Photoproduction of ω mesons off nuclei and impact of polarization on the meson-nucleon interaction

E. Chudakov, S. Gevorkyan, and A. Somov

Phys. Rev. C **93**, 015203 — Published 25 January 2016

DOI: 10.1103/PhysRevC.93.015203

Photoproduction of ω mesons off nuclei and impact of polarization on meson-nucleon interaction*

E. Chudakov,[1,†] S. Gevorkyan,[2,‡] and A. Somov[1,§]

[1] *Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA*

[2] *Joint Institute for Nuclear Research, 141980 Dubna, Russia*

(Dated: December 27, 2015)

Abstract

We use photoproduction of ω mesons off complex nuclei to study interactions of transversely and longitudinally polarized vector mesons with nucleons. Whereas the total cross section for interactions of the transversely polarized vector mesons with nucleons $\sigma_T = \sigma(V_T N)$ can be obtained from coherent photoproduction, measurements of vector meson photoproduction in the incoherent region provide a unique opportunity to extract the yet unmeasured total cross section for longitudinally polarized mesons $\sigma_L = \sigma(V_L N)$. The predictions for the latter strongly depend on the theoretical approaches. This work is stimulated by the construction of the new experiment GlueX at Jefferson Lab, designed to study the photoproduction of mesons in the beam energy range between 5 GeV and 12 GeV.

PACS numbers: 21.65.Jk, 24.10.Ht, 24.70.+s, 25.20.-x

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

† gen@jlab.org

‡ gevs@jlab.org

§ somov@jlab.org

I. INTRODUCTION

For particles with nonzero spin, such as vector mesons V (ρ, ω, φ), interactions with nucleons are represented by a set of polarization-dependent amplitudes and can result in different cross sections for transversely and longitudinally polarized vector mesons with nucleons. The meson-nucleon cross sections can be extracted by measuring the absorption of mesons in production off nuclei. We study the feasibility to measure the total cross sections for interactions of transversely and longitudinally polarized vector mesons with nucleons in the coherent and incoherent photoproduction of mesons off nuclei. The coherent photoproduction is described by the $\gamma A \to VA$ process, where the nucleus A remains in its ground state. The incoherent production is given by the $\gamma A \to VA'$ reaction, where A' denotes the target excitation or its break-up products.

The first indication that interaction of a vector meson V (ρ, ω, φ) with a nucleon can depend on the meson polarization comes from the ρ electroproduction data. The ratio of production cross sections for a proton target can be represented as $R = \sigma(\gamma_L p \to \rho_L p)/\sigma(\gamma_T p \to \rho_T p) = \xi^2 \frac{Q^2}{m_\rho^2}$, where the parameter ξ corresponds to the ratio of the longitudinal to transverse ρ^0 total cross sections $\xi = \sigma_L(\rho p)/\sigma_T(\rho p)$. The value of ξ obtained from measurements is $\xi \approx 0.7$ [1], while the naive quark model predicts equal cross sections $\sigma_L(\rho p) = \sigma_T(\rho p)$.

The calculations of the valence quark distribution in hadrons based on the generalized QCD sum rules technique [2, 3] suggests that the meson polarization can impact interactions with nucleons. In this approach the valence quarks distribution in transversely and longitudinally polarized vector mesons are significantly different. In the longitudinally polarized vector meson 80% of the momentum is carried by valence quarks, leaving only about 20% of the momentum for gluons and sea quarks, which are responsible for strong interactionss [3]. This results in a dependence of interactions on meson polarization. According to recent calculations [4, 5], light-cone wave functions of the ρ meson computed in the AdS/QCD approach [6] have significantly different dependence on the light cone momentum for longitudinal and transverse polarizations, which would lead to different interactions of polarized mesons with nucleons [7].

Dependence of vector particle interactions on the particle's polarization has been known for many years in the case when the constituents of the particle are in the D-wave state. A good example of such effect is the deuteron interaction with matter [8]. The D-wave component in the deuteron wave function leads to different absorption in matter for transversely and longitudinally polarized deuterons. This effect was experimentally measured and described in Ref. [9]. There are also predictions that the interaction of mesons with nonzero orbital momentum with nucleons is strongly correlated with the meson polarization [10, 11]. For the ground-state S-wave vector mesons (ρ, ω, φ) the D-wave component in their wave functions can emerge as a result of the Lorentz transformation [12].

