n)}}(R) \) has no imaginary part. Thus, we have multiplied \( V_{f^{(n)}}(R) \) by a complex factor \( N_R + iN_I \). In the present analysis, we fix \( N_R = 1 \) and optimize \( N_I \) to fit experimental data for elastic scattering. It should be noted that in three-body CDCC calculation made before for \(^{12}\text{C} \) scattering on various target nuclei (21, 22), the prescription above was successful in reproducing experimental data.

The convergence of the four-body CDCC solution is tested for \(^6\text{He}+^{12}\text{C} \) scattering at 18 MeV. Figure 2 shows the energy-integrated breakup cross section, i.e., the sum of the cross sections to all breakup channels, calculated with sets I–III. The results of sets II and III are in good agreement with each other, but the result of set I is somewhat different from them. Meanwhile, as for the elastic cross section shown in Fig. 3, the three sets give the same cross section shown by the solid line. Thus, the four-body CDCC solution converges with set II. Furthermore, we have confirmed that similar convergence is also seen with respect to extending \( y_{\text{max}}, r_{\text{max}} \). The optimum value of \( N_f \) determined from the measured elastic cross section is 0.5 at \( E_{\text{in}} = 18 \text{ MeV} \), which is the same as that for \(^6\text{Li} \) scattering at various \( E_{\text{in}} \) (21, 22). It should be noted that all calculations shown in Figs. 2 and 3 use the same value of \( N_f \). Also for \(^6\text{He}+^{12}\text{C} \) scattering at 229.8 MeV, we can see similar convergence of the elastic and energy-integrated breakup cross sections with respect to extending the model-space. Comparison between the calculated and measured elastic cross sections is shown in Fig. 4. In this case the optimum value of \( N_f \) is 0.3. In Figs. 3 and 4 the dotted lines represent the elastic cross sections due to the single-channel calculation. Then, the difference between the solid and dotted lines shows the effect of the four-body breakup on the elastic cross section. For both \( E_{\text{in}} \), the effect is sizable, properties of which are discussed later.
Recently, it was reported in Ref. [11] that the total reaction cross section for $^6\text{He}+^{209}\text{Bi}$ is much larger than that for $^6\text{Li}+^{209}\text{Bi}$ at similar energies relative to the Coulomb barrier energies because of the large $E1$ excitation strength of $^6\text{He}$ to the continuum. Meanwhile, for $^6\text{He}+^{12}\text{C}$ scattering at 18 MeV, the $E1$ excitation of $^6\text{He}$ is negligible because $E_{in}$ is much higher than the Coulomb barrier energy (about 3 MeV). As shown in Fig. 5, however, we find that 10% enhancement of the total reaction cross section is still left. The open circles represent the total reaction cross sections for $^6\text{He}+^{12}\text{C}$ at 18 and 229.8 MeV calculated by four-body CDCC, while the filled circles show those for $^6\text{Li}+^{12}\text{C}$ in the energy range 20–318 MeV calculated by three-body CDCC [21, 22], where the microscopic $dl^2\text{He}$ model is assumed for $^6\text{Li}$ structure. As mentioned above, the resulting optimum $N_f$ value for $^6\text{Li}+^{12}\text{C}$ scattering is about 0.5, i.e., almost independent of $E_{in}$.

In order to investigate the origin of the 10% enhancement, we perform the three-body CDCC calculation by assuming the di-neutron model for $^6\text{He}$ structure; in the model, the di-neutron density is assumed to be the same as that of the deuteron, and then the resulting $^6\text{He}$ density is close to the $^6\text{Li}$ one. The result of this calculation is shown by the open triangle in Fig. 5. The difference between the open triangle and the open circle at 18 MeV is due to the Borromean structure of $^6\text{He}$, which is referred to as the Borromean effect. The effect dominates about half the 10% enhancement. The rest of the enhancement is mainly due to the difference of the Coulomb barrier energies between $^6\text{He}+^{12}\text{C}$ and $^6\text{Li}+^{12}\text{C}$. Actually, when the Coulomb potential for $^6\text{He}+^{12}\text{C}$ is replaced artificially by that for $^6\text{Li}+^{12}\text{C}$, the CDCC calculation based on the di-neutron model (the filled triangle) gives the total reaction cross section close to the filled circle at 20 MeV. As for $^6\text{He}+^{12}\text{C}$ scattering at 229.8 MeV, we have confirmed through the same analysis that the Borromean effect becomes negligible as well as the effect of the difference of the Coulomb barrier between $^6\text{He}+^{12}\text{C}$ and $^6\text{Li}+^{12}\text{C}$. This suggests no enhancement theoretically. Nevertheless, Fig. 5 shows that the total reaction cross section for $^6\text{He}+^{12}\text{C}$ is even smaller than that for $^6\text{Li}+^{12}\text{C}$ at the similar energy. This curious behavior is due to the fact that $N_f = 0.3$ for $^6\text{He}+^{12}\text{C}$ while $N_f = 0.5$ for $^6\text{Li}+^{12}\text{C}$ at this high energy. In fact, the total reaction cross section is enhanced by changing $N_f$ from 0.3 to 0.5 in four-body CDCC calculation for $^6\text{He}+^{12}\text{C}$, and the resulting cross section almost reproduces the corresponding one for $^6\text{Li}+^{12}\text{C}$. The origin of the small $N_f$ value for the $^6\text{He}$ scattering is not clear at this moment, so more systematic experimental data are highly desirable for $^6\text{He}$ scattering.

