Parity Violation in Proton–Deuteron Scattering

A. I. Milstein\textsuperscript{a, b}, N. N. Nikolaev\textsuperscript{c, *}, and S. G. Salnikov\textsuperscript{a, b}

\textsuperscript{a} Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia
\textsuperscript{b} Novosibirsk State University, Novosibirsk, 630090 Russia
\textsuperscript{c} Landau Institute for Theoretical Physics, Russian Academy of Sciences, Chernogolovka, Moscow region, 142432 Russia

* e-mail: nikolaev@itp.ac.ru

Received August 13, 2020; revised August 13, 2020; accepted August 13, 2020

Effects of parity violation in the interaction of relativistic polarized protons and deuterons are discussed. $P$-odd asymmetries in the total and elastic scattering cross sections, in the dissociation cross section, and in the inelastic scattering cross section with the production of mesons are estimated within the Glauber approach. It is shown that the $P$-odd effect in the interaction of polarized deuterons with unpolarized protons is larger than that in the interaction of polarized protons with unpolarized deuterons. A significant $P$-odd asymmetry is found in the channel of dissociation of the polarized deuteron.

DOI: 10.1134/S0021364020180083

INTRODUCTION

The interference of the amplitudes of strong and weak interactions is responsible for parity violation in nuclear and hadronic processes [1, 2]. Effects observed in nuclear processes and in processes of scattering of low-energy protons and neutrons are usually described by phenomenological meson–baryon interactions (see review [3]). Despite numerous theoretical [4–15] and experimental [19–22] works, the problem of parity violation in high-energy hadronic processes remains open. Significant progress in the understanding of this effect can be expected in polarization experiments at the Nuclotron-based Ion Collider fAcility (NICA) [23, 24]. Possible experiments at NICA on search for parity violation in the interaction of longitudinally polarized protons or deuterons with an unpolarized target were discussed in [25].

In our recent work [26], $P$-odd asymmetry in nucleon–nucleon scattering at NICA energies was estimated. The structure of weak currents is such that the leading contribution to $P$-odd asymmetry in proton–proton scattering comes from radiative corrections caused by charge-exchange strong interactions. It was shown that, in order to detect a larger effect, it is preferable to measure $P$-odd asymmetry in elastic scattering because asymmetry in inelastic cross sections is strongly suppressed.

In this work, we generalize the results obtained in [26] to $P$-odd asymmetry in proton–deuteron scattering at NICA energies. In contrast to nucleon–nucleon scattering, this scattering includes the quasielastic scattering channel with the dissociation of a deuteron into the proton–neutron continuum. Enhancement similar to the enhancement of asymmetry in elastic scattering [26] was also found for the dissociation of the longitudinally polarized deuteron on an unpolarized proton. $P$-odd asymmetry in the interaction of the polarized deuteron with the unpolarized proton is larger than that in the interaction of the polarized proton with the unpolarized deuteron. This is important for experimental capabilities because the acceleration of polarized deuterons in the NICA energy range is free of spin resonances, which are numerous in the case of polarized protons. To separate $P$-odd asymmetry in the elastic scattering and dissociation of accelerated deuterons, where a large effect is expected, we emphasize the possibility of using an internal hydrogen jet target with the detection of recoil protons [27].

NUCLEON–NUCLEON SCATTERING

The total amplitude of high-energy elastic proton–nucleon scattering $T(q_\perp)$, where $q_\perp$ is the transverse momentum of the scattered proton, can be represented in the form [26]

$$T(q_\perp) = T_s(q_\perp) + T_W(q_\perp) + T_{\text{int}}(q_\perp),$$

$$T_{\text{int}}(q_\perp) = -\frac{i}{2} \int \frac{d^2q_\perp'}{(2\pi)^2} T_s(q_\perp') T_W(q_\perp - q_\perp').$$