The only attempt to study the impact of the vector meson polarization on its absorption was made many years ago [13] using the charge exchange reaction $\pi^- + A \to \rho^0 + A'$. Incoherent cross sections and polarizations of ρ mesons were measured for different nuclear targets. At first glance the experimental data supported the assumption that $\sigma_T(\rho N) = \sigma_L(\rho N)$. However, there are reasons against such a conclusion. It was shown [14] that due to the low energy of the primary beam ($E_\pi = 3.7$ GeV) and the large decay width of the ρ meson some mesons decay inside the nucleus, which complicated the interpretation of the experimental data.

II. PHOTOPRODUCTION OF ω MESONS

In the early 70's many experiments were carried out to study photoproduction of vector mesons on nuclei [1]. These experiments had two main goals:

- Extraction of vector meson-nucleon total cross sections $\sigma(VN)$ in order to check quark model predictions.
- Verification of the vector dominance model (VDM) and finding the limits of its validity.

The first ω photoproduction experiments at high energies using a large set of nuclei were carried out by the Rochester group at Cornell [16, 17] and the Bonn-Pisa group at DESY [18]. The mean photon energies used at Cornell were 6.8 GeV and 9.0 GeV. The ω mesons were detected via the 3π decay mode. The Bonn-Pisa group used beam photons with a mean energy of 5.7 GeV. The ω mesons were reconstructed using the $\pi^0\gamma$ decay mode. Both experiments confirmed the quark model prediction: $\sigma(\omega N) = \sigma(\rho N) = (\sigma(\pi^+ N) + \sigma(\pi^- N))/2$, but the measured value of the photon-omega coupling constant $\frac{f_\omega^2}{4\pi}$ was much higher than the storage ring results and SU(3) predictions [1]. A later experiment at a mean energy of 3.9 GeV was performed at the electron synchrotron NINA at Daresburry [19]. The nuclear absorption of ω mesons was found to be in agreement with the previous experiments. The value of $\frac{f_\omega^2}{4\pi}$ extracted from the experimental data was consistent with the predictions of SU(3) although with large experimental errors. The discrepancies in the measured value of the coupling constant were still not resolved. The total cross section $\sigma(\omega N)$ was extracted from the coherent part of the photoproduction cross section, whereas the incoherent part was considered to be a background.

Recently, the photoproduction of omega mesons was measured at the CBELSA/TAPS [20] experiment via the decay $\omega \to \pi^0\gamma$ and at the E01-112 experiment at Jefferson Lab [22] using the rare electromagnetic decay $\omega \to e^+e^-$. The main goal was to investigate the impact of the nuclear environment on the vector mesons mass, decay width, and meson absorption. In order to have a significant fraction of the mesons decay in the nuclei, the energies of the detected mesons were restricted to 1-2 GeV, where the large contribution from nucleon resonances complicates the interpretation of experimental results [23]. The E01-112 experiment observed a significantly stronger absorption of the ω meson than that measured by the CBELSA/TAPS collaboration. Both experiments obtained a relatively large in-medium width of ω mesons, which disagrees with measurements of the KEK-E325 experiment [21], where ω mesons were produced using a 12 GeV proton beam. The KEK-E325 collaboration also reported the ω-meson mass shift, which is not confirmed by the CBELSA/TAPS and E01-112 experiments. Disagreements between the experimental measurements are not fully understood.

In all these experiments no attempt was done to separate absorption of transversely and longitudinally polarized omega mesons. This effect can potentially be studied using the GlueX detector in Hall D [24], the new experimental facility constructed at Jefferson Lab. The Hall D facility provides a photon beam produced by 12 GeV electrons using the bremsstrahlung process. The experiment will allow to study photoproduction of mesons by reconstructing both neutral and charged final states in the beam energy range between 5 GeV and 12 GeV. Photoproduction of ω mesons on nuclear targets in the GlueX kinematic region is a unique way to study the dependence of the strong interaction on the polarization of vector mesons. The reasons are as follows:

- Photoproduction of ω mesons on nucleons $\gamma N \to \omega N$ at the photon energies of several GeV is determined by t-channel Pomeron exchange (diffraction, natural parity exchange) and one-pion-exchange (unnatural parity exchange). The pion exchange leads to production of longitudinally polarized ω mesons, unlike the diffraction process, which results in the production of transversely polarized mesons due to s-channel helicity conservation. The contributions from the diffraction and pion exchange are almost equal at a photon energy of $E_\gamma = 5$ GeV [1]. Measuring the ω meson production at different energies would provide data samples with different contributions of the longitudinally polarized ω mesons.

- In the coherent photoproduction the unnatural exchange part of the elementary amplitude cancels out since in the coherent processes the amplitudes for interactions with protons and neutrons are added with the opposite signs. Therefore, from the coherent photoproduction one can extract only the total cross section of transversely polarized vector mesons on nucleons.

