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Physics Letters B 608 (2005) 215–222
PHYSICS LETTERS B
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ϕ photo-production from Li, C, Al, and Cu nuclei at $E_\gamma = 1.5$–2.4 GeV

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Received 8 November 2004; received in revised form 28 December 2004; accepted 10 January 2005

Available online 17 January 2005

Editor: V. Metag

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doi:10.1016/j.physletb.2005.01.023

Abstract

The photo-production of ϕ mesons from Li, C, Al, and Cu at forward angles has been measured at $E_\gamma = 1.5$–2.4 GeV. The number of events for incoherent ϕ photo-production is found to have a target mass number dependence of $A^{0.72\pm0.07}$ in the kinematical region of $|t| \leqslant 0.6\ \text{GeV}^2/c^2$. The total cross section of the ϕ–nucleon interaction, $\sigma_{\phi N}$, has been estimated as 35^{+17}_{-11} mb using the A-dependence of the ϕ photo-production yield and a Glauber-type multiple scattering theory. This value is much larger than $\sigma_{\phi N}$ in free space, suggesting that the ϕ properties might change in the nuclear medium.

PACS: 13.25.-k; 13.75.-n; 14.40.Cs

The modification of vector mesons in nuclear matter is of interest in hadron physics. A broadening of the width and/or a decrease of the mass have been predicted for the ϕ meson in the nuclear medium because of partial restoration of chiral symmetry [1] or the meson–nucleon interaction in the nuclear medium [2–4]. The mass shift of the ϕ meson has been experimentally studied in the p–A reaction at the normal nuclear density [5], and in high-energy heavy-ion collisions [6]. However, no clear evidence has been observed.

According to the OZI rule, the total ϕ–N cross section, $\sigma_{\phi N}$ should be small since the ϕ meson consists of almost pure $s\bar{s}$. If $\sigma_{\phi N}$ in the nuclear medium is the same as that in free space, the incoherent ϕ photo-production cross section from a nucleus, σ_A^{inc}, is approximately proportional to the target mass number, A, since almost all the produced ϕ mesons are expected to go outside the nucleus without interacting with a nucleon. If $\sigma_{\phi N}$ becomes larger in the nuclear medium, some fraction of photo-produced ϕ mesons would interact with nucleons in the nucleus and disappear via inelastic reactions. In this case, the A-dependence sizeable deviates from $\sigma_A \propto A^1$.

Only one measurement of ϕ photo-production from various nuclei is reported at $E_\gamma = 6.4$–9.0 GeV [7], where coherent production is dominant. The value of $\sigma_{\phi N}$ is not accurately determined from the data of coherent production. On the other hand, $\sigma_{\phi N}$ in free space is well determined to be 7.7–8.7 mb from the ϕ photo-production cross section on the proton, $da/dt|_{t=0}$, at $E_\gamma = 4.6$–6.7 GeV, where the energy dependence of the γ–ϕ coupling is assumed to be constant on the basis of the vector meson dominance model (VDM) [8]. A quark model [9] gives a prediction of 13.0 ± 1.5 mb for $\sigma_{\phi N}$ [8]. This value is deduced from the total $\pi^\pm p$ and $K^+ p$ cross sections obtained at the high energy limit. The obtained and predicted values of $\sigma_{\phi N}$ in free space are much smaller than other meson–nucleon total cross sections $\sigma_{\omega N}$, $\sigma_{\rho N}$, and $\sigma_{\eta N}$ (~ 30 mb) [10].

The $\sigma_{\phi N}$ in the nuclear medium can be determined by using a Glauber-type multiple scattering theory for incoherent production [11]. The incoherent production cross section from nuclei, $d\sigma_A^{\text{inc}}/dt$, is described as a product of the ϕ photo-production cross section on the nucleon, $d\sigma_N/dt$, and the effective nucleon number, A_{eff}, which is a function of the nucleon density distribution and $\sigma_{\phi N}$. The main background from coherent ϕ photo-production is suppressed near the threshold energy because the momentum-transfer is high even at 0° due to the heavy mass of the ϕ meson. Thus, the $\sigma_{\phi N}$ in the nuclear medium is expected to be determined less ambiguously near the threshold energy as compared with those at high energies.

