PHYSICAL REVIEW C **78**, 031601(R) (2008)

Effects of ground-state correlations on high energy scattering off nuclei: The case of the total neutron-nucleus cross section

M. Alvioli, C. Ciofi degli Atti, I. Marchino, and V. Palli
Department of Physics, University of Perugia and Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Via A. Pascoli, I-06123, Italy

H. Morita
Sapporo Gakuin University, Bunkyo-dai 11, Ebetsu 069, Hokkaido, Japan

(Received 22 July 2008; published 5 September 2008)

With the aim at quantitatively investigating the longstanding problem concerning the effect of short-range nucleon-nucleon correlations on scattering processes at high energies, the total neutron-nucleus cross section is calculated within a parameter-free approach which, for the first time, takes into account, simultaneously, central, spin, isospin, spin-isospin, and tensor nucleon-nucleon correlations, and Glauber elastic and Gribov inelastic shadowing corrections. Nuclei ranging from ^{4}He to ^{208}Pb and incident neutron momenta in the range 3 GeV/c–300 GeV/c are considered; the commonly used approach which approximates the square of the nuclear wave function by a product of one-body densities is carefully analyzed, showing that NN correlations can play a non-negligible role in high energy scattering off nuclei

DOI: 10.1103/PhysRevC.78.031601 PACS number(s): 21.30.Fe, 25.40.−h, 24.10.Ht, 24.10.Cn

Nowadays interpretation of high precision particle-nucleus and nucleus-nucleus scattering experiments at medium and high energies, aimed at investigating the state of matter at short distances, should require in principle also a consideration of possible effects from nucleon-nucleon (NN) short-range correlations (SRC), particularly in view of recent experimental data on lepton and hadron scattering off nuclei which provided quantitative evidence on SRC and their possible effects on dense hadronic matter [1]. Thanks to recent progress in the theoretical description of the many-body nuclear wave function, we have therefore undertaken a systematic study of the effects of SRC in medium and high energy scattering of nuclei, starting with a novel calculation of the total neutron-nucleus (nA) cross section $\sigma_{\rm tot}^{nA}$ at high energies. This quantity has been experimentally measured with high precision in a wide kinematical range and has been the object of many theoretical analyzes since it appears to be very sensitive to various relevant phenomena, such as Glauber elastic [2] and Gribov inelastic [3] diffractive shadowing, which, in turn, have a relevant impact on the interpretation of color transparency phenomena and relativistic heavy ion processes (see, e.g., [4,5]).

It is well known that although the major mechanism which explains the experimental evidence $\sigma_{\rm tot}^{nA} \ll A\sigma_N$ ($\sigma_N \equiv \sigma_{\rm tot}^{NN}$) is Glauber elastic shadowing, a quantitative explanation of the experimental data requires also the introduction of Gribov inelastic shadowing [4,6,7]. Most calculations of $\sigma_{\rm tot}^{nA}$ so far performed were however based upon the so-called one-body-density approximation, in which all terms but the first one of the exact expansion of the square of the nuclear wave function in terms of density matrices [2,8] are disregarded, which amounts to neglect all kinds of NN correlations. Although the necessity and interest to investigate the effects of the latter have been stressed by several authors [4,7], first of all by Glauber himself [2], only few qualitative calculations have been performed in ^{4}He [9] and in heavy nuclei [10,11]. The aim of this work is to illustrate a novel, parameter-free calculation of $\sigma_{\rm tot}^{nA}$ within a realistic treatment of SRC [12,13]. In this sense, our work is similar in its motivations to that of Ref. [14], where state-of-the-art quantum Monte Carlo (QCM) wave functions, for $A \leqslant 6$ nuclei, have been used to treat reaction cross sections of halo nuclei, evaluating the Glauber phase shift exactly by Monte Carlo integration.