- In the incoherent photoproduction the cross section on the nucleus is the sum of the photoproduction cross sections on individual nucleons. As a result ω mesons with both polarizations can be produced [1]. This can be used to study the interaction of longitudinally polarized vector mesons with matter [15].

The coherent and incoherent photoproduction of ω mesons will be described in Section 3 and Section 4.

III. COHERENT PHOTOPRODUCTION

Coherent photoproduction of vector mesons on nuclear targets

$$\gamma + A \to V + A \tag{1}$$

has been studied for many years and is well described by Glauber multiple scattering theory [1]. The invariant momentum transfer q in the process (1) can be expressed through the minimum longitudinal momentum q_L and the two dimensional transverse momentum $\vec{q}_\perp$

[1] In this paper we define the polarization in the helicity reference frame.

defined as:

$$t \equiv (k-p)^2 \simeq -(\frac{m_V^2}{2k})^2 - 4|\vec{k}|\ |\vec{p}|\ \sin^2\frac{\theta}{2} \quad \text{for} \quad M_A \gg k \gg m_V$$
$$q_L^2 \equiv -(\frac{m_V^2}{2k})^2$$
$$\vec{q}_\perp{}^2 \equiv -4|\vec{k}|\ |\vec{p}|\ \sin^2\frac{\theta}{2}, \tag{2}$$

where k and p are the momenta of the beam photon and the vector meson, respectively, m_V is the meson mass, and M_A is the mass of the nucleus. For the coherent reaction the nuclear target remains in the ground state after the meson is produced. The production amplitude of the vector meson with helicity $\lambda = 0, \pm 1$ on the nucleus can be presented as

$$F^\lambda(q_\perp, q_L) = f_N^\lambda(0)\ F_A^\lambda(q_\perp, q_L)$$
$$F_A^\lambda(q_\perp, q_L) = \int d^2b\ dz\ e^{i(q_L z + \vec{q}_\perp \vec{b})}\ \rho(b,z)\ \exp\{-\frac{\beta^\lambda}{2}\int_z^\infty dz'\ \rho(b,z')\} \tag{3}$$

Here $f_N^\lambda(0)$ is the diffractive part of the photoproduction amplitude of the vector meson on the nucleon in the forward direction ($\theta = 0$), $F_A^\lambda(q_\perp, q_L)$ is the nuclear form factor modified by the meson absorption, and $\vec{b}$ is the impact parameter. The nucleon density $\rho(b,z)$ is normalized to the atomic weight $\int \rho(b,z) d^2b dz = A$. The complex parameter $\beta^\lambda = \sigma_V^\lambda(1 - i\alpha_V^\lambda)$ is related to the total meson-nucleon cross section σ_V^λ and the ratio of the real to imaginary parts of the forward meson-nucleon scattering amplitude α_V^λ.

The coherent amplitude represents a sum of photoproduction amplitudes on individual nucleons. For isoscalar nuclei, the contribution to the coherent process from pion exchange can be neglected because the interaction amplitudes of a particle with isotopic spin one with protons and neutrons have the opposite signs and cancel out[2]. The coherent production is dominated by the Pomeron exchange mechanism, where the photon helicity is preserved at small momenta transfer (s-channel helicity conservation), i.e., transverse photons ($\lambda = \pm 1$ in the helicity frame) produce only transversely polarized vector mesons. The differential cross section of the coherent process can be written as follows:

$$\rho_{\lambda\lambda'}^A \frac{d\sigma_A}{dt} = \rho_{\lambda\lambda'} f_N^{*\lambda}(0) f_N^{\lambda'}(0) F_A^{*\lambda}(q_\perp, q_L) F_A^{\lambda'}(q_\perp, q_L), \tag{4}$$

where $\rho_{\lambda\lambda'}^A, \rho_{\lambda\lambda'}$ are vector meson spin density matrix elements for production on nuclei and nucleons, respectively. Using the relation between the diagonal elements of the spin density

[2] For nuclei with unequal numbers of protons and neutrons, small corrections can be taken into account.

matrix $\rho_{00} + \rho_{11} + \rho_{-1-1} = 1$ we obtain the well known expression [1] for the coherent photoproduction of vector mesons:

$$\frac{d\sigma_A}{dt} = | \; F_A(q_\perp, q_L, \sigma_T) \; |^2 \;\; \frac{d\sigma_N}{dt}\bigg|_{t=0} \tag{5}$$

The study of the coherent photoproduction of ω mesons allows one to obtain the cross section of interactions of transversely polarized ω mesons with nucleons[3] σ_T and to determine the ω photoproduction cross section on nucleons at zero angle for natural parity exchange, $\frac{d\sigma_N}{dt}\big|_{t=0}$, which can be expressed in the vector dominance model as

$$\frac{d\sigma_N}{dt}\bigg|_{t=0} = \frac{4\pi}{\gamma_\omega^2}\frac{\alpha}{64\pi}\sigma_\omega^2(1+\alpha_\omega^2), \tag{6}$$

where $\frac{\gamma_\omega^2}{4\pi}$ is the ω - photon coupling constant, α is the fine structure constant, σ_ω is the total $\sigma(\omega N)$ cross section, and α_ω is the ratio of the real to imaginary parts of the $\omega N \to \omega N$ amplitude.