The experiment was carried out using the laser–electron photon facility at SPring-8 (LEPS). Photons were produced by backward Compton scattering with an ultra-violet Ar laser from 8 GeV electrons in the storage ring. The recoil electrons were momentum analyzed by a bending magnet in the storage ring, and were detected by a tagging counter placed at the exit of the bending magnet. The experimental setup is described elsewhere [12].

The nuclear targets used in the experiment were Li, C, Al, and Cu with thicknesses of 100, 36, 24, and 3 mm, respectively. All the targets used were natural. The Li target block was placed in a target box filled with Ar gas. The windows of the target box were sealed with 50 μm aramid sheets. To minimize the difference of the acceptances among different target thicknesses and to reduce a systematic error caused in the acceptance correction, each of the other three targets was set by dividing into three pieces with the same center of gravity and with the same standard deviation of the position along the photon beam direction as those of the Li target. To avoid the systematic errors due to the change of the beam conditions, targets were exchanged every two hours.

Charged particles produced at the target were detected at forward angles with the LEPS spectrometer which consisted of a dipole magnet, a silicon-strip vertex detector, three multi-wire drift chambers, a plastic scintillator behind the target (SC), and a plastic scintillator hodoscope placed downstream of the tracking detectors [12]. A particle mass for each track was reconstructed by using the time of flight and momentum information. Kaons were identified within 4σ of the mass resolution, which was momentum dependent and was about 30 MeV/c^2 for 1 GeV/c kaons. The pion contamination in kaons due to particle misidentification was 3% for 1 GeV/c kaons. The ϕ mesons produced in the targets were selected by utilizing the vertex position of the K^+K^- events along the photon beam direction as shown in Fig. 1(a). The position resolution at SC was typically 2 mm, and the K^+K^- events produced at SC was clearly separated. Fig. 1(b) shows the K^+K^- invariant mass spectrum for the $\gamma\mathrm{Cu} \to K^+K^-X$ reaction. A clear peak was observed, and similar peaks were observed for the same reaction on other targets as well.

The measured mass and width are consistent with those of the free ϕ meson [13]. The experimental shape of the peak in the invariant mass spectrum has been fitted by the sum of a Breit–Wigner function convoluted with a Gaussian resolution function and a background term,

$$N(m) = C \int_{-\infty}^{+\infty} L(m_0, \Gamma_0; m') \frac{1}{\sqrt{2\pi\sigma_0^2}} \times e^{-(m-m')^2/2\sigma_0^2}\, dm' + bB(m), \tag{1}$$

where σ_0 denotes the resolution, and $L(m_0, \Gamma_0; m)$ represents the Breit–Wigner function with the centroid of m_0 and the width of Γ_0. The background term $B(m)$ is assumed to have a shape same as those for non-resonant K^+K^- production, which are calculated by a Monte Carlo (MC) simulation with the assumption of the three-body phase space of the reaction $\gamma N \to K^+K^-N$. In the case that σ_0 is fixed to the values predicted by the MC simulation, the fitted mass m_0 and width Γ_0 of the ϕ meson are consistent with those in free space, where the fitting region was 1000–1060 MeV/c^2. The mass and width of the ϕ meson would not change from its free-space values since almost all the ϕ mesons decay outside a nucleus ($\gtrsim 95\%$) in the momentum range from 1.0 to 2.2 GeV/c. In the case that the σ_0 for each target is treated as a free parameter instead of Γ_0, the fitted value of σ_0 is consistent with the value estimated by the MC simulation. The predicted σ_0 and the fitting results are summarized in Table 1.