Here, $T_s(q_\perp)$ is the strong interaction amplitude, $T_W(q_\perp)$ is the weak interaction amplitude including radiative corrections to the $P$-odd Hamiltonian caused by the strong interaction, and $T_{\text{int}}(q_\perp)$ is the so-called absorption correction to the weak amplitude, which can be easily obtained in the eikonal approach. Taking
into account the conservation of the s-channel helicity for pN scattering amplitudes (here and below, N = p,n), one can use the standard parameterization [28] (difference from alternative parameterizations [29, 30] is insignificant and is not discussed):

\[ T_{s}^{pN}(q_{\perp}) = \delta_{\lambda_{1}\lambda_{2}}\delta_{\lambda_{3}\lambda_{4}}t_{s}^{pN}(q_{\perp}), \]
\[ t_{s}^{pN}(q_{\perp}) = (-e_{pN} + i)\sigma_{s,tot}^{pN}\exp(-B_{pN}q_{\perp}^{2}/2), \] (2)

where \( \lambda_{1} \) and \( \lambda_{2} \) (\( \lambda_{3} \) and \( \lambda_{4} \)) are the helicities of the initial (final) particles (\( \lambda_{i} = \pm 1 \)). At momentum transfers inside the diffraction cone, the ratio of the real and imaginary parts of the amplitude \( e_{pN} \) and the slope of the cone \( B_{pN} \) can be considered as constants. With an acceptable accuracy, \( t_{s}^{pp}(q_{\perp}) = t_{s}^{pn}(q_{\perp}) \equiv t_{s}(q_{\perp}) \) can be set in the NICA energy range [28]. In numerical estimates, we use the parameters

\[ e_{pN} = e = -0.5, \quad \sigma_{s,tot}^{pN} = \sigma_{s,tot}^{pN} = 50 \text{ mb}, \]
\[ B_{pN} = B = 9 \text{ GeV}^{-2}. \] (3)

The corresponding elastic scattering cross section is

\[ \sigma_{s,tot}^{pN} = \frac{1}{16\pi} \int |T_{s}^{pN}(q_{\perp})|^{2} \frac{d^{2}q_{\perp}}{16\pi^{2}} = \frac{(1 + e^{2})\sigma_{s,tot}^{pN}}{16\pi B} = 17.8 \text{ mb}. \] (4)

According to [26], the weak-interaction amplitudes \( T_{W}^{pN}(q_{\perp}) \) have different dependences on the momentum transfer and helicities:

\[ T_{W}^{pp}(q_{\perp}) = \lambda_{1}\delta_{\lambda_{1}\lambda_{2}}\delta_{\lambda_{3}\lambda_{4}}t_{W}^{pp}(q_{\perp}), \]
\[ T_{W}^{pn}(q_{\perp}) = \lambda_{1}\delta_{\lambda_{1}\lambda_{2}}\delta_{\lambda_{3}\lambda_{4}}t_{W}^{pn}(q_{\perp}), \]
\[ t_{W}^{pp}(q_{\perp}) = c_{pp}R(q_{\perp}), \quad t_{W}^{pn}(q_{\perp}) = c_{pn}F^{2}(q_{\perp}), \]
\[ F(q_{\perp}) = \frac{\Lambda^{4}}{(\Lambda^{2} + q_{\perp}^{2})^{2}}, \]
\[ R(q_{\perp}) = \frac{4}{\pi} \int \frac{F^{2}(k_{\perp})d^{2}k_{\perp}}{(k_{\perp}^{2} - q_{\perp}^{2})^{2} + m_{p}^{2},} \]
\[ c_{pp} = 5 \text{ nb}, \quad c_{pn} = -7.8 \text{ nb}, \]
\[ \Lambda = 1 \text{ GeV}, \quad m_{0} = 770 \text{ MeV}. \]

It is noteworthy that \( c_{pp} \) and \( c_{pn} \) have opposite signs.

Using the optical theorem \( \sigma_{tot} = -1\text{Im}T(0) \), we find the weak-interaction corrections \( \sigma_{W,tot}^{pp} \) and \( \sigma_{W,tot}^{pn} \) to the total pp and pn scattering cross sections:

\[ \sigma_{W,tot}^{pp} = \lambda_{1}\lambda_{2}\lambda_{3}\lambda_{4}S_{W}^{pp}, \]
\[ \sigma_{W,tot}^{pn} = \lambda_{1}\lambda_{2}\lambda_{3}\lambda_{4}S_{W}^{pn}, \] (6)
\[ S_{W}^{pp} = 3.7 \text{ nb}, \quad S_{W}^{pn} = -2.47 \text{ nb}. \]

The relation between \( S_{W}^{pp} \) and \( S_{W}^{pn} \) is determined not only by the relation between \( c_{pp} \) and \( c_{pn} \) but also by different dependences of the amplitudes \( t_{W}^{pp} \) and \( t_{W}^{pn} \) on \( q_{\perp} \).