The cross section $\frac{d\sigma_N}{dt}\big|_{t=0}$ can be independently measured in ω photoproduction on nucleons using linearly polarized photons [26]. The photon polarization allows one to distinguish contributions from natural and unnatural parity exchange production mechanisms. The beam of polarized photons used by the GlueX experiment will provide an opportunity to measure the photoproduction cross section $\frac{d\sigma_N}{dt}\big|_{t=0}$ of ω mesons on both nuclei and nucleons and consequently to extract the ω - photon coupling constant. GlueX results are expected to help to sort out the contradictions in the measurements of the photon - omega coupling constant by the previous experiments and the SU(3) symmetry predictions [16, 18, 19, 27].

IV. INCOHERENT PHOTOPRODUCTION

We consider photoproduction of ω mesons with different polarizations on nuclei in the reaction

$$\gamma + A \to \omega + A', \tag{7}$$

where A' denotes the nuclear target excitation or the target break-up products. The incoherent photoproduction can be measured in the typical momentum transfer range 0.1 $\text{GeV}^2 <$

[3] The authors of the work [18] used an angular distribution $1+\cos^2\theta$ for the decay mode $\omega \to \pi^0\gamma$ assuming the transverse polarization of ω mesons in both coherent and incoherent photoproduction. This assumption is, strictly speaking, correct only for the coherent photoproduction.

$|t| < 0.5$ GeV^2, where the Glauber multiple scattering theory can be applied[4]. Two approaches based on the Glauber multiple scattering theory can be used to describe incoherent photoproduction.

• The first model has been known for many years [28] and was widely used [18, 30, 31]. In this model, ω mesons are produced on a nucleon with the momentum transfer q and subsequently interact with the nuclear medium. We generalized this approach to account for potentially different absorptions of transversely and longitudinally polarized mesons. The cross section of the process (7) can be written as:

$$\frac{d\sigma_A(q)}{dt} = \frac{d\sigma_0(q)}{dt}(\rho_{00}N(\sigma_L) + (1-\rho_{00})N(\sigma_T))$$
$$N(\sigma) = \int \frac{1-\exp(-\sigma\int\rho(b,z)dz)}{\sigma}d^2b, \tag{8}$$

where $d\sigma_0(q)/dt$ is the differential cross section of the ω meson photoproduction on nucleon, $\sigma_{T,L}$ is the total ω-nucleon cross section for longitudinally and transversely polarized mesons, and ρ_{00} is the ω meson spin density matrix element corresponding to the fraction of longitudinally polarized ω mesons. If $\sigma_T = \sigma_L$ the nuclear transparency has the well known form $A_{\text{eff}} = \frac{d\sigma_A}{dt}/\frac{d\sigma_0(q)}{dt} = N(\sigma)$. Spin density matrix elements for photoproduction on nuclei ρ^A_{00} and nucleons ρ_{00} are related as

$$\rho^A_{00} = \frac{N(\sigma_L)}{\rho_{00}N(\sigma_L) + (1-\rho_{00})N(\sigma_T)}\rho_{00} \tag{9}$$

For $\sigma_T = \sigma_L$, $\rho^A_{00} = \rho_{00}$. For $\sigma_T \neq \sigma_L$, ρ^A_{00} depends on the nuclear mass number A.

• A second approach to characterize incoherent photoproduction takes into account the interference of two amplitudes in the photoproduction process: production of a vector meson on one of the nucleons in the nucleus and production of the vector meson on the nucleon in the forward direction with subsequent scattering of the meson on another nucleon acquiring transverse momentum [29]. A similar interference effect takes place in incoherent electroproduction of vector mesons and has to be taken into account in the studies of color transparency, i.e., weakening of vector meson absorption in nuclei with the increase of the mass of the virtual photon Q^2. Studies of the color transparency are complicated by the dependence

[4] At smaller momenta one has to take into account the suppression due to the exclusion principle (see e.g. [32]), while for a larger momentum transfer it is necessary to consider incoherent multiple scattering of ω mesons.