To determine the background subtracted ϕ-yield normalized by incident photon numbers, first, the ϕ meson events, N_{KK}, are selected by gating the K^+K^- events in the K^+K^- invariant mass spectrum from 1005 to 1035 MeV/c^2 (see Fig. 1(b)). The number of background events in the ϕ peak region, N_{BG}, are estimated by

$$N_{\mathrm{BG}} = N_{\mathrm{tail}} \frac{N_{\mathrm{peak}}^{\mathrm{MC}}}{N_{\mathrm{tail}}^{\mathrm{MC}}}, \tag{2}$$

where N_{tail} means the observed number of events in the tail region from 1050 to 1100 MeV/c^2. The $N_{\mathrm{peak}}^{\mathrm{MC}}$ and $N_{\mathrm{tail}}^{\mathrm{MC}}$ are the estimated number of events in the region of 1005–1035 and 1050–1100 MeV/c^2, respectively, for the calculated non-resonant K^+K^- events. The fraction of the background events is small (5–7%). The background events due to mis-identification of a pion as a kaon are negligibly small.

The number of events for ϕ photo-production cross section is normalized by taking into account the number of hits in the tagging counter, N_{tag}, the attenuation of the photon flux in the target material, η_{att}, the number of target nuclei, N_τ, the live time of the data taking system, η_{DAQ}, and the acceptance correction, η_{acc}. The normalized number of events, Y, is then written as

$$Y = \frac{N_{KK} - N_{\mathrm{BG}}}{N_{\mathrm{tag}} N_\tau \eta_{\mathrm{att}} \eta_{\mathrm{DAQ}} \eta_{\mathrm{acc}}}. \tag{3}$$

The normalized number of ϕ photo-production events for each target is estimated by averaging data for horizontally and vertically polarized incident photons to reduce the ambiguity in acceptance correction due to the different decay asymmetry [14]. The transmission rate, i.e., survival rate of tagged photons at the tar-

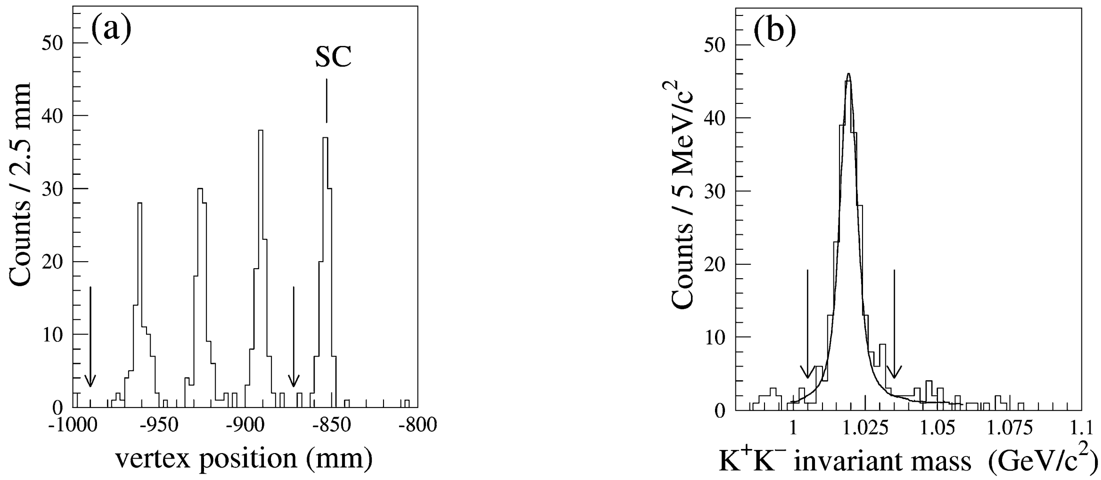

Fig. 1. (a) The vertex position distribution of the K^+K^- events along the photon beam direction for the $\gamma\mathrm{Cu} \to K^+K^-X$ reaction. The cut points to select the K^+K^- events generated at the target are indicated by the arrows. (b) The K^+K^- invariant mass spectrum for Cu. The solid curve shows the fitting result with the free m_0 and Γ_0 parameters given in the text. The cut points to select the ϕ events are indicated by the arrows.

