

Photoproduction of vector mesons on nuclei with GlueX

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Abstract

We propose to measure the photoproduction cross sections of vector mesons on ^{12}C , ^{28}Si , ^{120}Sn , and ^{208}Pb nuclear targets for the photon beam energy range between 6 GeV and 12 GeV with the GlueX experimental setup. The energy dependence of nuclear transparency for these nuclei will be extracted and used to test the theoretical models. Existing experimental data of the photoproduction of ρ mesons do not show the predicted dependence of the nuclear transparency on energy. Our data will test this. The cross section of the longitudinally polarized ω meson with nucleons $\sigma_L = \sigma(\omega_L N)$ will be determined for the first time. This information is important for the interpretation of color transparency effects in electroproduction of vector mesons.

I. INTRODUCTION

We propose to study the photoproduction of light vector mesons with the GlueX detector using a set of nuclear targets: C, Si, Sn, and Pb. The nuclear transparency for these mesons will be measured in the large beam energy range between 6 GeV and 12 GeV and compared with predictions of the theoretical models. The primary goal of the experiment is to:

- Measure the nuclear transparency ($T = \frac{\sigma_A}{A\sigma_N}$, where σ_A and σ_N are production cross sections on nuclei and nucleon, respectively) of ω mesons in photoproduction off complex nuclei, which will be used to study interactions of transversely and longitudinally polarized ω mesons with nucleons [1]. According to measurements at SLAC [2], at GlueX energies and modest transfer momenta, longitudinally polarized ω mesons will be produced due to the pion exchange process [42]. The total cross section for interactions of the transversely polarized vector mesons with nucleons $\sigma_T = \sigma(V_T N)$ can be obtained from the coherent photoproduction. Measurements of ω meson photoproduction in the incoherent region provide a unique opportunity to extract the yet unmeasured total cross section for longitudinally polarized vector mesons $\sigma_L = \sigma(V_L N)$.

The knowledge of $\sigma_T(VN)$ and $\sigma_L(VN)$ is particularly important in the interpretation of the effect of color transparency [3] in the electroproduction of vector mesons off nuclei, manifested in the decrease of the absorption due to the decrease of the size of a photon's hadronic component with Q^2 . On the other hand, the number of longitudinally polarized vector mesons grows [4] with Q^2 and if $\sigma_T \gg \sigma_L$ color transparency screening effects

cannot completely account for the reduced absorption; some of the effect is due to the weaker absorption of longitudinally polarized vector mesons compared with the transversely polarized one. Measurement of the absorption of ω mesons in photoproduction by real photons has a certain advantage compared with the electroproduction. In the real photoproduction at modest transfer momenta $|t| \leq 1 \text{ GeV}^2$, the color transparency effect is absent. The reduced absorption will solely be a result of the difference between σ_T and σ_L .

- Measure the dependency of the nuclear transparency of light vector mesons on the beam energy. These measurements are expected to shed light on disagreements between the theoretical predictions and experimental results [5, 6]. The decrease of the nuclear transparency with energy predicted by the theory [6] was not observed in ρ [7] and π^\pm, π^0 photoproduction [8, 9].

II. PHYSICS MOTIVATION

For particles with nonzero spin, such as vector mesons $V (\rho, \omega, \phi)$, 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.

The first indication that interaction of a vector mesons $V (\rho, \omega, \phi)$ with a nucleon depends on the meson polarization comes from the ρ electroproduction data. The ratio of production cross sections for a proton target can be represented as $R = \sigma(\gamma_L p \rightarrow \rho_L p) / \sigma(\gamma_T p \rightarrow \rho_T p) = \xi^2 \frac{Q^2}{m_\rho^2}$, 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 $\xi \approx 0.7$ [10], while the naive quark model predicts equal cross sections $\sigma_L(\rho p) = \sigma_T(\rho p)$. In the case of ϕ electroproduction [11] this ratio is $\xi \approx 0.6$. Some interpretations of the deep inelastic scattering data using the generalized vector dominance model [12] also allow for the large difference between $\sigma_L(V p)$ and $\sigma_T(V p)$ ($\xi \approx 0.25$).

The 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 [13]. 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 in Dubna [14] and Juelich [15]. There are also predictions that the interaction of mesons with nonzero orbital momentum with nucleons is strongly correlated with the meson polarization [16, 17]. 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 [18]. The origin of a difference between $\sigma_T(VN)$ and $\sigma_L(VN)$ explained by the appearance of a D-wave contribution in the vector meson wave function in the infinite momentum frame.

The only attempt to study the impact of the vector meson polarization on its absorption was made many years ago at ITEP [19] using the charge exchange reaction $\pi^- + A \rightarrow \rho^0 + A'$. The incoherent cross section and polarization of ρ mesons were measured on a set of different nuclei: C, Al, Cu, Pb. Due to the dominance of the pion exchange in this process a large fraction of longitudinally polarized ρ mesons was produced. 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 [20] 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 complicates the interpretation of the experimental data.

The total cross sections of ρ and $f(1270)$ mesons with a nucleon were measured at Argonne [21] using the charge exchange process on neon nuclei $\pi^+ + Ne \rightarrow \rho(f) + Ne'$. In order to account for decays of the ρ mesons in nuclei ($p_\pi = 3.5$ GeV/c) the total cross section is required to be $\sigma(\rho N) \approx 12$ mb, which contradicts to the value $\sigma(\rho N) \approx 27$ mb obtained from the ρ meson photoproduction on nuclei. From our point of view this difference is a result of distinction between $\sigma_T(\rho N)$ and $\sigma_L(\rho N)$. In the charge exchange process mainly longitudinally polarized ρ mesons are produced, whereas in the photoproduction ρ mesons are transversely polarized.

The knowledge of the cross section $\sigma_L(VN)$ is important for interpreting the color screening effect in leptonproduction [22]. The idea of the color transparency (CT) is that an object (hadron) produced in certain hard-scattering processes has a smaller probability to interact in the nuclear matter due to its smaller size compared with the physical hadron. As a result, the color transparency increases the nuclear transparency. On the other hand, the nuclear transparency depends on the values of $\sigma_L(VN)$ and $\sigma_T(VN)$. Fig. 1 represents the dependence of the nuclear transparency in the ρ meson electroproduction as a function of the virtuality of

the photon Q^2 . The ρ meson absorption in nuclei decreases with the increase of the Q^2 , which is accounted for the CT effect. At the same time, the fraction of longitudinally polarized vector mesons also grows at large Q^2 as shown on the right plot of Fig. 1. If we assume that $\sigma_T(VN) \gg \sigma_L(VN)$, the effect of the absorption weakening at large Q^2 cannot be entirely described by the CT; differences between interactions of longitudinally and transversely polarized vector mesons with nucleon have to be considered.

The total cross sections $\sigma_T(VN)$ and $\sigma_L(VN)$ can be calculated in the framework of the color dipole model [24, 25]. The dependence of $\sigma_L(\rho N)$ and $\sigma_T(\rho N)$ on the energy $W = \sqrt{s}$ computed for different choices of the ρ meson wave functions is shown in Fig. 2 [26]. The cross sections obtained for the boosted gaussian wave function [27] are shown on the left plot and ADC/QCD holographic [28] wave function [29, 30] are presented on the right plot. The cross section $\sigma_L(\rho N)$ is predicted to be smaller than $\sigma_T(\rho N)$ for both wave functions.