of the incoherent cross section on the energy ν via the coherence length $l_c = \frac{1}{q_L} = \frac{2\nu}{Q^2+m_V^2}$, leading to a decrease of the incoherent cross section at higher energies [34–36]. Taking ω meson polarization into account, the incoherent cross section on nuclei is given by the expression:

$$\rho^A_{\lambda\lambda'}\frac{d\sigma_A(q)}{dt} = \int d^2b\ dz\ \rho(b,z)\phi^{*\lambda}(b,z)\phi^{\lambda'}(b,z)$$
$$\phi^{\lambda}(b,z) = f^{\lambda}_p(q)\exp\{-\frac{\beta^{\lambda}}{2}\int_z^{\infty} dz'\rho(b,z')\}$$
$$-\frac{2\pi}{ik}f^{\lambda}_p(0)f^{\lambda}_s(q)\int dz'\ \rho(b,z')e^{iq_L(z'-z)}\exp\{-\frac{\beta^{\lambda}}{2}\int_{z'}^{\infty} dz''\ \rho(b,z'')\}, \tag{10}$$

where $f^{\lambda}_p(q)$ and $f^{\lambda}_s(q)$ are the amplitudes of the ω meson photoproduction on a nucleon ($\gamma N \to \omega N$) and the elastic scattering ($\omega N \to \omega N$), respectively. Assuming the same t-slopes for the elementary amplitudes $f_p(q)$ and $f_s(q)$ the incoherent cross section for the diagonal elements ($\lambda = \lambda' = 0, \pm 1$) of the spin density matrix can be written as:

$$\rho^A_{\lambda\lambda}\frac{d\sigma_A(q)}{dt} = \rho_{\lambda\lambda}\frac{d\sigma_0(q)}{dt}\int d^2b\ dz\ \rho(b,z) \mid \phi^{\lambda}(b,z) \mid^2$$
$$\phi^{0}(b,z) = \exp\{-\frac{\sigma_L}{2}\int_z^{\infty} dz'\ \rho(b,z')\}$$
$$\phi^{\pm 1}(b,z) = \exp\{-\frac{\sigma_T}{2}\int_z^{\infty} dz'\ \rho(b,z')\}$$
$$-\frac{\sigma_T}{2}\int^{z} dz'\ \rho(b,z')e^{iq_L(z'-z)}\exp\{-\frac{\sigma_T}{2}\int_{z'} dz''\ \rho(b,z'')\} \tag{11}$$

As can be seen the cross section for longitudinally polarized mesons does not depend on energy (ϕ^0 does not depend on q_L). There is no energy-dependent contribution to the production cross section from the amplitude interference effect because the photoproduction amplitude of longitudinally polarized mesons at zero angle is zero. The interference is present in the photoproduction of transversely polarized ω mesons. Similar to equations (8) and (9) the incoherent cross section and the spin density matrix element ρ^A_{00} for longitudinally polarized ω mesons can be written as

$$\frac{d\sigma_A(q)}{dt} = \frac{d\sigma_0(q)}{dt}\left(\rho_{00}N(\sigma_L) + (1-\rho_{00})W(q_L,\sigma)\right)$$
$$W(q_L,\sigma) = \int \rho(b,z) \mid \phi^{\pm 1}(b,z) \mid^2\ d^2b dz$$
$$\rho^A_{00} = \frac{N(\sigma_L)}{\rho_{00}N(\sigma_L) + (1-\rho_{00})W(q_L,\sigma_T)}\rho_{00} \tag{12}$$

In the limit of small photon energies, the term $W(q_L, \sigma_T)$ approaches $N(\sigma_T)$ from Eq.(8).

The nuclear transparency $A_{\text{eff}} = \frac{d\sigma_A}{dt} / \frac{d\sigma_0(q)}{dt}$ as a function of the mass number is presented in Fig. 1 for two photon beam energies of 5 GeV and 9 GeV. The value of the transverse ω-nucleon cross section is set to $\sigma_T(\omega N) = 26$ mb according to the measurements in coherent production [18]. We used the spin density matrix element $\rho_{00} = 0.2$ in the helicity frame as measured in photoproduction on nucleons [26]. The transparency is computed assuming the same ω-nucleon cross sections for the transversely and longitudinally polarized mesons $\sigma_L = \sigma_T = 26$ mb, and two times smaller, $\sigma_L = 13$ mb. Two boundary conditions, denoted by $A_{\text{eff}}(\infty)$ and $A_{\text{eff}}(0)$, correspond to infinite beam energy and the energy-independent nuclear transparency given by Eq. 8. The A-dependence of the density matrix element ρ^A_{00} on nuclei for $\sigma_L = 13$ mb and $\sigma_L = 26$ mb and various beam energies is shown in Fig. 2. The boundary conditions are denoted by $\rho(\infty)$ and $\rho(0)$. Fig. 3 presents the nuclear transparency A_{eff} and the density matrix element ρ^A_{00} as a function of the σ_L for the lead nucleus target. For the nuclear density we adopt the Woods-Saxon parametrization:

$$\rho(r) = \rho_0 \frac{1}{1 + \exp(\frac{r-R}{c})}, \tag{13}$$

with $R = 1.12A^{1/3}$ and c=0.545 fm.