Table 1
The summary of the invariant mass resolution σ_0 and the fitting results. (a) The invariant mass resolutions predicted by the Monte Carlo (MC) simulation. (b) The fitting results in the case that σ_0 is fixed to be the value estimated in the MC simulation. (c) The fitting results in the case that the width of the ϕ meson, Γ_0, for each target is fixed to be the same as that of the free ϕ meson (4.26 MeV/c^2 [13])

Parameter (MeV/c^2)		Li	C	Al	Cu
(a)	σ_0	1.6 ± 0.1	1.9 ± 0.1	2.3 ± 0.1	2.1 ± 0.1
(b)	m_0^{fit}	1019.7 ± 0.2	1020.1 ± 0.3	1019.5 ± 0.3	1019.3 ± 0.3
	Γ_0^{fit}	3.4 ± 0.4	5.0 ± 0.7	4.9 ± 0.8	4.9 ± 0.8
(c)	m_0^{fit}	1019.7 ± 0.2	1020.1 ± 0.3	1019.5 ± 0.3	1019.3 ± 0.3
	σ_0^{fit}	1.3 ± 0.4	2.0 ± 0.5	2.3 ± 0.4	2.4 ± 0.4

get position, is needed for determining the ϕ photo-production cross section. However, $\sigma_{\phi N}$ can be determined directly from the normalized number of events which is proportional to the ϕ photo-production cross section since the transmission rate is the same for all the targets. The number of events and the normalization factors are summarized in Table 2.

The measured momentum-transfer square $|t|$ ranges up to 0.6 GeV$^2/c^2$. Fig. 2(a) shows the $\tilde{t} = |t| - |t|_{\mathrm{min}}$ distribution for C, where $|t|_{\mathrm{min}}$ is the minimum $|t|$ given under the assumption that the target is a proton at rest. The $\tilde{t}$ distribution is fitted with a function of $d\sigma/d\tilde{t} = C\exp(-b\tilde{t})$ in the region of $\tilde{t} =$ 0.0–0.5 GeV$^2/c^2$. The slope parameters, b, are 3.6 ± 0.9, 4.5 ± 1.0, 3.1 ± 0.9, and 4.5 ± 1.0 (GeV$^2/c^2)^{-1}$ for Li, C, Al, and Cu, respectively. Any of these slope parameters is consistent with that for ϕ photo-production on the proton, $b = 2.1$–3.0 (GeV$^2/c^2)^{-1}$ at SAPHIR [15], or $b = 3.38 \pm 0.23$ (GeV$^2/c^2)^{-1}$ at LEPS [14]. The number of all the ϕ events for each target is found to be proportional to $A^{0.63\pm0.05}$ as shown in Fig. 2(b).

It is reported in Ref. [16] that the contribution of the coherent process cannot be negligibly small especially for light nuclear targets even at $E_\gamma \sim 2$ GeV. The coherent production in Li has been evaluated in the missing energy spectrum. The missing energy, E_x, is defined as

$$E_x = m_X - m_A, \tag{4}$$

where m_X is the missing mass in the reaction $\gamma A \to \phi X$, and m_A stands for the mass of the target nucleus.