In the simplified parameterization (2), the \( P \)-odd corrections \( \sigma_{W,tot}^{pN} \) to elastic pN scattering cross sections coincide with the \( P \)-odd corrections to the corresponding total cross sections. The suppression of \( P \)-odd corrections to inelastic cross sections is in essence a general consequence of the unitarity condition in the approximation linear in the weak interaction.

**EFFECTS OF WEAK INTERACTIONS IN PROTON–DEUTERON SCATTERING**

Here, we follow the Glauber approach [31–33]. A new diffraction dissociation channel (quasielastic scattering) to the proton–neutron continuum without the production of mesons, \( pd \rightarrow (pn)p \), where, as will be shown, large \( P \)-odd asymmetry is possible, should be separately considered.

The amplitude \( T_{s}^{pd} \) of elastic scattering caused by the strong interaction has the form

\[ T_{s}^{pd}(q_{\perp}) = \delta_{\lambda_{p}\lambda_{d}}\delta_{\lambda_{d}\lambda_{d}}t_{s}^{pd}(q_{\perp}), \]
\[ t_{s}^{pd}(q_{\perp}) = [t_{s}^{pp}(q_{\perp}) + t_{s}^{pn}(q_{\perp})]F_{D}\left(\frac{q_{\perp}}{2}\right) \]
\[ -i \int d^{2}q_{\perp}^{2}(q_{\perp}^{2} - q_{\perp}^{2})t_{s}^{pn}(q_{\perp}^{2} + q_{\perp}^{2})F_{D}\left(\frac{q_{\perp}}{2}\right). \] (7)

Here, \( \lambda_{p} \) and \( \lambda_{d} \) (\( \lambda_{d} \) and \( \lambda_{d} \)) are the helicities of the initial and final protons (deuterons), respectively. The single scattering amplitude includes the deuteron form factor \( F_{D}(q_{\perp}/2) \), and the double scattering amplitude small in the diffraction cone region of elastic \( pd \) scattering is responsible for Glauber screening. The deuteron form factor can be estimated with a sufficient accuracy using the pure s-wave function \( \phi(r) \):

\[ F_{D}(q) = \int d^{3}r|\phi(r)|^{2}\exp(-i\mathbf{q} \cdot \mathbf{r}). \]

The formula

\[ F_{D}(q) = \frac{2b}{(b - 1)x}\left[\arctan\left(\frac{x}{2}\right) - \frac{1}{2}\text{Si}\left(\frac{x}{b}\right)\right] \]
\[ -\frac{1}{4}\text{Si}\left(\pi + \frac{x}{b}\right) + \frac{1}{4}\text{Si}\left(\pi - \frac{x}{b}\right), \]
\[ \text{Si}(x) = \int_{0}^{x}dy\sin y, \quad b = 2.5, \]
\[ x = q/\kappa, \quad \kappa = 45.7 \text{ MeV} \]

obtained in the square well model is in good numerical agreement with those obtained in other models.
The expression for the total \( pd \) scattering cross section follows from the optical theorem in the form

\[
\sigma_{s,tot}^{pd} = 2\sigma_{s,tot} - \Delta \sigma_G = 96 \text{ mb},
\]

\[
\Delta \sigma_G = \frac{1}{2}(1 - \epsilon^2)\sigma_{s,tot}^2
\]

\[
\times \int \frac{d^2 q_\perp}{(2\pi)^2} \exp(-Bq_\perp^2)F_D(q_\perp) = 4 \text{ mb}.
\]

The correction \( \Delta \sigma_G \) corresponding to Glauber screening is small because of a large size of the deuteron, \( \Delta \sigma_G \ll \sigma_{s,tot}^{pd} \). In view of the obvious dominance of the single scattering amplitude, \( P \)-odd asymmetry in \( pd \) scattering will be similar to asymmetry in elastic \( pN \) scattering. The total elastic \( pd \) scattering cross section will be noticeably suppressed by the form factor of the deuteron. In the same approximation of a loose deuteron, the differential cross section for quasielastic deuteron. In the same approximation of a loose deuteron, the differential cross section for quasielastic deuteron will be close to the sum of the differential cross sections for elastic \( pp \) and \( pn \) scattering. Correspondingly, we expect that the observation in [26] on the enhancement of the \( P \)-odd asymmetry in elastic \( pN \) scattering will exist in both elastic and quasielastic \( pd \) scattering. We omit the discussion of the deuteron charge-exchange process \( (d \rightarrow pp) \) having a negligible cross section.