V. SUMMARY

We discussed the motivation for ω meson photoproduction measurements on nucleons and different nuclei in the energy range 5 GeV $< E_\gamma <$ 12 GeV in the experimental Hall D at at Jefferson Lab. Coherent photoproduction of ω mesons on nuclei allows one to extract the total cross section of the interaction of transversely polarized vector mesons with nucleons $\sigma_T(\omega N)$ and to measure the vector dominance model ω-photon coupling constant. The coupling constant can be independently obtained by measuring photoproduction of ω mesons on nucleons using the Hall D beam of linearly polarized photons. These measurements should help to resolve certain inconsistencies in the results of the previous experiments and the SU(3) symmetry predictions.

Measurements of the photoproduction cross section and omega meson spin density matrix elements in the incoherent region ($|t| \geq 0.1$ GeV) will allow the determination of the total cross section of longitudinally polarized vector mesons with nucleons $\sigma_L(\omega N)$ and thus shed light on the impact of vector meson polarization on strong interactions. Availability of such measurements at different beam energies is essential to check the models of incoherent photoproduction. Neither the absorption of longitudinally polarized mesons, nor the spin density matrix elements on nuclei in photoproduction have been measured so far.

VI. ACKNOWLEDGMENTS

This work was supported by the Department of Energy. Jefferson Science Associates, LLC operated Thomas Jefferson National Accelerator Facility for the United States Department of Energy under contract DE-AC05-06OR23177. We would like to thank Stan Brodsky for helpful comments and suggestions. We are also thankful to Elton Smith and Simon Taylor for their help in preparing this paper. Sergey Gevorkyan appreciates the hospitality of Jefferson Lab where this work has been done.

[1] T. H. Bauer, R. D. Spital, D. R. Yennie and F. M. Pipkin, Rev. Mod. Phys. **50**, 261 (1978).

[2] B. L. Ioffe and A. G. Oganesian, Phys. Rev. D **63**, 096006 (2001).

[3] B. L. Ioffe, arXiv:hep-ph/0209254 (2002).

[4] J. R. Forshaw and R. Sandapen, JHEP **1011**, 037 (2010).

[5] J. R. Forshaw and R. Sandapen, Phys. Rev. Lett. **109**, 081601 (2012).

[6] G. F. de Teramond and S. J. Brodsky, Phys. Rev. Lett. **102**, 081601 (2009).

[7] S. R. Gevorkyan, in preparation.

[8] V. Franco and R. J. Glauber, Phys. Rev. Lett. **22**, 370 (1969).

[9] L. Azhgirey *et al.*, Part. Nucl., Letters **7**, 49 (2010).

[10] L. Gerland *et al.*, Phys. Rev. Lett. **81**, 762 (1998).

[11] J. Hufner *et al.*, Phys. Rev. D **62**, 094022 (2000).

[12] W. Jaus, Phys. Rev. D **44**, 2851 (1991).

[13] A. Arefyev *et al.*, Yad. Fiz. **27**, 161 (1978).

[14] A. Pak, A. V. Tarasov, Yad. Fiz. **22**, 91 (1975).

[15] S. R. Gevorkyan and A. V. Tarasov, JETP Letters **15**, 684 (1972).

[16] H. J. Behrend *et al.*, Phys. Rev. Lett. **24**, 1246 (1970).

[17] J. Abramson *et al.*, Phys. Rev. Lett. **36**, 1428 (1976).

[18] P. L. Braccini *et al.*, Nucl. Phys. B **24**, 173 (1970).

[19] T. J. Brodbeck *et al.*, Nucl. Phys. B **136**, 95 (1978).

[20] F. Dietz *et al.*, Eur. Phys. J. A **51**, 6 (2015); D. Trnka *et al.*, Phys. Rev. Lett. **94**, 192303 (2005); M. Nanova *et al.*, Phys. Rev. C **82**, 035209 (2010); M. Kotulla *et al.*, Phys. Rev. Lett. **100**, 192302 (2008).

[21] M. Naruki *et al.*, Phys. Rev. Lett. **96**, 092301 (2006).