In terms of Glauber elastic (G) and Gribov inelastic (IS) scattering one has

$$\sigma_{\rm tot}^{nA} = \sigma_A^G + \sigma_A^{IS} = \frac{4\pi}{k} Im\left[F_{00}^G(0) + F_{00}^{IS}(0)\right], \qquad (1)$$

where $F_{00}^{G(IS)}(0) = \frac{ik}{2\pi}\int d\boldsymbol{b}_n \Gamma_{00}^{G(IS)}(\boldsymbol{b}_n)$ is the forward elastic scattering amplitude, and $\Gamma_{00}^{G(IS)}$ the nuclear elastic profile function. The latter, in case of elastic Glauber scattering, has the well-known form

$$\Gamma_{00}^G(\boldsymbol{b}_n) = 1 - \prod_{j=1}^{A}\langle\psi_0|[1 - \Gamma_N(\boldsymbol{b}_n - \mathbf{s}_j)]|\psi_0\rangle, \qquad (2)$$

where $\psi_0 \equiv \psi_0(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3, ...\mathbf{r}_A)$ ($\mathbf{r}_j = (\mathbf{s}_j, z_j)$) is the ground state wave function of the target nucleus, $\boldsymbol{b}_n$ the impact parameter of the neutron moving along the z-axis, and $\Gamma_N(\boldsymbol{b}_n)$ the NN elastic profile function. As for the Gribov inelastic profile, it describes, as depicted in Fig. 1, the diffractive dissociation of the neutron via the process $n + N \to X + N$, its deexcitation to the ground state by the process $X + N \to n + N$, and its elastic scattering off the target nucleons. In our approach, as in Ref. [4], we will consider, besides the elastic scattering of X, only two nondiagonal transitions ($n + N \to X + N$ and $X + N \to n + N$).Within such an approximation

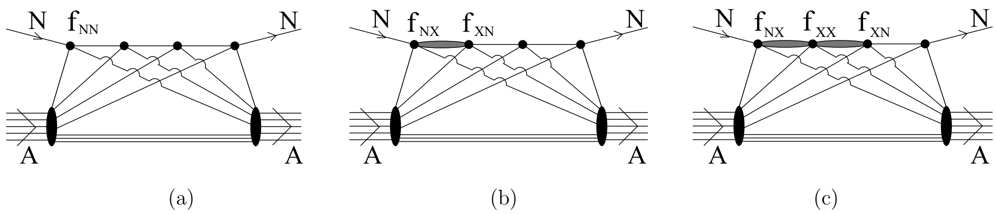

FIG. 1. Typical diagrams describing elastic N-A scattering: a) Glauber elastic scattering; b) and c) Gribov inelastic scattering. Black dots denote the particle-particle scattering amplitude.

one obtains [4]

$$\Gamma_{00}^{IS}(\boldsymbol{b}_n) = \sum_X \Bigg\{ \langle\psi_o| \sum_{i<j}^{A} \Gamma_{NX}(\boldsymbol{b}_n - \boldsymbol{b}_j)\Gamma_{XN}(\boldsymbol{b}_n - \boldsymbol{b}_i) e^{iq_X(z_i - z_j)} \Theta(z_j - z_i) \times \prod_{k \neq i,j}^{A} [1 - \Gamma_X(\boldsymbol{b}_n - \boldsymbol{b}_k)]\Theta(z_k - z_i)\Theta(z_j - z_k) \times \prod_{l \neq i,j}^{A} [1 - \Gamma_N(\boldsymbol{b}_n - \boldsymbol{b}_l)]\Theta(z_i - z_l)\Theta(z_l - z_j)|\psi_o\rangle \Bigg\}, \tag{3}$$

where $q_X = k_n - k_X$ is the longitudinal momentum transfer. The basic nuclear ingredient appearing in Eqs. (2) and (3) is $|\psi_0|^2$, which, in terms of density matrices, has the following form [2,8] [the center-of-mass (c.m.) δ function is omitted for ease of presentation but c.m. motion effects have been properly taken care of in calculations]:

$$|\psi_o(\boldsymbol{r}_1, \ldots, \boldsymbol{r}_A)|^2 = \prod_{j=1}^{A} \rho_1(\boldsymbol{r}_j) + \sum_{i<j} \Delta(\boldsymbol{r}_i, \boldsymbol{r}_j) \prod_{k \neq i,j} \rho_1(\boldsymbol{r}_k) + \sum_{(i<j)\neq(k<l)} \Delta(\boldsymbol{r}_i, \boldsymbol{r}_j)\Delta(\boldsymbol{r}_k, \boldsymbol{r}_l) \times \prod_{m \neq i,j,k,l} \rho_1(\boldsymbol{r}_m) + \cdots, \tag{4}$$

in which $\rho_1(\boldsymbol{r}_i)$ is the one-body density matrix (normalized to one) and $\Delta(\boldsymbol{r}_i, \boldsymbol{r}_j) = \rho_2(\boldsymbol{r}_i, \boldsymbol{r}_j) - \rho_1(\boldsymbol{r}_i)\rho_1(\boldsymbol{r}_j)$ the *two-body contraction*; the two-body density matrix $\rho_2(\boldsymbol{r}_i, \boldsymbol{r}_j)$ must satisfy the sequential condition $\int d\boldsymbol{r}_j \rho_2(\boldsymbol{r}_i, \boldsymbol{r}_j) = \rho_1(\boldsymbol{r}_i)$, leading to $\int d\boldsymbol{r}_j \Delta(\boldsymbol{r}_i, \boldsymbol{r}_j) = 0$. Note that in Eq. (4) only unlinked contractions have to be considered, and that the higher order terms, not explicitly displayed, include unlinked products of 3, 4, etc., two-body contractions, unlinked products of three-body contractions, describing three-nucleon correlations, and so on. By taking into account two-body correlations only, i.e., all terms of the expansion (4) containing all possible numbers of unlinked two-body contractions, one obtains [10,11] (from now on the optical limit, $A \gg 1$, will be used for ease of presentation):

$$\Gamma_{00}^{G}(\boldsymbol{b}_n) \simeq 1 - \exp\left[-A \int d\boldsymbol{r}_1 \rho_1(\boldsymbol{r}_1)\Gamma(\boldsymbol{b}_n - \boldsymbol{s}_1) + \frac{A^2}{2} \int d\boldsymbol{r}_1 d\boldsymbol{r}_2 \Delta(\boldsymbol{r}_1, \boldsymbol{r}_2)\Gamma(\boldsymbol{b}_n - \boldsymbol{s}_1)\Gamma(\boldsymbol{b}_n - \boldsymbol{s}_2)\right] \tag{5}$$

which yields the usual Glauber profile when $\Delta = 0$. Concerning Γ_{00}^{IS}, it can be reduced to an expression depending upon the total nucleon and diffractive cross sections σ_N and σ_r, respectively [4], which, within the approximation $\sigma_N = \sigma_r$ and disregarding correlations, provides the well-known Karmanov-Kondratyuk (KK) result [15]:

$$\Gamma_{00}^{IS}(\mathbf{b}_n) = -(2\pi)A^2 \int \left.\frac{d^2\sigma}{d^2q_T dM_X^2}\right|_{q_T=0} dM_X^2 e - \frac{\sigma_N}{2} T(\mathbf{b}_n) \times |F(q_L, \mathbf{b}_n)|^2. \tag{6}$$

Here $T(\mathbf{b}_n) = A\int_{-\infty}^{\infty} \rho(\mathbf{b}_n, z)\, dz$ is the thickness function, $F(q_L, \mathbf{b}_n) = \int_{-\infty}^{\infty} \rho(\mathbf{b}_n, z) exp(iq_L z)\, dz$ is the nuclear form factor, depending upon M_X through the relation $q_L = (M_X^2 - m_N^2)m_N/s$ ($s \simeq 2p_{\rm lab}$), and $d^2\sigma/(d^2q_T dM_X^2)$ is the differential cross section of the process $N + N \to N_X + N$ (M_X being the mass of N_X).