Study photoproduction of ω mesons on different nuclei and beam energies provides a unique opportunity to measure energy dependence of the nuclear transparency predicted by theoretical models [1] and extract the total cross section of longitudinally polarized mesons with nucleon $\sigma_L = \sigma(\omega N)$. Unlike ρ and ϕ mesons, which due to the s-channel helicity conservation in photoproduction are produced mainly transversely polarized, the pion exchange in the ω meson

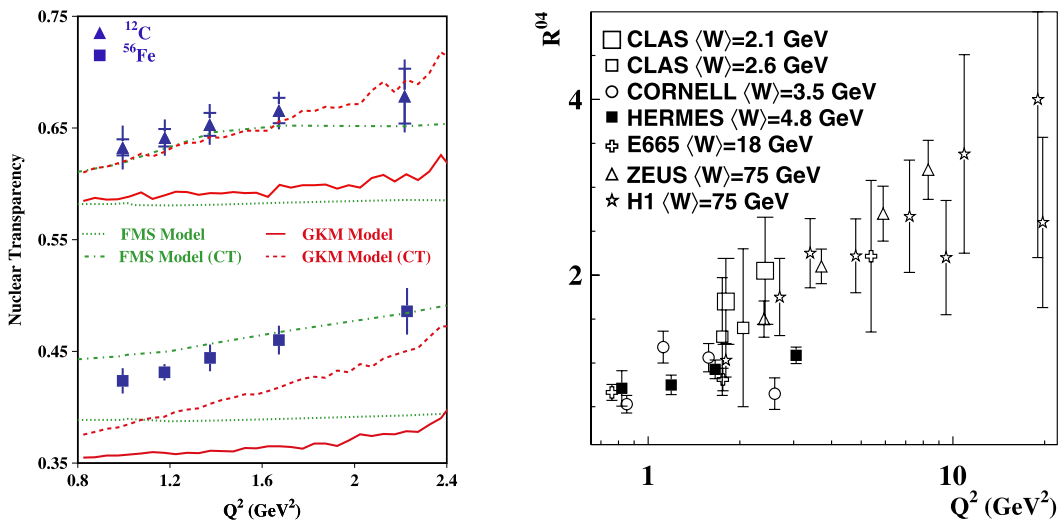


FIG. 1: Nuclear transparency as a function of Q^2 . Experimental data are from CLAS, JLab [23] (left). Q^2 dependence of the ratio of the longitudinal-to-transverse cross sections for exclusive ρ^0 production on proton [4] (right).

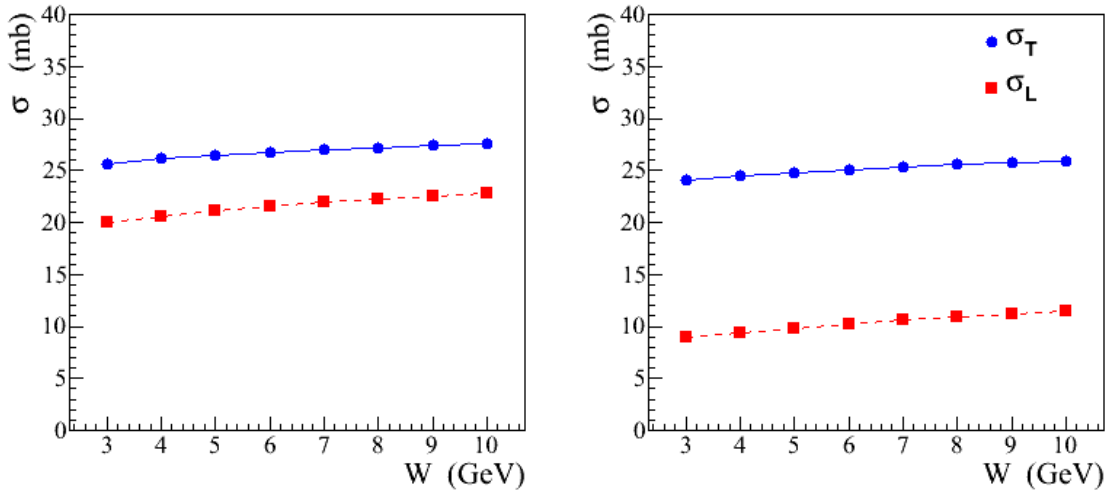


FIG. 2: Energy dependence of the total cross sections $\sigma_L(\rho N)$ and $\sigma_T(\rho N)$ computed for different ρ meson wave functions: boosted gaussian wave function [27] (left) and ADC/QCD holographic [28] wave function [29, 30](right).

photoproduction leads to the noticeable production of longitudinally polarized ω mesons [2]. The dependence of the spin density matrix elements on the invariant momenta transfer in the process $\gamma + p \rightarrow \omega + p$ measured by SLAC [2] is presented in Fig. 3. The fraction of the longitudinally polarized ω mesons determined by the value of ρ_{00} is significant even at large beam energies of $E_\gamma = 10$ GeV. The total cross sections of longitudinally and transversely polarized mesons with nucleon $\sigma_{L,T} = \sigma(\omega N)$ can be obtained from the incoherent and coherent photoproduction, respectively.

III. PHOTOPRODUCTION OF ω MESONS ON NUCLEI.

In the late 60's and early 70's many experiments were carried out to study vector mesons photoproduction on nuclei [5]. 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 [31, 32] and the Bonn-Pisa group at DESY [33]. 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 naive quark model prediction: $\sigma(\omega N) = \sigma(\rho N) = (\sigma(\pi^+ N) + \sigma(\pi^- N))/2$. A later experiment on ω photoproduction off nuclei at a mean energy of 3.9 GeV was performed at the electron synchrotron NINA at Daresbury [34]. The nuclear absorption of ω mesons was found to be in agreement with the previous experiments. 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 an undesirable background. Experiments confirmed quark model predictions for total cross section of vector mesons interaction with nucleon, which is not strange as long as from the coherent part of the cross section one extracts [1] only the transversely polarized mesons cross section $\sigma_T(\omega N)$.

Recently, the omega mesons photoproduction was measured by CBELSA/TAPS [35] collaboration via the decay $\omega \rightarrow \pi^0\gamma$ and at by the CLAS collaboration at Jefferson Lab [36]

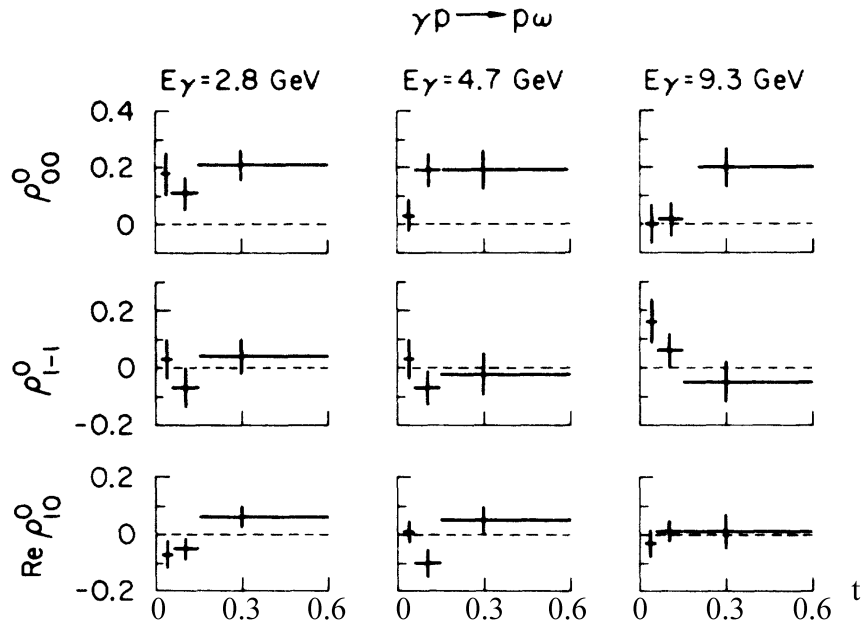


FIG. 3: Spin density matrix elements of ω mesons in the helicity system measured by the SLAC experiment [2].

using the rare electromagnetic decay mode $\omega \rightarrow e^+e^-$. The main goal 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 ω mesons decay in the nuclei, the mesons momentum in both experiments was low ($p_\omega \geq 0.8$ GeV in CLAS experiment and $p_\omega \geq 0.2$ GeV in CBELSA/TAPS experiment). At such low momenta the large contribution from nucleon resonances complicates the interpretation of experimental results [38].