[22] M. H. Wood *et al.*, Phys. Rev. Lett. **105**, 112301 (2010).

[23] S. Leupold, V. Metag and U. Mosel, Int. J. Mod. Phys. E **19**, 147 (2010).

[24] JLab Experiment E12-06-102, (2006) `http://www.jlab.org/exp_prog/proposals/06/PR12-06-102.pdf`.

[25] K. Schilling, P. Seyboth and G. E. Wolf, Nucl. Phys. B **15**, 397 (1970).

[26] . Ballam *et al.*, Phys. Rev. D **7**, 3150 (1973).

[27] A. Sibirtsev, K. Tsushima and S. Krewald, Phys. Rev. C **67**, 055201 (2003).

[28] C. A. Engelbrecht, Phys. Rev. **133**, B988 (1964).

[29] A. V. Tarasov, Part. Nucl., Letters **7**, 771 (1976).

[30] K. S. Kolbig and B. Margolis, Nucl. Phys. B **6**, 85 (1968).

[31] A. Sibirtsev, Ch. Elster, J. Speth arXiv:nucl-th/0203044 (2002).

[32] S. R. Gevorkyan *et al.*, Part. Nucl., Letters **9**, 18 (2012).

[33] G. Mcclellan *et al.*, Phys. Rev. Lett. **23**, 554 (1969).

[34] A. Airapetian *et al.*, Phys. Rev. Lett. **90**, 052501 (2003).

[35] B. Z. Kopeliovich, J. Nemchik, A. Schafer and A. V. Tarasov, Phys. Rev. C **65**, 035201 (2002).

[36] B. Z. Kopeliovich, J. Nemchik and I. Schmidt, Phys. Rev. C **76**, 015205 (2007).

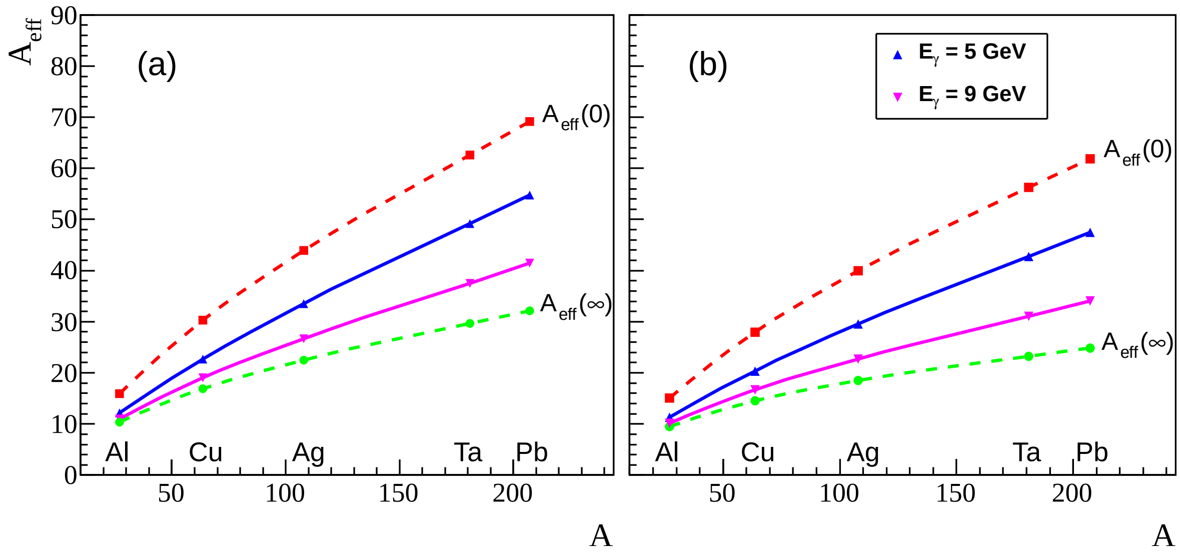

FIG. 1. Dependence of the nuclear transparency A_{eff} on the mass number for $\sigma_L = 13$ mb (left) and $\sigma_L = 26$ mb (right). A_{eff} is shown for different photon energies: $A_{\text{eff}}(\infty)$ and $A_{\text{eff}}(0)$ correspond to infinite energy and energy-independent transparency, respectively.