Finally, we calculate the dynamical polarization (DP) potential induced by the four-body breakup processes, in order to understand effects of the processes on the elastic scattering. The DP potential $U_{\text{DP}}^{j}(R)$ is given by

$$U_{\text{DP}}^{j}(R) = U_{eq}^{j}(R) - U_{\text{Coul}}^{j}(R), \quad (11)$$
In conclusion, a fully quantum-mechanical method of treating four-body nuclear breakup is presented by extending the continuum-discretized coupled-channels method. The method called four-body CDCC is applied to $^6$He+$^{12}$C scattering at 18 and 229.8 MeV in which $^6$He easily breaks up into two neutrons and $^4$He. In four-body CDCC, three-body continuum states of $^6$He are discretized by diagonalizing the internal Hamiltonian of $^6$He with the Gaussian basis functions. The validity of four-body CDCC is confirmed by clear convergence of the calculated elastic and energy-integrated breakup cross sections with respect to increasing the number of the Gaussian basis functions. We can say from the convergence that the Gaussian basis functions form an approximate complete set in a finite configuration space being important for four-body nuclear breakup processes. Furthermore, we find a 10% enhancement of the total reaction cross section of $^6$He+$^{12}$C at 18 MeV relative to that of $^6$Li+$^{12}$C at the similar energy. Half of the 10% enhancement is due to the Borromean structure of $^6$He. For the elastic scattering, the four-body breakup processes make, in particular, the imaginary part of the double-folded potential deep, which is originated in the Borromean structure of $^6$He. In the present analysis four-body Coulomb breakup is neglected. However, it would be possible to treat the Coulomb breakup within the present framework if the complex-range Gaussian basis functions are taken.

Further work along this line is highly expected.

The authors would like to thank Y. Sakuragi and M. Kawai for helpful discussions. This work has been supported in part by the Grants-in-Aid for Scientific Research (12047233, 14540271) of Monbukagakusyou of Japan. Numerical calculations were performed on FUJITSU VPP5000 at JAERI.

[1] I. Tanihata et al., Phys. Lett. 160B, 380 (1985).
[2] N. C. Summers et al., Phys. Rev. C 66, 014614 (2002).
[3] J. A. Christley et al., Nucl. Phys. A624, 275 (1997).
[4] J. S. Al-Khalili et al., Nucl. Phys. A581, 331 (1995).
[5] J. S. Al-Khalili et al., Phys. Lett. B 378, 45 (1996).
[6] V. Lapoux et al., Phys. Rev. C 66, 034608 (2002).
[7] B. Abu-Ibrahim and Y. Suzuki, Phys. Rev. C 70, 011603 (2004).
[8] M. Milin et al., Nucl. Phys. A730, 285 (2004).
[9] M. Kamimura et al., Prog. Theor. Phys. Suppl. 89, 1 (1986).
[10] N. Austern et al., Phys. Rev. Lett. 63, 2649 (1989); Phys. Rev. C 53, 314 (1996).
[11] N. Keeley et al., Phys. Rev. C 68, 054601 (2003).
[12] T. Matsumoto et al., Phys. Rev. C 68, 064607 (2003).
[13] For a review, E. Hiyama et al., Progress in Particle and Nuclear Physics 51, 223 (2003).
[14] R. A. D. Piyadasa et al., Phys. Rev. C 60, 044611 (1999).
[15] S. Saito, Prog. Theor. Phys. 41, 705 (1969).
[16] S. Funada et al., Nucl. Phys. A575, 93 (1994).
[17] E. Hiyama and M. Kamimura, Nucl. Phys. A588, 35 (1995).
[18] G. R. Satchler and W. G. Love, Phys. Rep. 55, 183 (1979).
[19] M. Kamimura, Nucl. Phys. A531, 456 (1981).
[20] A. M. Kobos et al., Nucl. Phys. A384, 65 (1982).
[21] Y. Sakuragi et al., Prog. Theor. Phys. Suppl. 89, 136 (1986); Y. Sakuragi, Phys. Rev. C 35, 2161 (1987).
[22] C. Samanta et al., J. Phys. G 23, 1697 (1997).
[23] T. Egami et al., nucl-th/0405050 (2004).