We have calculated $\sigma_{\rm tot}^{nA}$ using the two-body density obtained from the fully-correlated wave function of Refs. [12,13], $\psi_0 = \hat{F}\phi_0$, where $\hat{F} = \prod_{i<j}[\sum_{k=1}^{8} f_k(r_{ij})\hat{O}_k(ij)]$ is a correlation operator generated by the realistic Argonne $V8'$ interaction [16], and ϕ_0 a mean field (MF) wave function. The above wave function largely differs from the Jastrow one, featuring only central correlations, since the operator $\hat{F}$ generates central ($\hat{O}_1 = 1$), spin ($\hat{O}_2(ij) = \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j$), isospin ($\hat{O}_3(ij) = \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j$), spin-isospin ($\hat{O}_4(ij) = (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j)(\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j)$), tensor ($\hat{O}_5(ij) = \boldsymbol{S}_{ij}$), tensor-isospin ($\hat{O}_6(ij) = \boldsymbol{S}_{ij}(\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j)$), etc., correlations. In our approach the contraction $\Delta(\boldsymbol{r}_1, \boldsymbol{r}_2)$ exactly satisfies the sum rule $\int d\boldsymbol{r}_1 \Delta(\boldsymbol{r}_1, \boldsymbol{r}_2) = 0$, since the one-body density $\rho_1(\boldsymbol{r}_1)$ exactly results from the integration of $\rho_2(\boldsymbol{r}_1, \boldsymbol{r}_2)$. Note, moreover, that our one-body point density and radii are in agreement with electron scattering data [17]. The Glauber profile has been chosen in the usual form, $\Gamma(\boldsymbol{b}_n) = \sigma_{\rm tot}(4\pi b_0^2)^{-1}(1 - i\alpha)exp(-\boldsymbol{b}_n^2/2b_0^2)$, with the energy-dependent parameters taken from [18]; the parameters for the inelastic shadowing were taken from [6].

The results of calculations for ^{4}He, ^{12}C, ^{16}O and ^{208}Pb are presented in Figs. 2 and 3. The left panel shows the results obtained without correlations, i.e., taking into account only the first term in Eq. (4), whereas the results presented in the right panel include the effects of two-nucleon correlations (for ^{4}He we have calculated the cross section to all orders finding that three- and four-nucleon correlations produce negligible effects). The results presented in Figs. 2 and 3 show that: (i) if, as in the present paper, realistic one-body densities are considered the disagreement with the experimental data is not

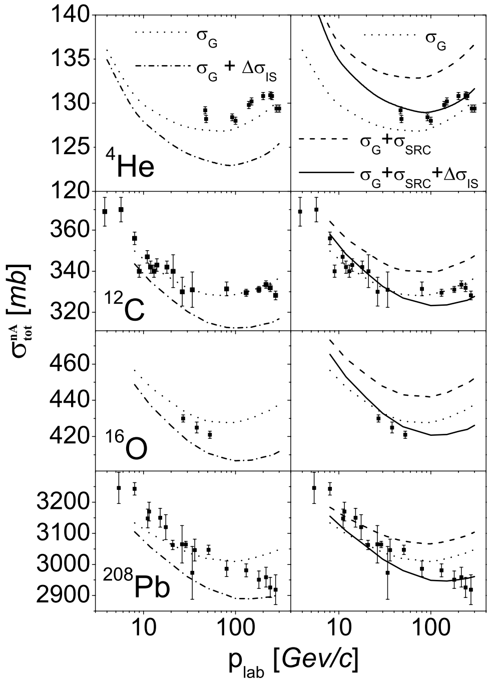

FIG. 2. $\sigma_{\rm tot}^{nA}$ vs $p_{\rm lab}$. Left panel: Glauber single density approximation (σ_G; dots) and Glauber plus Gribov inelastic shadowing ($\sigma_G + \Delta\sigma_{IS}$; dot-dash). Right panel: Glauber (σ_G; dots); Glauber plus SRC ($\sigma_G + \sigma_{SRC}$; dashes); Glauber plus SRC plus Gribov inelastic shadowing ($\sigma_G + \sigma_{SRC} + \Delta\sigma_{IS}$; full). Experimental data from [6,19].