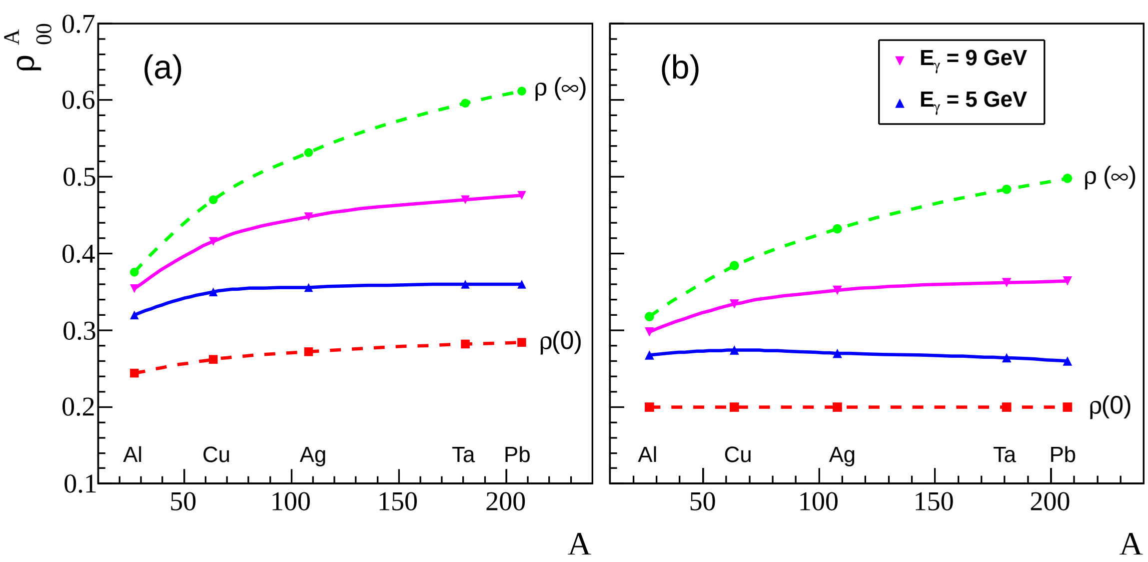

FIG. 2. A-dependence of the spin density matrix element ρ^A_{00} for $\sigma_L = 13$ mb (left) and $\sigma_L = 26$ mb (right). ρ^A_{00} is shown for different photon energies: $\rho(\infty)$ and $\rho(0)$ correspond to infinite energy and energy-independent ρ^A_{00}, respectively.

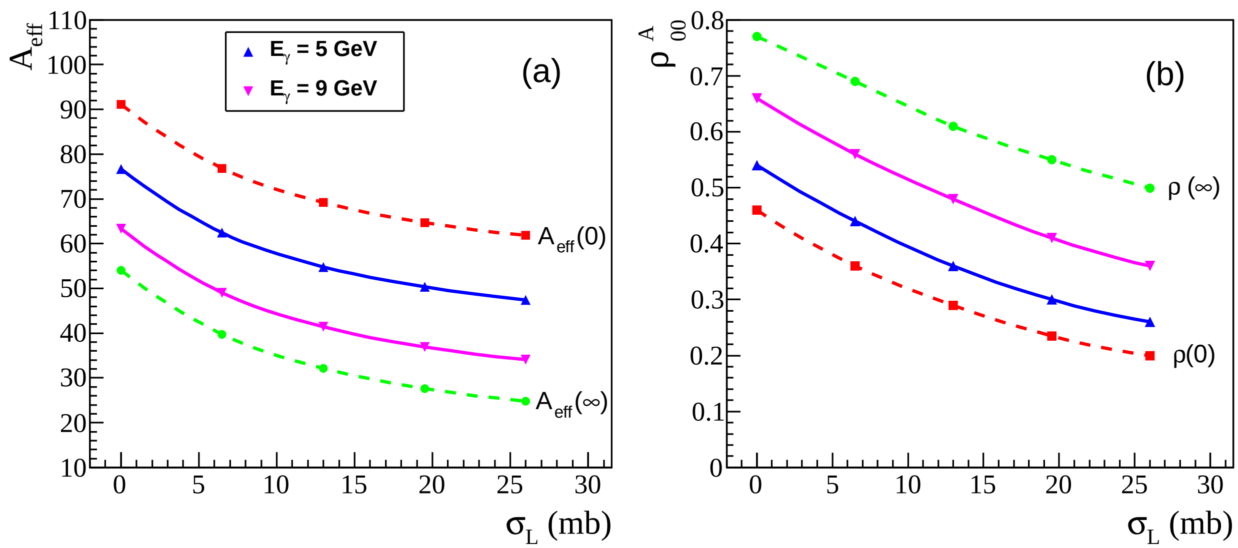

FIG. 3. The nuclear transparency A_{eff} (a) and the spin density matrix element ρ_{00}^A (b) as a function of σ_L for lead nucleus. The transverse ω-nucleon cross section σ_T and the spin density matrix element ρ_{00} are taken to be 26 mb and 0.2, respectively.