Table 2
Summary of the number of events and the normalization factors. N_{KK}: the observed number of the K^+K^- events in the ϕ peak region, N_{BG}: the estimated number of background events in the ϕ peak region, N_{tag}: the tagged photon flux, η_{att}: the attenuation of the photon flux in the target material, N_τ: the number of target nuclei, η_{DAQ}: the live time of the data taking system, and η_{acc}: the acceptance correction

	Li	C	Al	Cu
N_{KK}	348	267	286	238
N_{BG}	21.3 ± 4.5	16.4 ± 4.1	21.4 ± 4.5	11.2 ± 3.2
$N_{tag} \times 10^{-10}$	7.15	6.97	9.76	23.31
$N_\tau \times 10^{-23}$	4.63	3.12	1.45	0.254
η_{att}	0.976	0.948	0.906	0.926
η_{DAQ}	0.922	0.899	0.874	0.911
$\eta_{acc} \times 10^2$	5.84 ± 0.06	5.74 ± 0.06	5.79 ± 0.07	6.12 ± 0.07

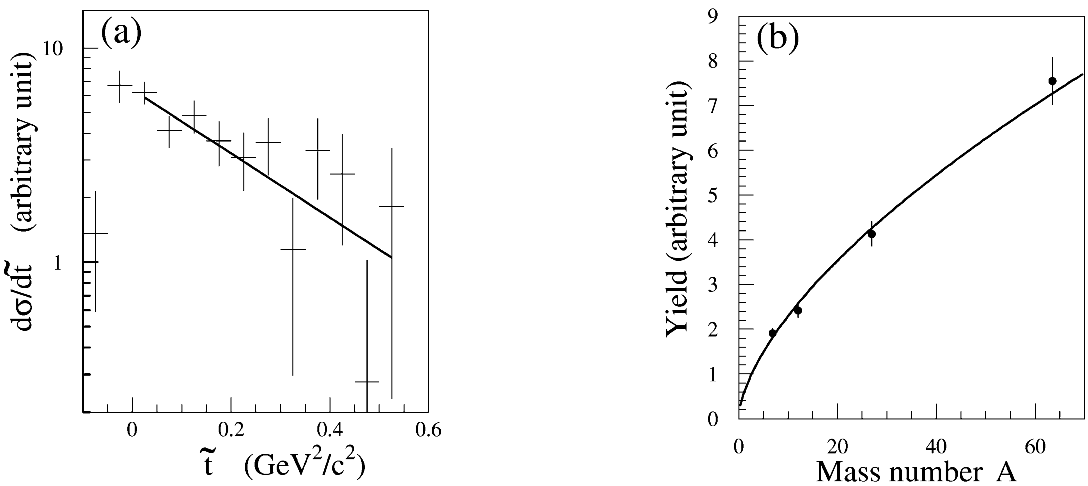

Fig. 2. (a) The $\tilde{t} = |t| - |t|_{min}$ distribution for the $\gamma C \to K^+K^-X$ reaction. The data points are fitted with the form $d\sigma/d\tilde{t} = C\exp(-b\tilde{t})$. (b) The A-dependence of the ϕ meson photo-production from nuclei. The data points are fitted with the parameterization $A^{0.63}$. The error bars for the data are statistical only.

Fig. 3(a) shows the missing energy spectrum for Li together with the simulation results for the coherent $\gamma A \to \phi A$ and the incoherent $\gamma N \to \phi N$ processes. The Fermi motion and the binding energy are taken into account for the incoherent process in the MC simulation. The missing energy spectrum of coherent ϕ photo-production concentrates at 0 MeV within the experimental resolution, and that of incoherent production is distributed in the positive energy region. The missing energy spectrum for the coherent process is symmetrical around 0 MeV with a resolution of 19 MeV (σ). Assuming that there are no ϕ events produced incoherently in the negative E_x region, the total coherent events are estimated to be twice the number of events in the negative E_x region. The number of the coherent ϕ photo-production events in Li is then 82.0 ± 12.8.

Since the coherent contribution is relatively small for the heavier target, the incoherent events in the negative E_x region may not be negligible. The coherent ϕ contributions in the other targets are evaluated theoretically using the estimated one in Li as an input. The contribution of the coherent process is proportional to the square of the nuclear form factor [18],

$$\frac{d\sigma}{dq} \propto \left|AF(q)\right|^2, \tag{5}$$

where q is the three-dimensional momentum-transfer. The coherent contribution is evaluated by integrating $d\sigma/dq$ over the kinematically allowed region of q.