The CLAS collaboration observed a significantly stronger absorption of the ω meson than measured by the CBELSA/TAPS collaboration[43]. Both experiments obtained a relatively large in-medium width of ω mesons and $\sigma(\omega N)$ total cross section, which disagrees with measurements of the KEK-E325 experiment [39], 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 up to now.

In all these experiments no attempt was done to separate the absorption of transversely and longitudinally polarized omega mesons. This effect can potentially be studied using the GlueX detector in Hall D, 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 look as follows:

- Photoproduction of ω mesons on nucleons $\gamma N \rightarrow \omega N$ 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 [5]. 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 [1].
- 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. This can be used to study the interaction of longitudinally polarized vector mesons with the matter [1].

IV. COHERENT PHOTOPRODUCTION

The differential cross section of coherent photoproduction of ω (nuclear target remains in the ground state) $\gamma + A \rightarrow \omega + A$ reads [1]:

$$\frac{d\sigma}{dt} = \frac{d\sigma_N(0)}{dt} |F_A(q_L, q, \sigma_T)|^2, \quad (1)$$

where $\frac{d\sigma_N(0)}{dt}$ is the diffractive part of the forward cross section on the nucleon $\gamma(k) + N \rightarrow \omega(p) + N$, and $F_A(q_L, q, \sigma_T)$ is the nucleus form factor, which accounts for the ω absorption in nucleus. The form factor depends on the photon energy through the longitudinal momentum transferred $q_L = \frac{m_\omega^2}{2k}$. The two dimensional transverse momentum \vec{q} is given by the standard relation $\vec{q}^2 = 4kpsin^2\frac{\theta}{2}$, thus the invariant transfer momenta: $t = (k - p)^2 = -q_L^2 - q^2$. In the coherent photoproduction, where one has to sum the elementary amplitude from different nucleons the part of photoproduction amplitude on nucleon relevant to one pion exchange has a different signs for photoproduction on proton and neutron. This leads to cancellation of one pion exchange part[44] and to production of only transversely polarized ω mesons in coherent photoproduction on nuclei [1]. Figure 4 shows the dependence of the form factor on the transfer momentum for two nuclei and different values of $\sigma_T(\omega N)$.

V. INCOHERENT PHOTOPRODUCTION

We propose to study two main physics topics using incoherent photoproduction of vector mesons:

- measure energy dependence of the nuclear transparency of vector mesons,
- measure the nuclear transparency and spin density matrix elements for ω mesons with the aim to extract the yet unmeasured cross section of longitudinally polarized ω mesons with nucleons.

Measurements of A-dependence of the nuclear transparency of vector mesons at different energies relevant to GlueX are important because they will provide information related to the long standing problem: weak energy dependence of the nuclear transparency measured for ρ mesons at Cornell [7], which contradicts theoretical predictions [6]. The nuclear transparency measured at two photon energies $E_\gamma = 4$ GeV and $E_\gamma = 8$ GeV is shown in Fig. 5. In this figure, the nuclear transparency is defined as $A_{eff} = \sigma_A/\sigma_N$, and hereafter we will follow this definition. The transparencies are similar for these energies within the errors limit unlike the theoretical calculations [6], which predict the significant decrease of the transparency with energy due to the impact of the energy-dependent coherence length $\tau_c = \frac{1}{q_L} = \frac{2E_\gamma}{m_V^2}$ on the incoherent photoproduction.

Especially interesting are measurements of the incoherent photoproduction of ω mesons on a set of nuclei [1]. Unlike the coherent photoproduction from which one can extract only the value of the transverse cross section $\sigma_T(\omega N)$, measuring ω cross section and spin density matrix elements on nuclei in the incoherent photoproduction allows one to determine the value of

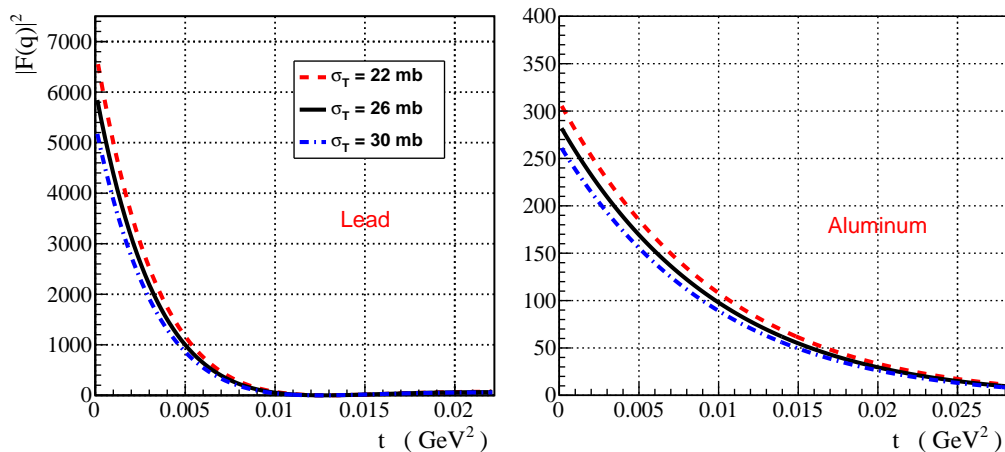


FIG. 4: Dependence of the nuclear form factors on the invariant transfer momentum for different cross sections of transversely polarized ω mesons with nucleons.

unknown longitudinal cross section $\sigma_L(\omega N)$. The incoherent part of the photoproduction cross section of ω mesons in the typical range of the momentum transfer $0.1 \text{ GeV}^2 < t < 0.5 \text{ GeV}^2$ can be presented in the following form [1]:

$$\begin{aligned} \frac{d\sigma_A(q)}{dt} &= \frac{d\sigma_0(q)}{dt} (\rho_{00} N(0, \sigma_L) + (1 - \rho_{00}) N(k, \sigma_T)) \\ N(0, \sigma) &= \int \frac{1 - \exp(-\sigma \int \rho(b, z) dz)}{\sigma} d^2b \\ N(k, \sigma) &= \int \rho(b, z) |E(b, z)|^2 dz d^2b \\ E(b, z) &= \exp(-\frac{\sigma}{2} \int_z \rho(b, z') dz') - \frac{\sigma}{2} \int_z^{\infty} \rho(b, z') dz' e^{iq_L(z'-z)} \exp(-\frac{\sigma}{2} \int_{z'} \rho(b, z'') dz'') \quad (2) \end{aligned}$$