The total contribution of the weak interaction to the amplitude of elastic scattering of the polarized proton by the polarized deuteron, \( T_{W}^{pd}(q_\perp) \), including all absorption corrections, has the form

\[
T_{W}^{pd}(q_\perp) = \delta_{\lambda_p, \lambda_d} F_{W}(q_\perp) + I_{W}(q_\perp)
\]

\[
- i \frac{1}{2} \int \frac{d^2 q_\perp'}{(2\pi)^2} \tau_s(q_\perp') F_{D}(q_\perp', 2)
\]

\[
- \frac{1}{2} \int \frac{d^2 q_\perp'}{(2\pi)^2} \tau_s(q_\perp'^2) F_{D}(q_\perp', 2) \tau_s(q_\perp'^2) F_{D}(q_\perp', 2)
\]

\[
\times \mathcal{F}_{\lambda_p, \lambda_d}(q_\perp + q_\perp') F_D(q_\perp'), \quad (10)
\]

The leading \( P \)-odd contribution \( \sigma_{W,el}^{pd} \) to the elastic scattering cross section is

\[
\sigma_{W,el}^{pd} = \int \frac{d^2 q_\perp}{8\pi^2} \text{Re} \left[ t_s^{pd}(q_\perp) \mathcal{F}_{\lambda_p, \lambda_d}(q_\perp) \right] \approx -\frac{\epsilon \sigma_{s,tot}^{pd}}{4\pi^2}
\]

\[
\times \int \frac{d^2 q_\perp}{8\pi^2} \text{exp}(-Bq_\perp^2) \mathcal{F}_{\lambda_p, \lambda_d}(q_\perp) F_{D}(q_\perp)/2.
\]

In the case of the scattering of the polarized proton by the unpolarized deuteron, \( \mathcal{F}_{\lambda_p, \lambda_d}(q_\perp) \) given by Eq. (10) with \( \lambda_d = 0 \) should be used, whereas \( \mathcal{F}_{\lambda_p, \lambda_d}(q_\perp) \) with \( \lambda_p = 0 \) should be used for the scattering of the polarized deuteron by the unpolarized proton.

Following the Franco–Glauber technique [32, 33], it is easy to obtain the \( P \)-odd correction to the cross section for quasielastic \( pd \) scattering. Omitting the details of calculations, we only state that the sum of elastic \( (\sigma_{W,el}^{pd}) \) and quasielastic \( (\sigma_{W,qel}^{pd}) \) \( P \)-odd scattering cross sections coincides with the correction \( \sigma_{W,tot}^{pd} \) to the total \( pd \) scattering cross section, which can be determined from the amplitude (10) using the optical theorem:

\[
\sigma_{W,tot}^{pd} = -\frac{\epsilon \sigma_{s,tot}^{pd}}{8\pi^2}
\]

\[
\times \int \frac{d^2 q_\perp}{8\pi^2} \text{exp}(-Bq_\perp^2/2) \mathcal{F}_{\lambda_p, \lambda_d}(q_\perp)|l + F_D(q_\perp)|.
\]

As in the case of inelastic \( pN \) scattering, \( P \)-odd asymmetry in inelastic \( pd \) scattering, where mesons are produced, is suppressed.

We now pass from the qualitative discussion to numerical estimates of the cross sections and corresponding asymmetries \( \mathcal{A} = \sigma_{W}/\sigma_{s} \) in the scattering of the polarized deuteron with \( \lambda_d = 1 \) by the unpolarized proton. Using the formulas obtained above, we find

\[
\sigma_{s,tot}^{pd} = 96 \text{ mb}, \quad \sigma_{W,tot}^{pd} = 2.1 \text{ nb}, \quad \mathcal{A}_{tot}^{pd} = 2 \times 10^{-8},
\]

\[
\sigma_{s,el}^{pd} = 20 \text{ mb}, \quad \sigma_{W,el}^{pd} = 0.7 \text{ nb}, \quad \mathcal{A}_{el}^{pd} = 3.5 \times 10^{-8},
\]

\[
\sigma_{s,qel}^{pd} = 22.4 \text{ mb}, \quad \sigma_{W,qel}^{pd} = 1.4 \text{ nb}, \quad \mathcal{A}_{qel}^{pd} = 6 \times 10^{-8}.
\]