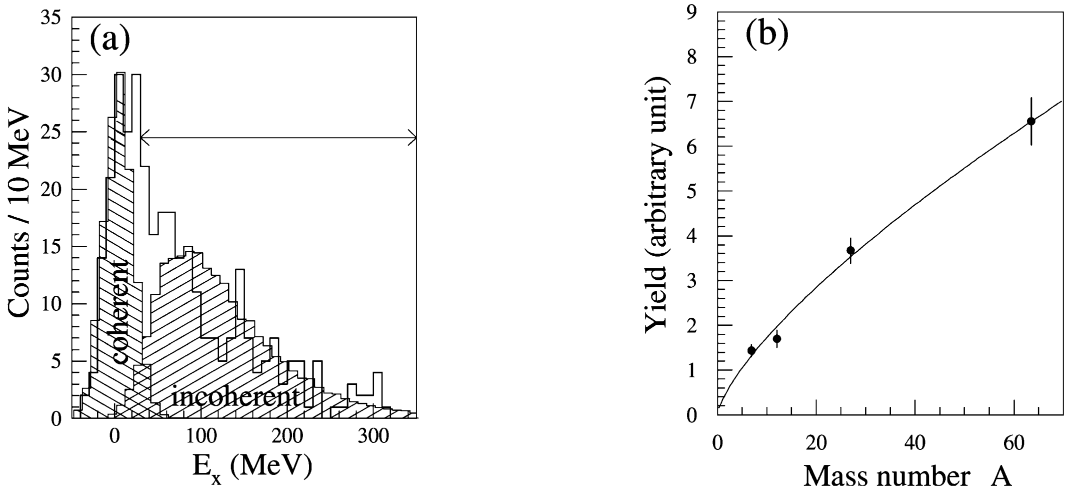

Fig. 3. (a) The missing energy spectrum of ϕ photo-production for the Li target. The hatched regions show the calculated spectra for the coherent and incoherent processes by the Monte Carlo simulation, and the normalization is made to guide the eyes. (b) The A-dependence of the number of events for ϕ photo-production from nuclei after the contribution of coherent production is subtracted. The data points are fitted with the parameterization $A^{0.72}$.

The number of ϕ mesons produced coherently is then estimated to be 72.9 ± 11.4, 30.9 ± 4.8, and 30.4 ± 4.7 for C, Al, and Cu, respectively. After subtracting the coherent contribution as the background, the normalized number of events gives a relation $\sigma_A \propto A^{0.72 \pm 0.07}$ as shown in Fig. 3(b).

In order to determine $\sigma_{\phi N}$ from the A-dependence of the ϕ photo-production yield, an optical model of a Glauber-type multiple scattering theory for incoherent production is applied [11]. In this model, the production cross section from a nucleus, $d\sigma_A^{\text{inc}}/dt$, is described as

$$\frac{d\sigma_A^{\text{inc}}}{dt} = A_{\text{eff}} \frac{d\sigma_N}{dt}, \tag{6}$$

where A_{eff} is the effective nucleon number and $d\sigma_N/dt$ is the production cross section on the nucleon. The A_{eff} for ϕ photo-production is expressed as a function of A, $\sigma_{\gamma N}$, and $\sigma_{\phi N}$;

$$A_{\text{eff}}(A, \sigma_{\gamma N}, \sigma_{\phi N}) = \frac{1}{\sigma_{\phi N} - \sigma_{\gamma N}} \int \left(e^{-\sigma_{\gamma N} T(\vec{b})} - e^{-\sigma_{\phi N} T(\vec{b})}\right) d^2 b,$$