Here $\rho(r)$ is the nuclear density; $\frac{d\sigma_0(q)}{dt} = \frac{d\sigma_N(q)}{dt} + \frac{d\sigma_U(q)}{dt}$ is the differential cross section of ω meson photoproduction on nucleon, which accounts for diffraction and unnatural parity exchanges; ρ_{00} is the spin density matrix element in the helicity system, relevant to the fraction of longitudinally polarized mesons in photoproduction on nucleon. In Fig. 6 and 7 we present the A-dependence of the nuclear transparency A_{eff} and the spin density matrix element ρ_{00}^A calculated according to Eq. (2) for two energies and three values of σ_L . The input values of $\rho_{00} = 0.2$ and total transverse ω -nucleon cross section [33] $\sigma_T(\omega N) = 26 \text{ mb}$ are taken from SLAC measurements [2]. The spin density matrix elements in photoproduction on nuclei and nucleons can be related as

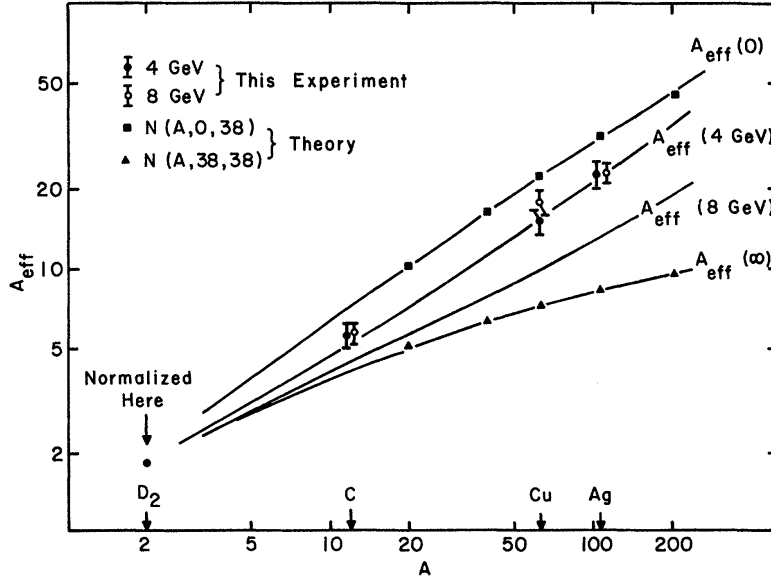


FIG. 5: Nuclear transparency for incoherent photoproduction of ρ mesons at $|t| = 0.1 \text{ GeV}^2$ and different energies [7].

follows [1]:

$$\rho_{00}^A = \frac{N(0, \sigma_L)}{\rho_{00}N(0, \sigma_L) + (1 - \rho_{00})N(k, \sigma_T)} \rho_{00} \quad (3)$$

Fig. 8 demonstrates our predictions for the dependence of A_{eff} and ρ_{00}^A on σ_L for lead nuclei.

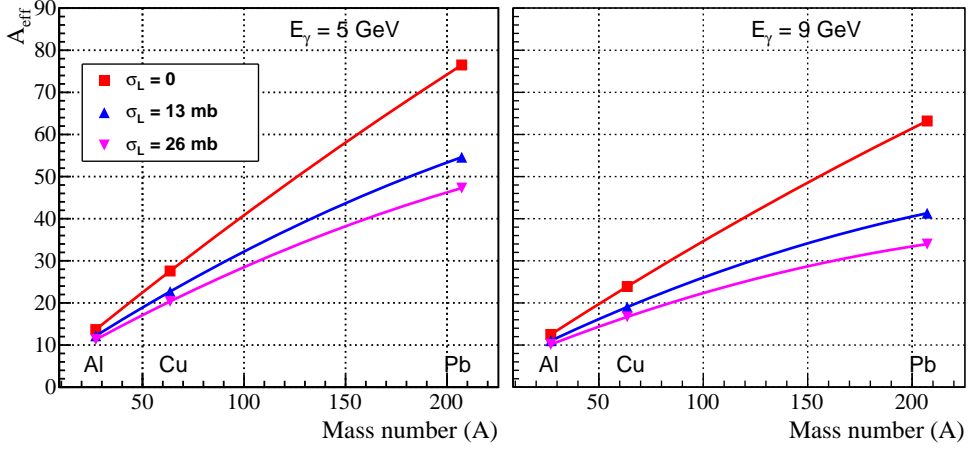


FIG. 6: Dependence of the nuclear transparency A_{eff} on the mass number for (a) $\sigma_L = 13$ mb and (b) $\sigma_L = 26$ mb.

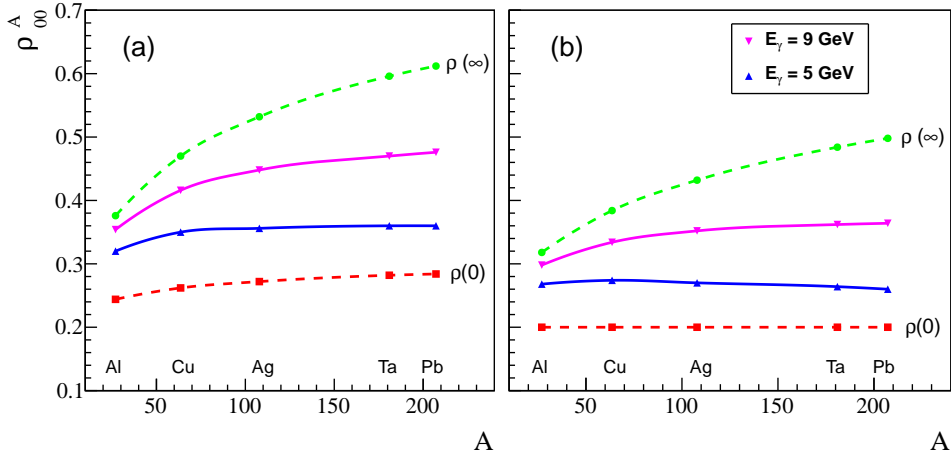


FIG. 7: A-dependence of the spin density matrix element ρ_{00}^A for (a) $\sigma_L = 13$ mb and (b) $\sigma_L = 26$ mb. ρ_{00}^A is shown for different photon energies. $\rho(\infty)$ $\rho(0)$ correspond to infinite energy and energy-independent ρ_{00}^A , respectively.

VI. MONTE CARLO SIMULATION

We studied reconstruction efficiencies of ω mesons in the beam energy range between 6 GeV and 12 GeV using detailed GlueX detector simulation. The ω mesons were generated in a $\gamma p \rightarrow \omega p$ reaction using Pythia event generator (with the Fermi motion of nucleons taken into account). Generated events were passed through the Geant simulation and were reconstructed using the official GlueX reconstruction package. The distribution of the invariant momentum transfer generated by Pythia is presented in Fig. 9. The slope of the distribution is similar to SLAC measurements [2] ($t = -7.5 \pm 0.8 \text{ GeV}^{-2}$ at the beam energy of 9 GeV). The typical GlueX reconstruction resolution on t for $\omega \rightarrow \pi^0 \gamma$ decays in the range $t > 0.1 \text{ GeV}^2$ is 0.016 GeV^2 . Invariant mass distributions $m_{\gamma\gamma}$ and $m_{3\gamma}$ are presented on the bottom plots of Fig. 9. Invariant mass resolutions for reconstructed π^0 and ω mesons constitute about 7.8 MeV and 33 MeV, respectively. The missing-mass resolution is 190 MeV.

