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

E. Chudakov, S. Gevorkyan, A. Somov

Abstract

We consider 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 total cross section for longitudinally polarized mesons interacting with nucleons $\sigma_L = \sigma(V_L N)$, which has not yet been measured and strongly depends on 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 a large beam energy range up to 12 GeV.

1 Introduction

Production of unstable particles off nuclei allows one to determine the total cross section of the unstable particle interaction with nucleons. For particles with nonzero spin, interactions with nucleons are defined by a set of amplitudes corresponding to the different particle polarizations.

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 $R = \sigma(\gamma_L p \to V_L p)/\sigma(\gamma_T p \to V_T p) = \xi \frac{Q^2}{m_\rho^2}$, where the parameter ξ corresponds to the ratio of 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 $\xi \approx 0.5$ [1], while the additive quark model predicts equal cross sections $\sigma_L(\rho p) = \sigma_T(\rho p)$.

Investigation 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 a longitudinally polarized vector mesons are significantly different. Eighty percent of the momentum of a longitudinally polarized vector meson is carried out by valence quarks, leaving only about 20% of the momentum for gluons and sea quarks, which are responsible for strong interactions, resulting in the possible dependence of interactions on meson polarizations [3]. Moreover, according to recent calculations [4, 5], light-cone wavefunctions of the ρ meson computed in the AdS/QCD approach [6] have significantly different behavior as a function of the fraction of the light cone momentum for longitudinal and transverse polarizations, which can 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 constituents of the particle are in the D-wave state. The vivid example of such effect is the deuteron interaction with matter [8]. An admixture of a D-wave component in the deuteron wave function leads to different absorption in the matter for transversely and longitudinally polarized deuterons. This effect was experimentally measured and described in [9]. There are also predictions that interactions of mesons with nonzero orbital momenta with nucleons are 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 when the transformation from the laboratory to the moving system is applied [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 $\pi^- + A \to \rho^0 + A'$. From the first glance it seemed that the experimental data supported the equality of the total cross sections $\sigma_T(\rho N) = \sigma_L(\rho N)$, but there are strong reasons against such conclusion. It was shown [14] that due to the insufficient 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 experimental data.

2 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.
- Verify the vector dominance model (VDM) and 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 energy used at Cornell corresponded to 6.8 GeV and 9.0 GeV and ω mesons were detected via the 3π decay mode. The Bonn-Pisa group used beam photons with a mean energy of 5.7 GeV and ω mesons were reconstructed using the $\pi^0\gamma$ decay mode. Both experiments confirmed the additive quark model prediction: $\sigma(\omega N) = \sigma(\rho N) = \sigma(\pi^+ N) + \sigma(\pi^- N)/2$, but the 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. A later experiment at a mean energy 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 previous experiments and the value of $\frac{f_\omega^2}{4\pi}$ extracted from the experimental data did not contradict to predictions of SU(3). Nevertheless due to large experimental errors, discrepancies in the measured value of the coupling constant could not be resolved. The total cross section of $\sigma(\omega N)$ was extracted from the coherent part of the photoproduction cross section, whereas the incoherent part was considered to be undesirable background.

Recently photoproduction of omega mesons was measured at ELSA [20] via the decay $\omega \to \pi^0\gamma$ and at JLab [21] using the rare electromagnetic decay $\omega \to e^+e^-$. The main goal of these experiments was to investigate the impact of the nuclear environment on the vector mesons mass and decay width. 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 [22] make the interpretation of experimental results controversial.

In these experiments no attempt was done to separate absorption of transversely and longitudinally polarized omega mesons. The effect can potentially be studied using the GlueX detector [23], the new experimental facility constructed at Jefferson Lab. GlueX will use a beam of photons produced by a 12 GeV electron beam using the bremsstrahlung process. The experiment will allow to study photoproduction of mesons by reconstructing both neutral and charged final states in the large beam energy range up to 12 GeV. Photoproduction of ω mesons on nuclear targets in the GlueX kinematic region is a unique way to obtain information on the possible 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 GeVs is determined by t-channel Pomeron exchange (diffraction, natural parity exchange) and one-pion-exchange (OPE) (unnatural parity exchange). The pion exchange leads to copious 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. Contributions from diffraction and pion exchange are almost equal at a photon energy of $E_\gamma = 5$ GeV [1]. Measuring ω meson production at different energies will provide data samples with different fractions of ω polarization.