For the interaction of the polarized proton with \( \lambda_p = 1 \) with the unpolarized deuteron, we have

\[
\sigma_{W,tot}^{pd} = -0.8 \text{ nb}, \quad \mathcal{A}_{tot}^{pd} = -0.9 \times 10^{-8},
\]

\[
\sigma_{W,el}^{pd} = -0.6 \text{ nb}, \quad \mathcal{A}_{el}^{pd} = -3 \times 10^{-8},
\]

\[
\sigma_{W,qel}^{pd} = -0.2 \text{ nb}, \quad \mathcal{A}_{qel}^{pd} = -8 \times 10^{-8}.
\]

The difference in signs and magnitudes of asymmetries is associated with a significant difference in the dependence of \( \mathcal{F}_{\lambda_p, \lambda_d}(q_\perp) \) on \( q_\perp \) for polarized protons and deuterons (see Fig. 1).
Since the $P$-odd Hamiltonian of the weak $pp$ interaction is determined by the radiative correction caused by the strong interaction, which is calculated with a low accuracy, the behavior of $\mathcal{T}$ shown in Fig. 1 can be considered only as qualitative. Two important conclusions follow from the presented estimates. First, in view of the expected $P$-odd asymmetry, the experiment on the scattering of polarized deuterons by unpolarized protons is favorable. It is also preferable for controlling the polarization of particles stored in the accelerator, since deuterons have no spin resonances in the NICA energy range, whereas protons have numerous spin resonances. Second, because of the magnitude of the expected asymmetry, it is preferable to separate elastic and quasielastic $pd$ scattering. Here, we briefly comment on the ongoing analysis of the attractive possibilities of using an internal hydrogen jet target, which is performed by the authors of [25], supported by the Russian Foundation for Basic Research (project no. 18-02-40092 MEGA).

When using a jet target (see, e.g., [27]), to detect elastic scattering, it is sufficient to measure the momentum transfer to the recoil proton, which is uniquely related to its scattering angle $\theta = q_\perp (2 m_p)$. The dissociation of a relativistic deuteron with $\gamma > 1$ into an $np$ pair with the excitation energy $\gamma^*$ makes an additional contribution to the longitudinal momentum of recoil protons, $\Delta q_\perp = \gamma^*/\gamma$, which increases the scattering angle $\theta$. In this case, the distribution in the transverse momentum of recoil protons is also broadened compared to purely elastic scattering. This makes it possible to detect quasielastic events with simultaneous discrimination of pion production events when $\gamma^* > m_\pi$.

CONCLUSIONS

To summarize, the effects of parity violation in the scattering of protons by deuterons at NICA energies have been analyzed. Using the Glauber approach, we have estimated the weak-interaction corrections to the total, elastic, inelastic, and dissociation cross sections in $pd$ scattering, as well as the corresponding spin asymmetries (see Eqs. (13) and (14)). According to our results, experiments on the scattering of polarized deuterons by unpolarized protons are preferable. This circumstance is particularly important because the acceleration of relativistic polarized deuterons is simpler than the acceleration of polarized protons. The results obtained should be taken into account when planning experiments at NICA.

ACKNOWLEDGMENTS

We are grateful to I.A. Koop and Yu.M. Shatunov for stimulating discussions.

FUNDING

This work was supported by the Russian Foundation for Basic Research (project no. 18-02-40092 MEGA).