Reconstruction efficiencies for $\omega \rightarrow \pi^+ \pi^- \pi^0$ and $\omega \rightarrow \pi^0 \gamma$ decays are listed in Table I. The efficiencies are computed for events where a recoil proton is required to be reconstructed and events where no proton reconstruction is required. The relative dependence of the reconstructed efficiency on the beam energy is found to be relatively small, on the level of 15%.

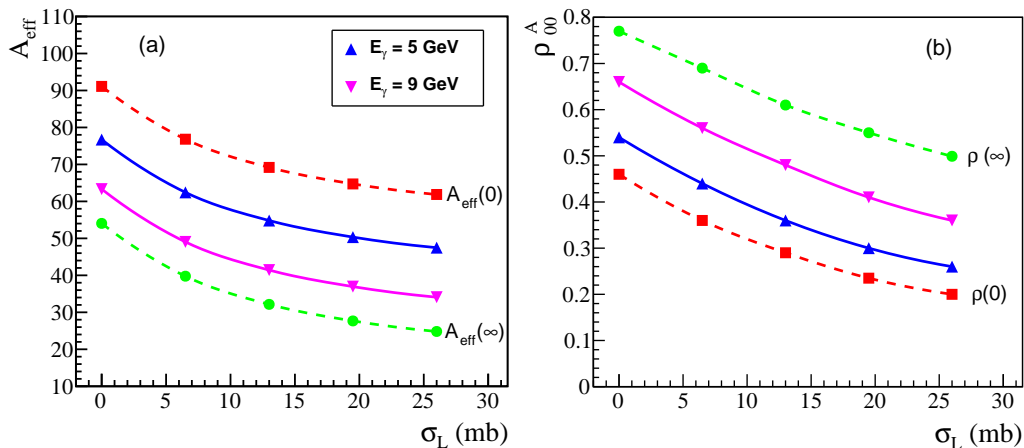


FIG. 8: (a) The nuclear transparency A_{eff} and (b) the spin density matrix element ρ_{00}^A as a function of σ_L for lead nucleus. The transverse ω - nucleon cross section σ_T and the spin density matrix element ρ_{00} are taken to be 26 mb and 0.2 respectively.

VII. RECONSTRUCTION OF ω MESONS

We studied capabilities to reconstruct ω mesons produced on nuclear targets by using the GlueX data with an empty target acquired in Spring 2017. In these data ω mesons can be produced on the target walls and the air downstream the target. The walls and the window are made from Kapton with the total thickness of about $280 \mu\text{m}$, which corresponds to about $2 \cdot 10^{21}$ atoms/cm² (assuming that Kapton consists mostly of Carbon). The target cell contains some cold H_2 gas remaining after the liquid hydrogen was drained from the cell. The density of the H_2 gas is estimated to be about $1.8 \cdot 10^{-3}$ g/cm³, which can be compared with the air density of $1.2 \cdot 10^{-3}$ g/cm³. The total number of hydrogen atoms in the cell corresponds to

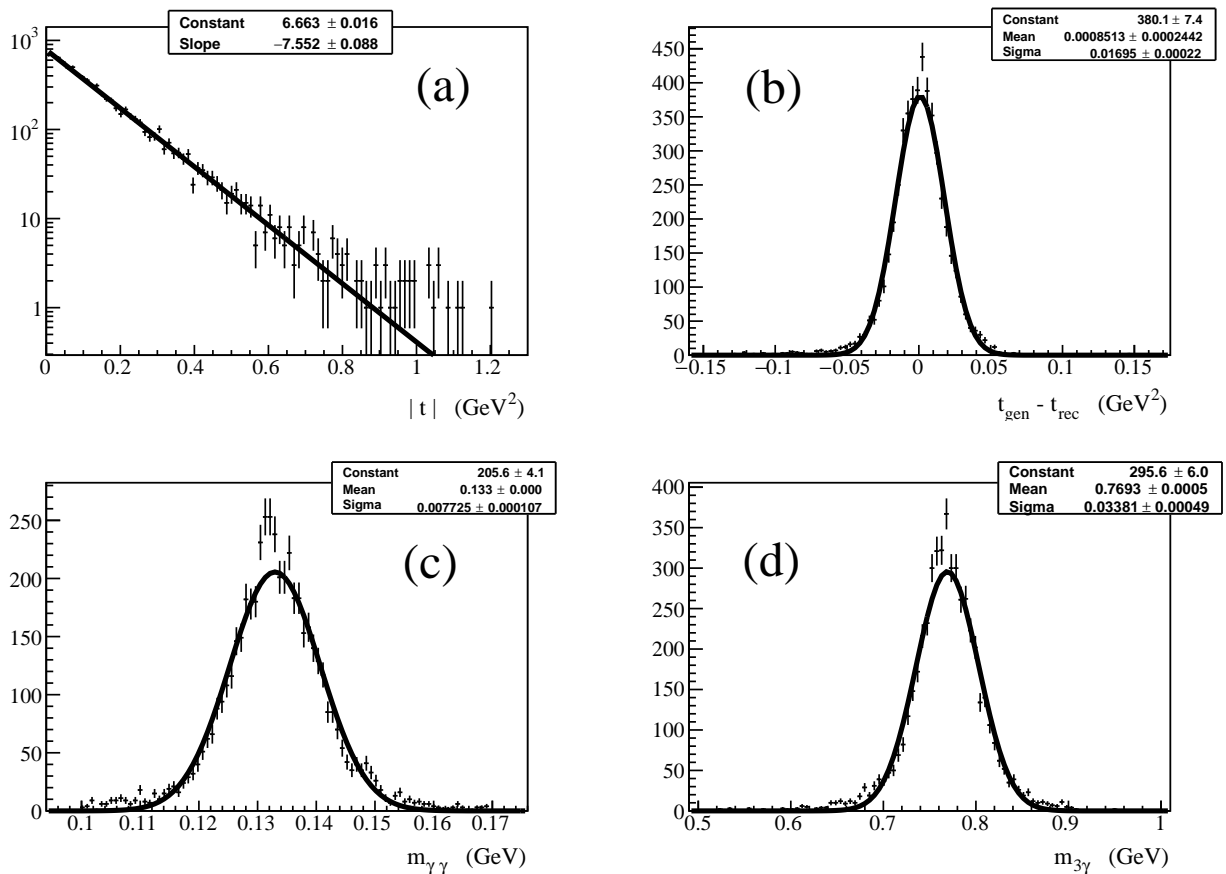


FIG. 9: Monte Carlo simulation for the reaction $\gamma p \rightarrow \omega p$, $\omega \rightarrow \pi^0 \gamma$ (a) Distribution of the invariant transfer momentum generated by Pythia (b) Resolution of the transfer momentum, $t_{\text{gen}} - t_{\text{rec}}$ for $t > 0.1 \text{ GeV}^2$ (c) Invariant mass $M_{\gamma\gamma}$ of reconstructed π^0 candidates (d) Invariant mass $M_{3\gamma}$.

	Final state			
	$p \pi^+ \pi^- \pi^0$	$\pi^+ \pi^- \pi^0$	$p \pi^0 \gamma$	$\pi^0 \gamma$
Efficiency (%)	12.9	21.4	28.5	51.9

TABLE I: Reconstruction efficiency of ω mesons produced in the $\gamma p \rightarrow \omega p$ reaction and decaying to $\omega \rightarrow \pi^+ \pi^- \pi^0$ and $\omega \rightarrow \pi^0 \gamma$ final states.

about $3.3 \cdot 10^{22}$ atoms/cm².