- In the coherent photoproduction $\gamma A \to \omega A$ (the nucleus left in its ground state) the unnatural exchange part of the elementary amplitude cancels out; in the coherent processes one has to sum amplitudes from different nucleons, and the pole exchange of particles with isospin one has different sign in production on protons and neutrons. Therefore, from coherent photoproduction one can extract only the total cross section of transversely polarized vector mesons off nucleons.

- Unlike the coherent production, in the incoherent photoproduction $\gamma A \to \omega A'$ (A' stands for the target excitation or its break-up products) the cross section on the nuclei is the sum of photoproduction cross sections on nucleons. As a result ω mesons with both polarizations can be produced in the incoherent process. This can be used to study interactions 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.

3 Coherent photoproduction

Coherent photoproduction of vector mesons on nuclei 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 in the process (1) can be expressed through the longitudinal[1] momentum q_L and the two dimensional transverse momentum $\vec{q}_\perp$ as follows:

$$\begin{aligned} t = (k-p)^2 &= -q_L^2 - \vec{q}_\perp{}^2 = -(\frac{m_\omega^2}{2k})^2 - 4|\vec{k}|\,|\vec{p}|\,sin^2\frac{\theta}{2} \\ |\vec{q}_\perp| &= q, \end{aligned} \tag{2}$$

where k and p are the momenta of the beam photon and the vector meson, respectively. For a coherent reaction a nuclear target remains in the ground state after the meson is produced. The production amplitude can be presented as

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

Here $f_N^\lambda(0)$ is the diffractive part of the photoproduction amplitude of the vector meson with helicity $\lambda = 0, \pm 1$ on a nucleon, $F_A^\lambda(q, q_L)$ is the nuclear form factor[2] modified by the meson absorption, and $\vec{b}$ is the impact parameter. $\sigma'_\lambda = \sigma_\lambda(1 - i\alpha_\lambda)$ denotes a scattering amplitude of a vector meson on a nucleon at zero angle, where σ_λ is the total meson-nucleon cross section and $\alpha_\lambda = \frac{Ref_\lambda(0)}{Imf_\lambda(0)}$ is the ratio of real to the imaginary parts of the forward $VN \to VN$ amplitude. Taking helicity of the produced meson into account, the differential cross section of the coherent process can be written as follows:

$$\rho^A_{\lambda\lambda'}\frac{d\sigma_A}{dt} = \rho^N_{\lambda\lambda'}\frac{d\sigma_N(0)}{dt} F_A^\lambda(q, q_L) F_A^{\lambda'}(q, q_L), \tag{4}$$

where $\rho^A_{\lambda\lambda'}$, $\rho^N_{\lambda\lambda'}$ are vector meson spin density matrix elements for production on nuclei and nucleon, respectively. The coherent amplitude represents a sum of photoproduction amplitudes on individual nucleons. For isoscalar nuclei, the contribution to the total amplitude from pion exchange can be neglected in the coherent process because elementary amplitudes of interactions of a particle with isotopic spin one with a proton and neutron have different signs and cancel out[3]. The coherent production is dominated by a pomeron

[1]The inverse of the longitudinal momentum transfer is called the coherence length $l_c = \frac{1}{q_L}$.

[2]The nucleon density $\rho(b, z)$ is normalized on the atomic weight $\int \rho(b, z)d^2bdz = A$.