$$T(\vec{b}) = A \int_{-\infty}^{+\infty} \rho(\vec{b}, z)\, dz, \tag{7}$$

where $\sigma_{\gamma N}$ stands for the total photon–nucleon cross section, $\vec{b}$ denotes the impact vector of the incident photon, and ρ is the nucleon density of the target nucleus. The effect of quasi-elastic collision between a ϕ meson and a nucleon in the nucleus is not included in Eq. (6) since the direction and energy change of the outgoing ϕ meson is small because of the small direct ϕNN coupling [16]. Assuming the same $d\sigma_N/dt$ for the proton and for the neutron, $\sigma_{\phi N}$ can be derived from the A-dependence of the ϕ photo-production cross sections. In this case, the absolute values of $d\sigma_A^{\text{inc}}/dt$ are not necessary. The normalized number of events for ϕ photo-production from nuclei, defined by Eq. (3) as Y, is described by that for ϕ photo-production on the nucleon, Y_N, and A_{eff}:

$$Y = A_{\text{eff}}(A, \sigma_{\gamma N}, \sigma_{\phi N}) \cdot Y_N. \tag{8}$$

The $\sigma_{\gamma N}$ is fixed to be 140 μb in the energy range from 1.5 to 2.4 GeV [13]. The nucleon density is given by normalizing the charge density distribution [17], where the proton and neutron density distributions are assumed to have the same r-dependence. The same branching ratio of the $\phi \to K^+K^-$ process for each target nucleus is used since almost all the ϕ mesons decay outside the nucleus. The measured Y values are fitted by Eq. (8) with $\sigma_{\phi N}$ and Y_N as free parameters. The value of $\sigma_{\phi N}$ is estimated to be 35^{+17}_{-11} mb from

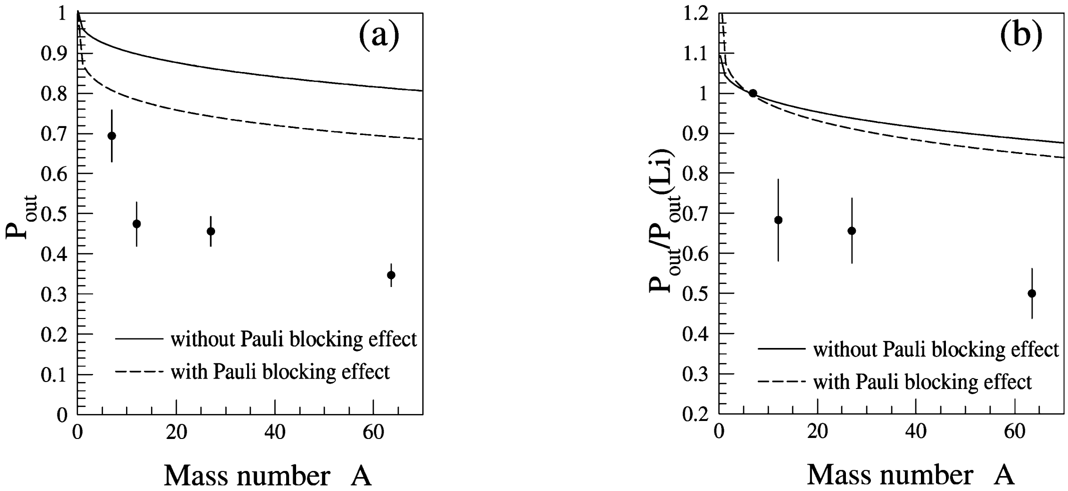

Fig. 4. (a) The probability $P_{out} = \sigma_A/(A\sigma_N)$. The overall normalization error (18%) is not included. The solid and dashed curves show the theoretical calculations given by Cabrera et al. [16] without and with Pauli-blocking correction for the ϕ meson scattering angle in the laboratory frame of 0°, respectively. (b) The ratio $P_{out}/P_{out}(\mathrm{Li})$. The solid and dashed curves show the theoretical calculations same as (a).

the A-dependence of the number of the ϕ events after the coherent contribution is subtracted.