We select $\omega \rightarrow \pi^+ \pi^- \pi^0$ candidates produced on the target walls or air by reconstructing the π^\pm vertex. Z-coordinate of reconstructed vertices is presented in Fig. 10. Red arrows on this plot around the walls and air, denote Z-coordinates of vertices of ω candidates accepted for the analysis. We consider events with only two oppositely charged pion track candidates, a proton track consistent with the dE/dx of a proton hypothesis in the drift chambers, and a π^0 candidate. Events with extraneous reconstructed tracks or clusters in the calorimeters are rejected. The energy of reconstructed ω mesons is required to be larger than 6 GeV. The invariant mass distribution $M_{\pi^+ \pi^- \pi^0}$ is presented in Fig. 11 for two types of events: (1) proton is reconstructed in the event (right plot) and (2) no proton candidate is found (left plot). A relatively small background is observed for $\omega \rightarrow \pi^+ \pi^- \pi^0$ decays for events with and without a reconstructed proton.

For reconstruction of $\omega \rightarrow \pi^0 \gamma$ decays we don't apply any constraints on the production vertex as there are no charged tracks in the final state except for some events with a recoil proton originating in the incoherent production on nuclei or in the $\gamma p \rightarrow \omega p$ reaction on the residual hydrogen gas in the target cell. The contribution to the production of ω mesons from the hydrogen gas is estimated to be smaller than that from nuclear photoproduction on the target walls and air. The invariant mass distribution $M_{3\gamma}$ is presented in Fig. 12. The ω peak on the mass distribution for events with no reconstructed proton (no vertex) is broad and shifted towards small masses. This can be accounted by the fact that ω mesons are produced on the air outside the target, at larger z, while in the reconstruction photons are assumed to originate from the center of the target, if vertex is not found. Under this assumption, the reconstruction angles between product decays are smaller than the real ones, resulting in the mass shift of π^0 and ω mesons. In the proposed experiment with a nuclear target, there will be no mass shift,

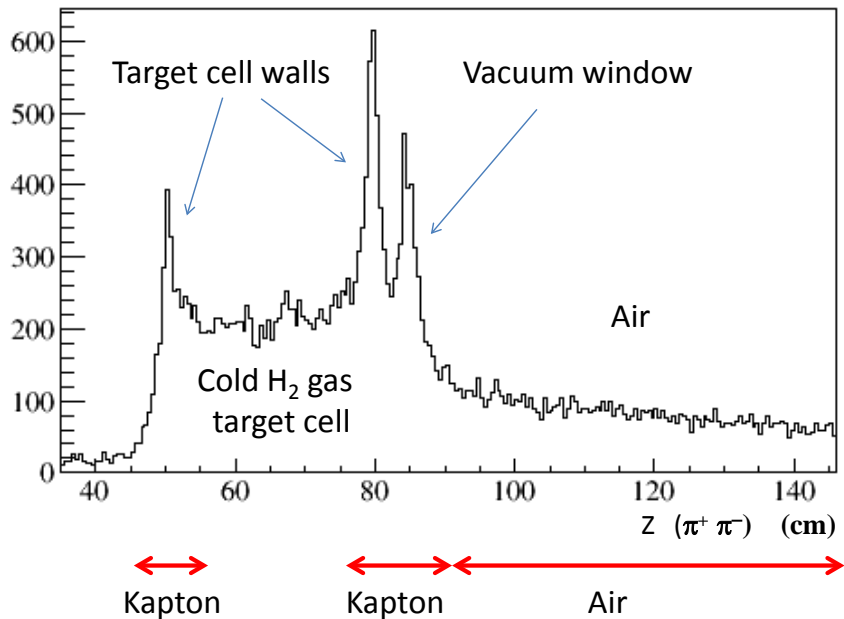


FIG. 10: Z-coordinate of reconstructed vertices of π^\pm mesons originating from $\omega \rightarrow \pi^+\pi^-\pi^0$ candidates in runs with an empty target. The target cell is 30 cm long with the center positioned at $Z = 65$ cm.

as the position of the foil target is well defined. Background from ω production on air and the target walls will be subtracted using runs with an empty target. As expected, there is no ω mass shift when a proton is reconstructed (see the right plot in Fig. 12). In this case the proton defines the production point for $\pi^0\gamma$. The signal to background ratio (S/B) for $\omega \rightarrow \pi^0\gamma$ is found to be relatively good, on the level of 2. In reality the S/B is expected to be better due to the narrower mass distribution of reconstructed ω mesons on a thin target with a well-defined position.

VIII. RUN CONDITIONS

Photoproduction of vector mesons will be studied in the large beam energy range $E_\gamma > 6$ GeV using a photon beam produced by 11.6 GeV CEBAF electrons incident on an amorphous radiator. The energy of a beam photon is reconstructed by detecting bremsstrahlung electrons in the tagger hodoscope (TAGH) and microscope (TAGM) scintillator detectors. The tagging

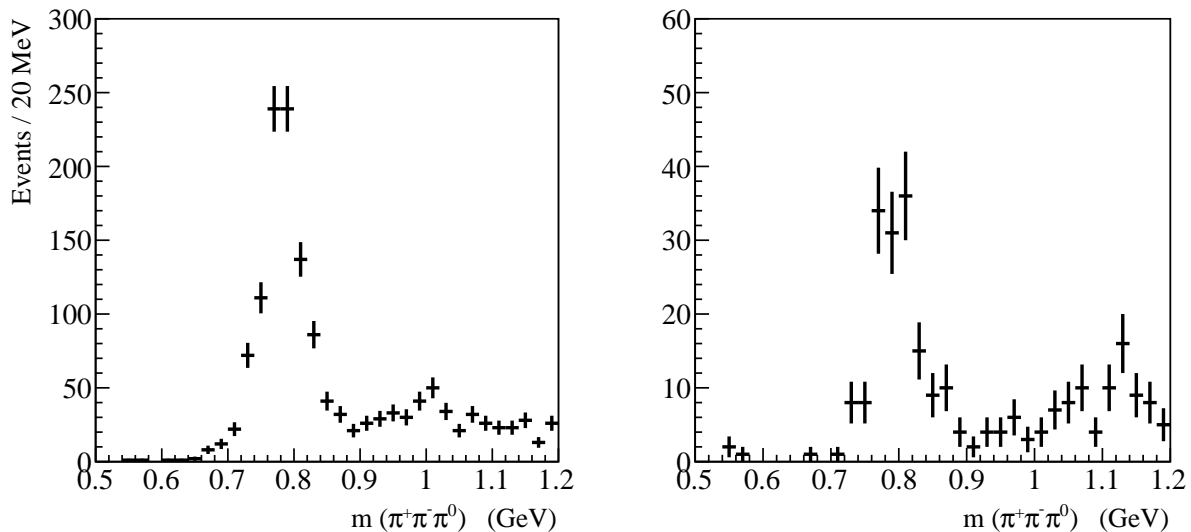


FIG. 11: Invariant mass distribution $M_{\pi^+\pi^-\pi^0}$ for events produced on target walls and air in runs with an empty target. The right plot corresponds to events with reconstructed proton. The left plot corresponds to events when no proton is found.

detectors provide a continuous energy coverage in the range between 7.8 GeV and 11.7 GeV and a typical electron detection efficiency of 90 – 95%. The TAGH counters are sampled below 7.8 GeV with an average sampling fraction of about 0.3. Reconstruction of the beam energy in the wide range is complicated due to the relatively large rate of accidental hits in the tagging detectors, i.e., hits originating from different events. In order to reduce the accidental rate, we are going to decrease the flux of uncollimated photons by a factor of 12 compared with the GlueX flux at high luminosity[45] and use larger collimator with a diameter of 5 mm. The fraction of events with multiple beam photons originating from the same beam bunch[46] in the energy between 6 GeV and 11.7 GeV is about 20%. The beamline conditions of the proposed experiment are listed in Table II.