[3]For nuclei with unequal numbers of protons and neutrons, small corrections cab be easily taken into account

exchange mechanism, where the beam photon helicity is preserved at small momenta transfer (s-channel helicity conservation), i. e., transverse photons ($\lambda = \pm 1$) produce only transversely polarized vector mesons. Therefore, from coherent photoproduction one can determine solely the value of the total cross section σ_T of transversely polarized vector mesons with a nucleon. Using the relation between diagonal elements of the spin density matrix $\rho_{00} + \rho_{11} + \rho_{-1-1} = 1$ we obtain the well known expression [1] for photoproduction of vector mesons in coherent region

$$\frac{d\sigma_A}{dt} = \frac{d\sigma_N(0)}{dt} \mid F_A(q, q_L, \sigma_T) \mid^2 \tag{5}$$

Accordingly, the total cross section $\sigma(\omega N)$ extracted from the coherent photoproduction corresponds to the cross section of transversely polarized mesons with nucleons [4] In order to obtain the total cross section of longitudinally polarized ω mesons with nucleons it is necessary to consider incoherent photoproduction. Measurements of the coherent photoproduction cross section allow to extract the photon-vector meson coupling. According to the vector dominance model the production cross section for omega mesons at zero angle for natural parity exchange is

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

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 contribution of the natural parity exchange to the total cross section can also be obtained by measuring omega photoproduction on nucleons using linearly polarized photons. The beam of polarized photons used by the GlueX experiment will provide such an opportunity. Thus, subsequent measurements of the coherent omega photoproduction off nuclei and by linearly polarized photons on nucleon should help to reconcile the contradictions in the values of the photon-omega coupling constant.

[4] The authors of the work [18] used an angular distribution $1+cos^2\theta$ for the decay mode $\omega \to \pi^0\gamma$ for both coherent and incoherent photoproduction, which is strictly speaking correct only for coherent photoproduction.

4 Incoherent photoproduction

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

$$\gamma + A \rightarrow \omega + A' \tag{7}$$

where A' denotes the nuclear target excitation or the target break-up products. The momentum transfer in (7) is limited to the typical range of $0.1\ \mathrm{GeV}^2 < |t| < 0.5\ \mathrm{GeV}^2$, where the Glauber multiple scattering theory can be applied[5].

Two approaches based on the Glauber multiple scattering theory can be used to describe incoherent photoproduction. The first model was known for many years [26] and was widely used [28, 18, 29]. We generalized this approach to account for the possibility of different absorptions of transverse and longitudinally polarized mesons. The cross section of the process (7) can be written as:

$$\begin{aligned} \frac{d\sigma_A(q)}{dt} &= \frac{d\sigma_0(q)}{dt}(\rho_{00}N(0,\sigma_L) + (1-\rho_{00})N(0,\sigma_T)) \\ N(0,\sigma) &= \int \frac{1-\exp(-\sigma\int\rho(b,z)dz)}{\sigma} d^2b, \end{aligned} \tag{8}$$

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 $A_{eff} = \frac{d\sigma_A}{dt}/\frac{d\sigma_0(q)}{dt} = N(0,\sigma)$. Spin density matrix elements for photoproduction on nuclei ρ_{00}^A and nucleons ρ_{00} are related as

$$\rho_{00}^A = \frac{N(0,\sigma_L)}{\rho_{00}N(0,\sigma_L) + (1-\rho_{00})N(0,\sigma_T)}\rho_{00} \tag{9}$$

If ω-nucleon cross sections are the same $\sigma_T = \sigma_L$ the omega spin density matrix element ρ_{00}^A equals to ρ_{00}. As follows from equation (9) ρ_{00}^A depends on the nuclear mass number A for $\sigma_T \neq \sigma_L$.

Another approach to characterize incoherent photoproduction takes into account the interference of two amplitudes in the photoproduction process:

[5] At smaller momenta one has to take into account the suppression due to the exclusion principle (see e.g. [30]), while for larger momenta transfer it is necessary to consider incoherent multiple scattering of ω mesons.

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 [27]. A similar interference effect takes place in incoherent electroproduction of vector mesons and has to be taken into account in the investigation 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 of the incoherent cross section on energy via the coherence length $l_c = \frac{1}{q_L} = \frac{2\nu}{Q^2+m_V^2}$, leading to the decrease of the incoherent cross section with increasing energies [32, 33, 34].