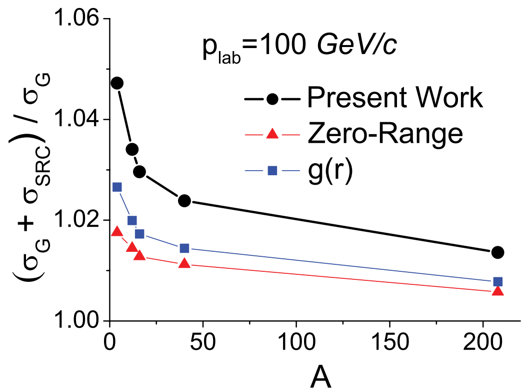

FIG. 3. (Color online) Ratio of the total cross section which includes correlations to the cross section without correlations; the figure shows our results obtained using the finite nuclei (dots) and nuclear matter (squares) two-body densities. Triangles correspond to the zero range approximation for the profile function.

dramatic, which is at variance with Ref. [6] where, as first stressed in [7], too large (by about 15%) nuclear radii have been used; (ii) within the one-body density approximation, inelastic shadowing corrections *increase* the nuclear transparency, which is a well-known result; (iii) NN correlations *decrease* the transparency (which is physically due to the reduction of the role of Glauber shadowing) and increase the total cross section (by an amount ranging from about 2% in ^{208}Pb up to about 5–6% in ^{4}He) spoiling the agreement with the experimental data provided by the Glauber calculation; (iv) the simultaneous inclusion of inelastic shadowing and two-nucleon correlations brings back theoretical calculations in good agreement with experimental data. Thus it appears that if the correct values of nuclear radii are used, the interpretation of the experimental data would require the consideration of *both* NN correlations and inelastic shadowing. We have also investigated the validity of the approximation in which the nuclear matter two-body density $\rho_2(\boldsymbol{r}_1, \boldsymbol{r}_2) = \rho_1(\boldsymbol{r}_1)\rho_1(\boldsymbol{r}_2)g(|\boldsymbol{r}_1 - \boldsymbol{r}_2|)$ is used for finite nuclei, leading to a strong violation of the sequential relation $\int d\mathbf{r}_2\rho_2(\boldsymbol{r}_1, \boldsymbol{r}_2) = \rho_1(\boldsymbol{r}_1)$ for nuclei with $A < 208$. Thus, when such an approximation is used to introduce correlations in light and medium-weight nuclei, a mismatch between the one-body density (usually taken from the experimental data) and the two-body density is generated.

To sum up, we have analyzed the effects of SRC on $\sigma_{\rm tot}^{nA}$ within a realistic and parameter-free approach to SRC using the correct values of nuclear radii and, at the same time, one-body densities which, unlike previous calculations, are exactly linked to the two-body densities by the sequential relation. The results we have obtained show that the effects of SRC, though being small in absolute value, could be of the same order as Gribov inelastic shadowing corrections. Such a result points to the necessity of (i) a systematic investigation of SRC effects on other high energy scattering processes (e.g., electroproduction of hadrons, large rapidity gap processes [5], heavy-ion collisions [21], etc.); (ii) an improved treatment of Gribov inelastic shadowing, going beyond the lowest order intermediate diffractive excitations (see, e.g., Ref. [20]). To conclude, we would like to point out that the smallness of SRC effects on $\sigma_{\rm tot}^{nA}$ does not imply that SRC effects on other quantities will also be small; as a matter of fact, preliminary results [22] show that SRC reduce the quasielastic cross section $\sigma_{\rm qel}^{pA}$ up to 15% in ^{12}C and ^{208}Pb. Calculations of elastic and quasielastic cross sections at energies ranging from HERA to LHC, are in progress and will be reported elsewhere.