We propose to use four nuclear targets: C, Si, Sn, Pb, with a thickness of 7% radiation length (the GlueX LH₂ target thickness is 3.5% X_0). Data will be taken on each individual target; multiple targets cannot be used in parallel due to the target misidentification in reconstruction of the multi-photon final state ($\pi^0\gamma$). Properties of nuclear targets are listed in Table III.

Reduction of the photon beam flux and using thin targets is also required by the electromagnetic and neutron backgrounds origination from nuclei. The neutron background is specifically

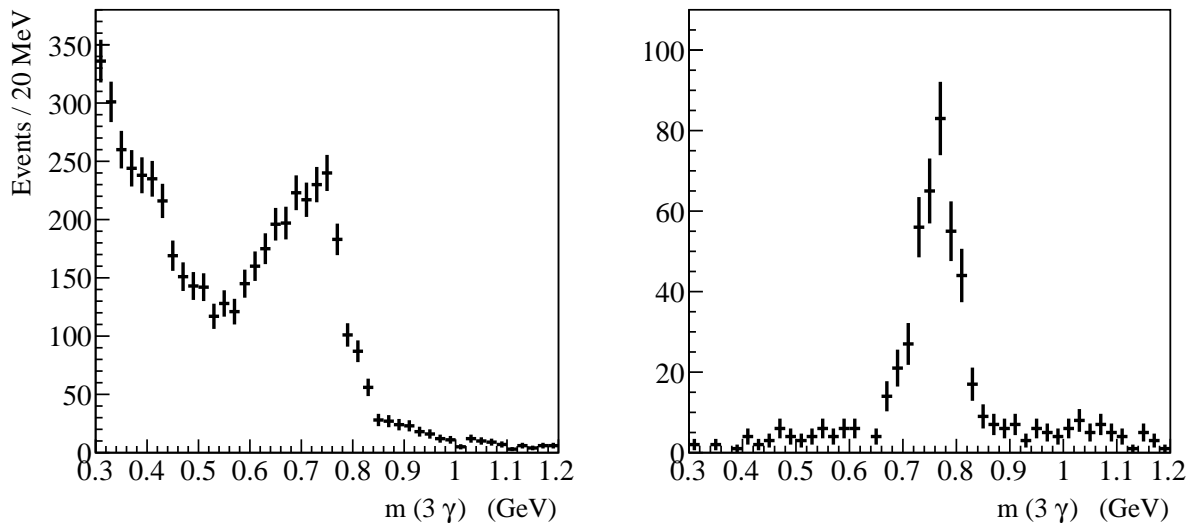


FIG. 12: Invariant mass distribution $M_{3\gamma}$ reconstructed in runs with an empty target. The right plot corresponds to events with reconstructed proton. The left plot corresponds to events when no proton is found.

critical for Silicon photomultipliers used in the barrel calorimeter and start counter. For the proposed run conditions, the electromagnetic background level (which is proportional to the photon flux and the target thickness in units of radiation lengths) is expected to be significantly smaller than for GlueX. The neutron background in the GlueX experiment was simulated using Geant provided by the RadCon group and Fluka for the LH_2 and liquid He targets [40]. The background induced by heavier nuclear targets can be scaled to He [41] and is not expected to exceed the GlueX level.

IX. PRODUCTION RATES AND BEAM REQUEST

Reconstruction efficiencies for $\omega \rightarrow \pi^0\gamma$ and $\omega \rightarrow \pi^+\pi^-\pi^0$ decays are described in Section 8. The number of reconstructed $\omega \rightarrow \pi^0\gamma$ decays produced in the incoherent process on a Carbon target as a function of the beam energy is presented in Fig. 13. The production rate is normalized to 1 day of taking data. In the simulation we used the realistic photon beam flux and efficiencies in the tagging detectors. The number of ω mesons reconstructed in the $\pi^0\gamma$ and $\pi^+\pi^-\pi^0$ final states on the proposed nuclear targets is listed in Table IV.

Conditions	GlueX	Proposed Exp
Collimator (mm)	3.4	5
Radiator thickness (X_0)	$2 \cdot 10^{-4}$ (Diamond)	10^{-4} (Aluminum)
Beam current (μA)	1.1	0.18
Photon beam energy range of interest (GeV)	8.4 - 9.1	6 - 11.7
Rate of uncollimated photons (Hz)	$1.2 \cdot 10^8$	$5.3 \cdot 10^7$
Photon rate on target (Hz)	$5 \cdot 10^7$	$1.5 \cdot 10^7$

TABLE II: Beamline conditions of the proposed experiment compared with GlueX.

	LH_2 (GlueX)	C	Si	Sn	Pb
A	1	12	28	119	207
Target thickness (X_0)	3.4%	7 %			
Relative EM background	1	0.3			
Number of atoms (N/cm^2)	$1.28 \cdot 10^{24}$	$1.5 \cdot 10^{23}$	$3.3 \cdot 10^{22}$	$3.1 \cdot 10^{21}$	$1.3 \cdot 10^{21}$
$N^{Target} \cdot A/N^{LH_2}$	1	1.4	0.7	0.3	0.2
Incoherent cross section (μb)					
6 GeV		17	30	75	119
12 GeV		12	20	45	67

TABLE III: Properties of nuclear targets proposed for the experiment.

We propose to take data for 28 days on several nuclear targets including calibration runs and runs with empty target. The profile of the requested beam time is shown in Table V. For each target, we plan to reconstruct about $10^3 \omega \rightarrow \pi^0 \gamma$ decays per 1 GeV beam energy range produced in the incoherent process.

We expect that the total error on the nuclear transparency measurements for each nuclear

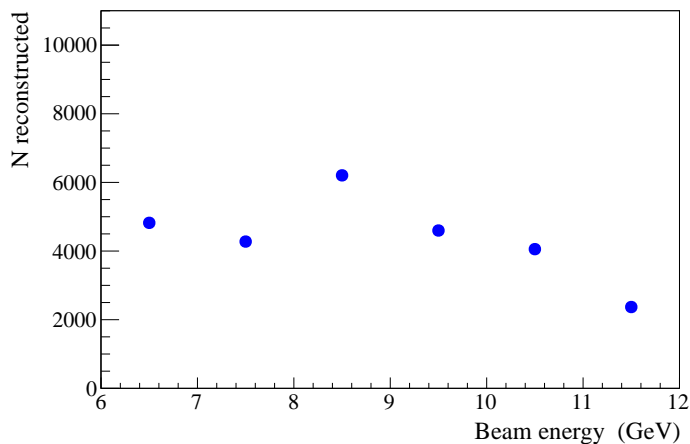


FIG. 13: The number of reconstructed $\omega \rightarrow \pi^0\gamma$ candidates produced in the incoherent process on a carbon target with the momentum transfer t between 0.1 GeV^2 and 0.5 GeV^2 as a function of the beam energy. The yield is normalized to 1 day of taking data.

target will be dominated by the systematic error, which should not exceed 5%. The list of possible main sources contributing to the systematic error is shown in Table VI. In the data analysis we will normalize the transparency to carbon data (or He data). This will allow us to avoid systematic uncertainties such as the ω production cross section on the nucleon and related reconstruction efficiencies. Expected errors on measurements of the energy dependence of the nuclear transparency (A_{eff}) are presented on the left plot of Fig 14. The nuclear transparency for different values of σ_L with projected errors from the proposed experiment is shown on the right plot of Fig 14.