Taking ω meson polarization into account, the relation between the incoherent cross section on nuclei and the cross section on nucleons is given by the expression:

$$\begin{aligned}
\rho^A_{\lambda\lambda'}\frac{d\sigma_A(q)}{dt} &= \int \rho(b,z)\phi^{\lambda}(b,z)\phi^{\lambda'}(b,z)d^2bdz \\
\phi^{\lambda}(b,z) &= f_p^{\lambda}(q)\exp(-\frac{\sigma_\lambda}{2}\int_z^{\infty}\rho(b,z')dz') \\
&- \frac{2\pi}{ik}f_p^{\lambda}(0)f_s(q)\int \rho(b,z')dz'e^{iq_L(z'-z)}\exp(-\frac{\sigma_\lambda}{2}\int_{z'}^{\infty}\rho(b,z'')dz''),
\end{aligned} \tag{10}$$

where $f_p^{\lambda}(q)$ and $f_s^{\lambda}(q)$ are the amplitudes of the ω meson photoproduction on a nucleon ($\gamma N \to \omega N$) and elastic scattering ($\omega N \to \omega N$), respectively. Assuming similar slopes of the elementary amplitudes $f_p(q)$ and $f_s(q)$ the incoherent cross section for diagonal elements ($\lambda = \lambda' = 0, \pm 1$) of the spin density matrix can be written as:

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

As can be seen from Eq. (11), the cross section for longitudinally polarized mesons does not depend on energy. The photoproduction amplitude of longitudinally mesons at zero angle is equal to zero. Therefore, there is no energy-dependent contribution to the production cross section from the amplitude interference effect described above; the interference is present in the photoproduction of transversely polarized ω mesons. The incoherent cross section and the spin density matrix element for the production of longitudinally polarized ω mesons can be written in forms similar to Eqs. (8) and (9) as:

$$\begin{aligned}
\frac{d\sigma_A(q)}{dt} &= \frac{d\sigma_0(q)}{dt}\left(\rho_{00}N(0,\sigma_L) + (1-\rho_{00})W(q_L,\sigma)\right) \\
W(q_L,\sigma) &= \int \rho(b,z) \mid \phi^{\pm 1}(b,z) \mid^2 d^2b dz \\
\rho_{00}^A &= \frac{N(0,\sigma_L)}{\rho_{00}N(0,\sigma_L) + (1-\rho_{00})W(q_L,\sigma_T)}\rho_{00} \qquad (12)
\end{aligned}$$

In these equations, the nuclear transparency term $W(q_L,\sigma_T)$ corresponding to transversely polarized mesons is similar to $N(0,\sigma_T)$ in Eq. (8), but contains energy-dependence due to the amplitude interference effect described above.

The nuclear transparency $A_{eff} = \frac{d\sigma_A}{dt}/\frac{d\sigma_0(q)}{dt}$ as a function of the mass number for two values of $\sigma_L = 13$ mb and $\sigma_L = 26$ mb is presented in Fig. 1. The nuclear transparency is shown for two photon beam energies from the GlueX experiment energy range of 5 GeV and 9 GeV. Two boundary conditions corresponding to infinite beam energy and the energy-independent nuclear transparency given by Eq. 8 are denoted as $A(\infty)$ and $A(0)$ on this plot. A-dependence of the density matrix element ρ_{00}^A on nuclei for $\sigma_L = 13$ mb and $\sigma_L = 26$ mb and different beam energies is shown in Fig. 2. The boundary conditions corresponding to infinite beam energy and the energy-independent ρ_{00}^A given by Eq. 9 are denoted as $\rho(\infty)$ and $\rho(0)$. Fig. 3 presents the nuclear transparency A_{eff} and the density matrix element ρ_{00}^A as a function of the σ_L for the lead nucleus target.