REFERENCES

1. Y. G. Abov, P. A. Krupchitsky, and Y. A. Oratovsky, Phys. Lett. 12, 25 (1964).
2. V. M. Lobashov, D. M. Kaminier, G. I. Kharkevich, V. A. Kniazkov, N. A. Lozovoy, V. A. Nazarenko, L. F. Sayenko, L. M. Smotritsky, and A. I. Yegorov, Nucl. Phys. A 197, 241 (1972).
3. S. Gardner, W. C. Haxton, and B. R. Holstein, Ann. Rev. Nucl. Part. Sci. 67, 69 (2017).
4. V. Brown, E. Henley, and F. Krejs, Phys. Rev. C 9, 935 (1974).
5. E. M. Henley and F. R. Krejs, Phys. Rev. D 11, 605 (1975).
6. V. B. Kopeliovich and L. L. Frankfurt, JETP Lett. 22, 295 (1975).
7. L. L. Frankfurt and V. B. Kopeliovich, Nucl. Phys. B 103, 360 (1976).
8. B. Desplanques, J. Donoghue, and B. Holstein, Ann. Phys. (N.Y.) 124, 449 (1980).
9. L. L. Frankfurt and M. I. Strikman, Phys. Lett. B 107, 99 (1981).
10. A. Barroso and D. Tadić, Nucl. Phys. A 364, 194 (1981).
11. T. Oka, Prog. Theor. Phys. 66, 977 (1981).
12. G. Nardulli and G. Preparata, Phys. Lett. B 117, 445 (1982).
13. B. G. Zakharov, Sov. J. Nucl. Phys. 39, 793 (1984).
14. B. G. Zakharov, Sov. J. Nucl. Phys. 42, 479 (1985).
15. T. Goldman and D. Preston, Nucl. Phys. B 217, 61 (1983).
16. J. M. Potter, J. D. Bowman, C. F. Hwang, J. L. McKibben, R. E. Mischke, D. E. Nagle, P. G. Debrunner, H. Frauenfelder, and L. B. Sorensen, Phys. Rev. Lett. 33, 1307 (1974).
17. D. E. Nagle, J. D. Bowman, C. Hoffman, J. McKibben, R. Mischke, J. M. Potter, H. Frauenfelder, and L. Sorensen, AIP Conf. Proc. 51, 224 (1979).

18. R. Balzer, R. Henneck, C. Jacquemart, J. Lang, M. Simonius, W. Haebler, C. Weddigen, W. Reichart, and S. Jaccard, Phys. Rev. Lett. 44, 699 (1980).

19. N. Lockyer, T. A. Romanowski, J. D. Bowman, C. M. Hoffman, R. E. Mischke, D. E. Nagle, J. M. Potter, R. L. Talaga, E. C. Swallow, D. M. Alde, D. R. Moffett, and J. Zyskind, Phys. Rev. D 30, 860 (1984).

20. V. Yuan, H. Frauenfelder, R. W. Harper, J. D. Bowman, R. Carlini, D. W. Macarthur, R. E. Mischke, D. E. Nagle, R. L. Talaga, and A. B. Mcdonald, Phys. Rev. Lett. 57, 1680 (1986).

21. P. D. Eversheim, W. Schmitt, S. Kuhn, F. Hinterberger, P. von Rossen, J. Chlebek, R. Gebel, U. Lahr, B. von Przeworski, M. Wiemer, and V. Zell, Phys. Lett. B 256, 11 (1991).

22. A. R. Berdoz, J. Birchall, J. B. Bland, et al., Phys. Rev. C 68, 034004 (2003).

23. V. D. Kekelidze, R. Lednicky, V. A. Matveev, I. N. Meshkov, A. S. Sorin, and G. V. Trubnikov, in Proceedings of the 3rd Large Hadron Collider Physics Conference LHCP 2015 (2016), p. 565.

24. I. A. Savin, A. Efremov, D. Peshekhanov, A. Kovalenko, O. Teryaeva, O. Shevchenko, A. Nagajcev, A. Guskov, V. Kukhtin, and N. Topilin, EPJ Web Conf. 85, 02039 (2015).

25. I. A. Koop, A. I. Milstein, N. N. Nikolaev, A. S. Popov, S. G. Salnikov, P. Yu. Shatunov, and Yu. M. Shatunov, Phys. Part. Nucl. Lett. 17, 154 (2020).

26. A. I. Milstein, N. N. Nikolaev, and S. G. Salnikov, JETP Lett. 111, 197 (2020).

27. A. Bujak, P. Devensky, A. Kuznetsov, B. Morozov, V. Nikitin, P. Nomokonov, Yu. Pilipenko, V. Smirnov, E. Jenkins, E. Malamud, M. Miyajima, and R. Yamada, Phys. Rev. D 23, 1895 (1981).

28. J. Ryckebusch, D. Debruyne, P. Lava, S. Janssen, B. van Overmeire, and T. van Cautere, Nucl. Phys. A 728, 226 (2003).

29. A. Sibirtsev, J. Haidenbauer, H.-W. Hammer, S. Krewald, and U.-G. Meissner, Eur. Phys. J. A 45, 357 (2010).

30. W. Ford and J. W. van Orden, Phys. Rev. C 87, 014004 (2013).

31. R. J. Glauber, Phys. Rev. 100, 242 (1955).

32. V. Franco and R. J. Glauber, Phys. Rev. 142, 1195 (1966).

33. R. J. Glauber and V. Franco, Phys. Rev. 156, 1685 (1967).

Translated by R. Tyapaev