As a cross check, the coherent contributions for the other targets are estimated using the exactly same technique as in the case of Li. In this case, σ_A is proportional to $A^{0.73\pm0.07}$, and $\sigma_{\phi N}$ is estimated to be 34^{+17}_{-11} mb. These are consistent with the former results. Similar results are also obtained by selecting the kinematical region for the incoherent process instead of subtracting the coherent contribution. When the events with E_x larger than 30 MeV are selected, $\sigma_A \propto A^{0.74\pm0.06}$ and $\sigma_{\phi N} = 30^{+12}_{-8}$ mb are obtained. The results are stable even if the missing energy cut is tightened up to 80 MeV. These values obtained in this experiment are much larger than $\sigma_{\phi N}$ free space, indicating the modification of the ϕ–N scattering amplitude in the nuclear medium.

On the basis of the ϕ self-energy in the nuclear medium, Cabrera et al. presents the A-dependence of the ϕ photo-production cross section from nuclei in terms of the variable $P_{out} = \sigma_A/(A\sigma_N) = Y/(AY_N)$, which represents the probability of a photo-produced ϕ meson going out a nucleus [16]. Fig. 4(a) shows the obtained P_{out} in the experiment and theoretical predictions given by Cabrera et al. as a function of A. It is noted that the averaged momentum of ϕ mesons in the present experiment is $\langle P_\phi \rangle = 1.8$ GeV$/c$, while theoretical predictions are made for $P_\phi = 2.0$ GeV$/c$. The obtained P_{out} are smaller than the theoretical predictions. The ϕ meson flux obtained in the experiment is almost half of the theoretical predictions. The absolute value of P_{out} obtained in the experiment depends on an applied model to deduce Y_N. However, the ratio of $P_{out}/P_{out}(\mathrm{Li})$ is model-independent. The ratios are smaller than the theoretical predictions as shown in Fig. 4(b). The theoretical calculations underestimate the decrease of photo-produced ϕ meson flux in the nucleus. This discrepancy implies that the ϕ–N interaction is stronger than theoretical estimations due to the modification of the ϕ properties in the nuclear medium.

In summary, the photo-production of ϕ mesons from Li, C, Al, and Cu nuclei at forward angles has been measured at $E_\gamma = 1.5$–2.4 GeV. The mass and width of the ϕ meson observed in the K^+K^- invariant mass spectrum are consistent with those of the free ϕ meson for all the nuclear targets used. There is a possibility that the reconstructed invariant mass is insensitive to possible in-medium modification of the ϕ meson for the high momenta of the measured ϕ mesons (1.0–2.2 GeV$/c$).

The A-dependence of the ϕ photo-production yields for $|t| \leqslant 0.6$ GeV$^2/c^2$ is found to be proportional to $A^{0.63\pm0.05}$. After subtracting the coherent contribution evaluated from the nuclear form factor, the yields are found to have the A-dependence of $A^{0.72\pm0.07}$. The total cross section of the ϕ-nucleon interaction, $\sigma_{\phi N}$, is estimated to be 35^{+17}_{-11} mb from the A-dependence. This value is much larger than $\sigma_{\phi N}$ in free space, suggesting that the ϕ properties might change in the nuclear medium although the change of the mass and width is not observed in the K^+K^- invariant mass spectra. The ratio $P_{\text{out}}/P_{\text{out}}(\text{Li})$ is smaller than the theoretical predictions, which implies that the in-medium modification might be larger than the predictions. It should be noted that there is still an ambiguity of the $\sigma_{\phi N}$ value in free space at low energies. It is important to establish the production mechanism for ϕ photoproduction on the proton near the threshold and to confirm the $\sigma_{\phi N}$ value in free space at low energies.

Acknowledgements

The authors wish to thank the SPring-8 staff for their dedicated efforts of providing a high quality beam. They also thank all the people who contributed to the construction of the LEPS facility. They gratefully acknowledge Dr. K. Hasegawa (Honjo Metal Co. Ltd.) for making the Li target suitable for the present experiment.

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