The value of the transverse ω-nucleon cross section in these plots is set to $\sigma_T(\omega N) = 26$ mb according to the measurements of σ_T in coherent production [18]. We used the spin density matrix element $\rho_{00} = 0.2$ in the helicity frame as measured in ω-nucleon photoproduction [25]. For the nuclear density we adopt the Woods-Saxon parametrization:

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

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

5 Conclusions

We discussed the perspectives of omega meson photoproduction measurements on different nuclei and nucleons in the energy range 5 GeV $< E_\gamma <$ 12 GeV of the GlueX detector at Jefferson Lab. The total cross section of transversely polarized vector mesons interactions with nucleon σ_T can be extracted from coherent photoproduction of omega mesons on nuclei. The beam of polarized photons used by GlueX can be used to separate the contribution to the total omega production cross section on nucleons from natural parity exchange (diffractive part) and therefore will allow to directly compare cross section measurements on nucleon and in coherent photoproduction on nuclei. Measurements of the ω-photon direct coupling constant $\frac{\gamma_\omega^2}{4\pi}$ in coherent photoproduction should help to resolve some discrepancies in the value of the coupling constant from previous experiments and as predicted by the SU(3) symmetry [16, 18, 19].

Measurements of the cross section in the incoherent region ($|t| \geq 0.1$ GeV) and omega meson spin density matrix elements will allow to determine the value of the total cross section of longitudinally polarized vector mesons with nucleons σ_L 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 models of incoherent photoproduction. Measurements of the absorption of the transversely and longitudinally polarized mesons separately, as well as measurements of the spin density matrix elements on nuclei in photoproduction have never been performed.

6 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. Sergey Gevorkyan appreciates the hospitality of Jefferson Lab where this work has been done.

References

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

[2] B.L.Ioffe, A. G. Oganesian, Phys. Rev. D63, 09606 (2001).

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

[4] J.R. Forshaw, R. Sandapen, JHEP 11,037 (2010).

[5] J.R. Forshaw, 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, R. 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.Huefner, B.Z.Kopeliovich, A. V. Tarasov, Phys. Rev. D62, 094022 (2000).

[12] W. Jaus, Phys. Rev. D44, 2851 (1991).

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

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

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

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

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

[18] P.Braccini et al. Nucl.Phys. B24, 173 (1970).

[19] T. J. Brodbeck et al., Nucl. Phys. B136,95 (1978).

[20] D.Trnka et al., Phys. Rev. Lett. 94,192303 (2005).

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

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

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

[24] K. Schilling, P. Seyboth, G. Wolf, Nucl. Phys. B15,397(1970).

[25] J. Ballam Phys. Rev. D7,3150 (1973).

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

[27] A. V. Tarasov, Phys. of Particles and Nuclei 7,771 (1976).

[28] K.S. Kolbig, B. Margolis, Nucl. Phys. B6, 85 (1968).

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

[30] S. R. Gevorkyan et al., Phys.of Particles and Nuclei Letters 9, 18 (2012).

[31] G. McClellan et al. Phys. Rev. Lett. 23,554 (1969).

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

[33] B. Z. Kopeliovich, J. Nemchik, A. Schafer,A.Tarasov Phys. Rev. C65, 035201 (2002).

[34] B. Z. Kopeliovich, J. Nemchik, I. Schmidt, Phys. Rev. C76, 015205 (2007).

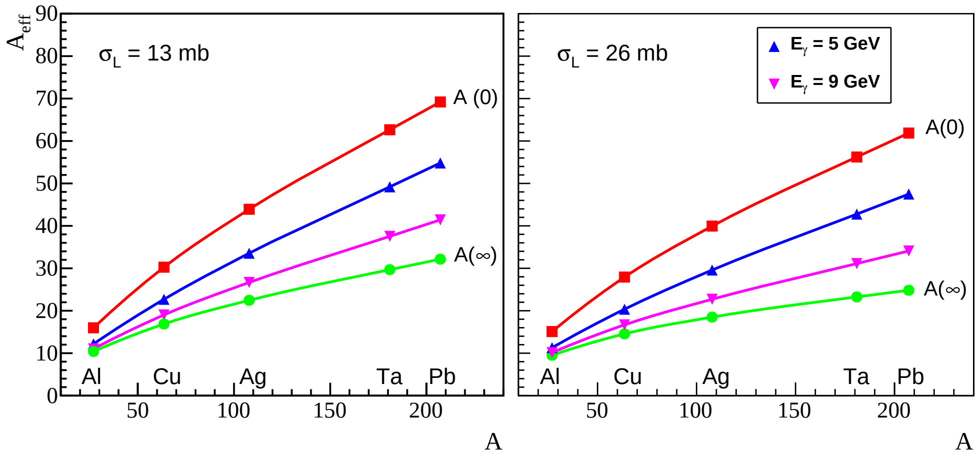

Figure 1: Dependence of the nuclear transparency A_{eff} on the mass number for $\sigma_L = 13$ mb (left) and $\sigma_L = 26$ mb (right). The dependence is shown for different energies described in the text.