C.dA. would like to thank B. Kopeliovich, M. Strikman, and D. Treleani for many useful discussions and N. Nikolaev for his suggestion to investigate the effects of SRC on the total cross sections. This work was supported in part by Fondecyt (Chile) grant 7070223; C.dA. is grateful to Departamento de Fisica, Universidad Tecnica Federico Santa Maria, Valparaiso, Chile, where the manuscript has been completed.

[1] K. S. Egiyan *et al.* (CLAS Collaboration), Phys. Rev. Lett. **96**, 082501 (2006); E. Piasetsky, M. Sargsian, L. Frankfurt, M. Strikman, and J. W. Watson, *ibid.* **97**, 162504 (2006); A. Tang *et al.*, *ibid.* **90**, 042301 (2003); R. Shneor *et al.*, *ibid.* **99**, 072501 (2007).
[2] R. J. Glauber, in *Lectures in Theoretical Physics*, edited by W. E. Brittin *et al.* (New York, (1959).
[3] V. N. Gribov, Sov. JETP **29**, 483 (1969); J. Pumplin and M. Ross Phys. Rev. Lett. **21**, 1778 (1968).
[4] B. K. Jennings and G. A. Miller, Phys. Rev. C **49**, 2637 (1994).

[5] B. Z. Kopeliovich, Phys. Rev. C **68**, 044906 (2003).
[6] P. V. Murthy, C. A. Ayre, H. R. Gustafson, L. W. Jones, and M. J. Longo, Nucl. Phys. **B92**, 269 (1975).
[7] N. N. Nikolaev, Sov. Phys. Usp. **24**, 531 (1981); Z. Phys. C **32**, 537 (1986).
[8] L. L. Foldy and J. D. Walecka, Ann. Phys. (NY) **54**, 447 (1969).
[9] H. Morita, Y. Akaishi, O. Endo, and H. Tanaka, Prog. Theor. Phys. **78**, 1117 (1987).
[10] E. J. Moniz and G. D. Nixon, Ann. Phys. (NY) **67**, 58 (1971).
[11] R. Guardiola and E. Oset, Nucl. Phys. **A234**, 458 (1974).
[12] M. Alvioli, C. Ciofi degli Atti, and H. Morita, Phys. Rev. C **72**, 054310 (2005).
[13] M. Alvioli, C. Ciofi degli Atti, and H. Morita, Phys. Rev. Lett. **100**, 162503 (2008).
[14] K. Varga, Steven C. Pieper, Y. Suzuki, and R. B. Wiringa, Phys. Rev. C **66**, 034611 (2002).
[15] V. A. Karmanov and L. A. Kondratyuk, JETP Lett. **18**, 266 (1973).
[16] B. S. Pudliner, V. R. Pandharipande, J. Carlson, S. C. Pieper, and R. B. Wiringa, Phys. Rev. C **56**, 1720 (1997).
[17] H. De Vries, C. W. De Jager, and C. De Vries, Nucl. Data Tables **36**, 495 (1987).
[18] K. Hikasa, Particle Data Group Phys. Rev. D **45**, R1 (1992); M. M. Block, K. Kang, and A. R. White, Int. J. Mod. Phys. A **77**, 4449 (1992).
[19] J. Engler *et al.*, Phys. Lett. **B32** 716 (1970); L. W. Jones *et al.*, *ibid.* **B36**, 509 (1971).
[20] B. Z. Kopeliovich, I. K. Potashnikova, and I. Schmidt Phys. Rev. C **73**, 034901 (2006).
[21] G. Baym, B. Blättel, L. L. Frankfurt, H. Heiselberg, and M. Strikman, Phys. Rev. C **52**, 1604 (1995).
[22] M. Alvioli, C. Ciofi degli Atti, H. Morita, and V. Palli (to be published).