The data sample acquired with the proposed experiment will allow to study nuclear transparency of other mesons decaying into different final states such as ϕ ($\phi \rightarrow K^+K^-$ and $\phi \rightarrow \pi^+\pi^-\pi^0$) and $K_s \rightarrow \pi^+\pi^-$ with an expected statistical errors of a few percent.

X. SUMMARY

We propose to use the GlueX detector to study the photoproduction of the vector mesons ρ, ω, ϕ on a set of nuclear targets: C, Si, Sn, and Pb in the large photon beam energy range between 6 GeV and 12 GeV. The primary goal of the experiment is to:

Target	N_{rec} per day ($\times 10^3$)			
	$\omega \rightarrow \pi^0\gamma$		$\omega \rightarrow \pi^+\pi^-\pi^0$	
	[6 - 9] GeV	[9 - 12] GeV	[6 - 9] GeV	[9 - 12] GeV
C	35.2 (15.8)	24.5 (11.0)	176 (79)	122.5 (55)
Si	12.9 (5.8)	8.6 (3.9)	64.5 (29)	43 (19.5)
Sn	3.0 (1.4)	1.7 (0.8)	15 (7)	8.5 (4.0)
Pb	1.9 (0.9)	1.0 (0.5)	9.5 (4.5)	5 (2.5)

TABLE IV: The number of reconstructed $\omega \rightarrow \pi^0\gamma$ and $\omega \rightarrow \pi^+\pi^-\pi^0$ decays produced in the incoherent process on different nuclei targets. Numbers in parenthesis correspond to ω mesons reconstructed in the t range between [0.1 - 0.5] GeV². The yield is normalized to 1 beam day.

Activity	Time (days)
C production	3
Si production	4
Sn production	6
Pb production	10
Empty target	3
Calibration	2
Total	28

TABLE V: Beam time request.

1. Measure nuclear transparency of ω mesons using incoherent photoproduction on different targets and extract the total cross section of longitudinally polarized ω mesons on a nucleon, $\sigma_L(\omega N)$. This knowledge is important for many theoretical models. The ω mesons will be identified using the $\omega \rightarrow \pi^0\gamma$ and $\omega \rightarrow \pi^+\pi^-\pi^0$ decay channels. The total error on the nuclear transparency measurements will be dominated by the systematic error, which is expected to be within 6% (see projected errors in Fig. 14).

Event selection and signal yield	3%
Measurements of ρ_{00}	4%
Target thickness	0.5% – 1%
Photon flux determination	1.5%
Reconstruction efficiencies	2%
Total	6%

TABLE VI: List of systematic errors expected in measurements of the nuclear transparency.

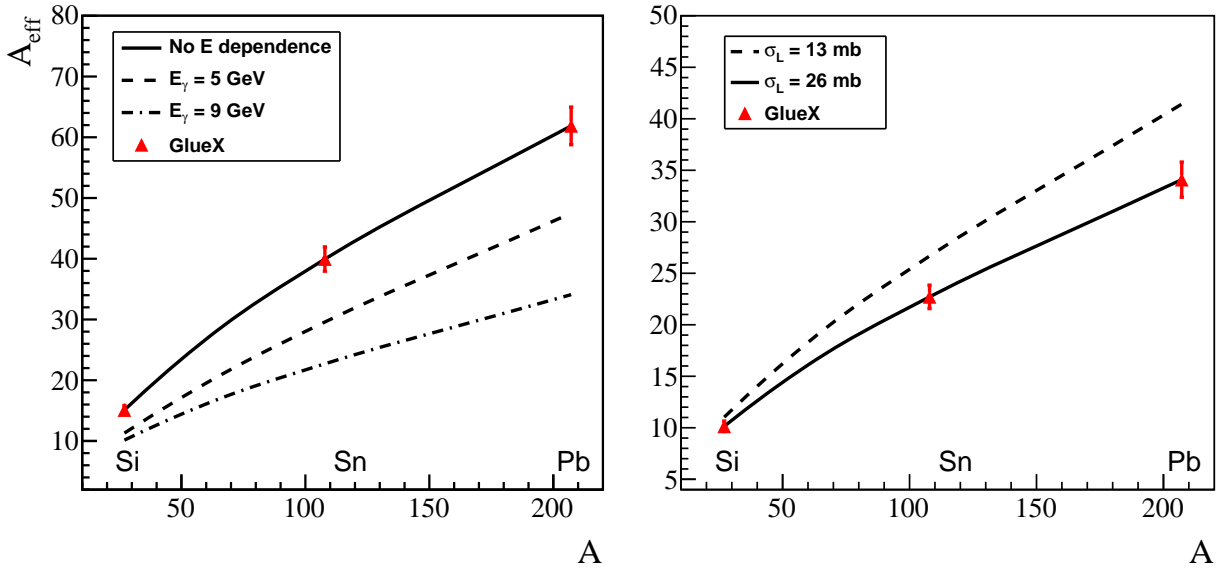


FIG. 14: Dependence of the nuclear transparency A_{eff} on the beam energy (left) and cross section σ_L (right). Markers correspond to the projected errors of the proposed experiment.

2. Measure spin density matrix elements for ω mesons using incoherent photoproduction, which will allow to unambiguously separate production of longitudinally and transversely polarized ω mesons. The dependence of the spin density matrix elements on the atomic weight A is the direct indication of the impact of the meson's polarization on interactions with nucleons and nuclei. These measurements should provide an independent way to extract $\sigma_L(\omega N)$.

3. Measure the nuclear transparency of light mesons such as ρ , ω , ϕ to study the dependency of the nuclear transparency on the beam energy and to compare measurements with the theoretical predictions. Such measurements will probe the degree of photon shadowing in nuclear matter and shed light on a long standing problem: the weak dependence of the measured nuclear transparency with energy, which contradicts theoretical predictions. Data samples acquired on each nuclear target will allow to measure the nuclear transparencies with statistical errors between 1% and 5%.

The data sample acquired with the experiment is expected to allow to study other physics topics. For example, the absorption of different projections of the total orbital momentum of a tensor meson $f_2(1270)$ can be measured[47]. Studies of the nuclear transparency in photoproduction of vector mesons can be extended to the region of the larger transfer momenta $|t| > 1 - 2 \text{ GeV}^2$, where the color transparency effects can be investigated [48].

The expected length of the experiment is 28 days of taking data. The detector will be operated at small luminosity. No modifications of the GlueX detector except replacing the LH_2 target with the nuclear targets are required.

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- [42] Unlike ω mesons, at these energies ρ and ϕ mesons are produced in the pure diffraction process and therefore are transversely polarized due to the s-channel helicity conservation.
- [43] In the first paper [35] the CBELSA/TAPS collaboration published the cross section $\sigma(\omega N) =$

70 mb, recently [37] the cross section is corrected to the much lower value.

- [44] Strictly speaking this is true only for symmetric nuclei. In the case of nuclei with unequal numbers of protons and neutrons, relevant corrections have to be taken into account in a known way.
- [45] The flux of collimated photons in GlueX in the coherent peak region is 5×10^7 γ /sec.
- [46] Time spacing between beam bunches is 4 ns.
- [47] $f_2(1270)$ meson can be clearly reconstructed with the GlueX detector
- [48] The proposal to study the color transparency in photoproduction of mesons at large transfer momentum using the GlueX detector will be presented at PAC.