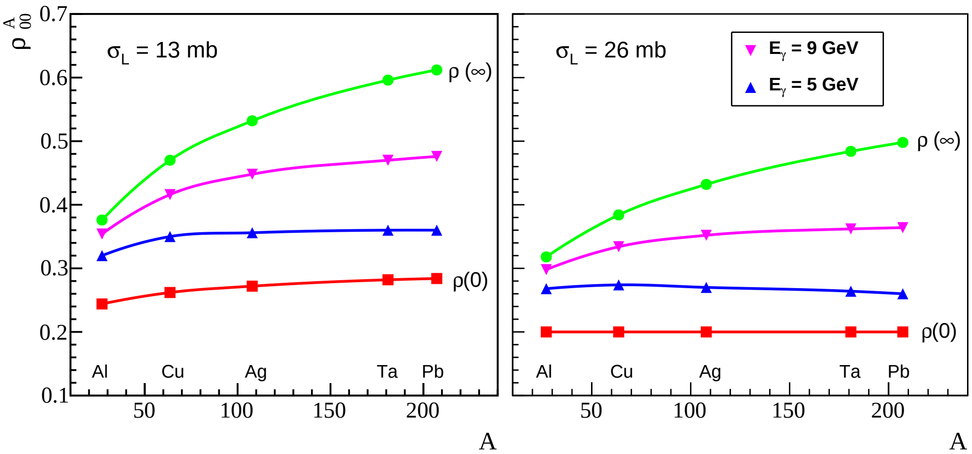

Figure 2: A-dependence of the spin density matrix element ρ_{00}^{A} for σ_L = 13 mb (left) and $\sigma_L = 26$ mb (right). The dependence is shown for different energies described in the text.

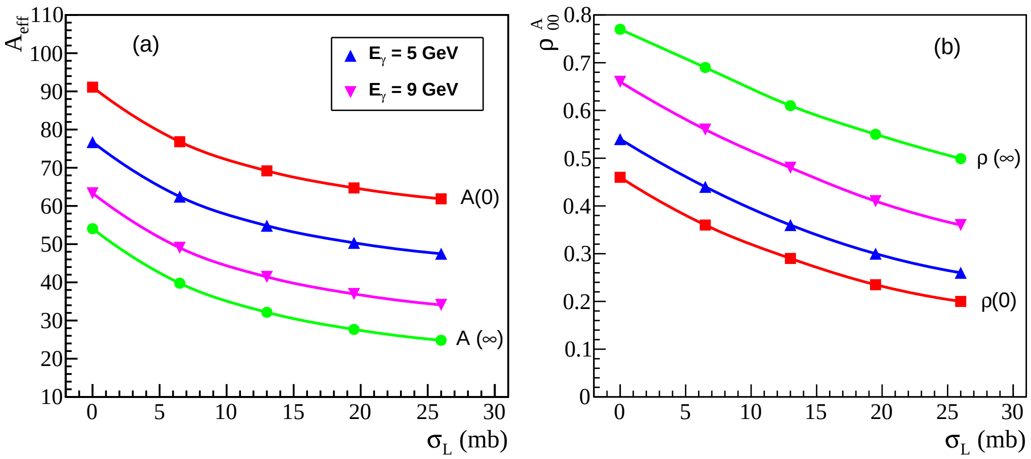

Figure 3: The nuclear transparency A_{eff} (a) and the spin density matrix element ρ_{00}^{A} (b) as a function of σ_L for lead nucleus.