\( \phi \) photo-production from Li, C, Al, and Cu nuclei at \( E_\gamma = 1.5–2.4 \) GeV

T. Ishikawa\(^{a,1}\), D.S. Ahn\(^{b,2}\), J.K. Ahn\(^{b}\), H. Akimune\(^{c}\), W.C. Chang\(^{d}\), S. Daté\(^{e}\), H. Fujimura\(^{f,g}\), K. Hicks\(^{h}\), T. Hotta\(^{f}\), K. Imai\(^{a}\), H. Kawai\(^{i}\), K. Kino\(^{f}\), H. Kohri\(^{f}\), T. Matsumura\(^{f,g,4}\), T. Mibe\(^{f,g,5}\), K. Miwa\(^{a}\), M. Miyabe\(^{a}\), M. Morita\(^{f}\), T. Murakami\(^{a}\), N. Muramatsu\(^{g,2}\), H. Nakamura\(^{k}\), M. Nakamura\(^{a,6}\), T. Nakano\(^{f}\), M. Niiyama\(^{a}\), M. Nomachi\(^{k}\), Y. Ohashi\(^{e}\), T. Ooba\(^{i}\), D.S. Oshuev\(^{d}\), C. Rangacharyulu\(^{j}\), A. Sakaguchi\(^{k}\), Y. Shiino\(^{i}\), Y. Sakemi\(^{f}\), H. Shimizu\(^{f}\), Y. Sugaya\(^{k}\), M. Sumihama\(^{k,g,7}\), Y. Toi\(^{m}\), H. Toyokawa\(^{e}\), C.W. Wang\(^{d}\), T. Yorita\(^{f,8}\), M. Yosoi\(^{a}\), R.G.T. Zegers\(^{f,9}\)

\(^{a}\) Department of Physics, Kyoto University, Kyoto 606-8502, Japan
\(^{b}\) Department of Physics, Pusan National University, Busan 609-735, Korea
\(^{c}\) Department of Physics, Konan University, Kobe 658-8501, Japan
\(^{d}\) Institute of Physics, Academia Sinica, Taipei 11529, Taiwan
\(^{e}\) Japan Synchrotron Radiation Research Institute, Mikazuki 679-5198, Japan
\(^{f}\) Research Center for Nuclear Physics, Osaka University, Ibaraki 567-0047, Japan
\(^{g}\) Advanced Science Research Center, Japan Atomic Energy Research Institute, Tokai 319-1195, Japan
\(^{h}\) Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA
\(^{i}\) Graduate School of Science and Technology, Chiba University, Chiba 263-8522, Japan
\(^{j}\) Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, Saskatchewan S7N5E2, Canada
\(^{k}\) Department of Physics, Osaka University, Toyonaka 560-0043, Japan
\(^{l}\) Laboratory of Nuclear Science, Tohoku University, Sendai 982-0826, Japan
\(^{m}\) Physical Engineering Group, Miyazaki University, Miyazaki 889-2192, Japan

Abstract
The photo-production of $\phi$ 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 $\phi$ photo-production is found to have a target mass number dependence of $A^{0.72\pm0.07}$ in the kinematical region of $|t| \leq 0.6$ GeV$^2/c^2$. The total cross section of the $\phi$-nucleon interaction, $\sigma_{\phi N}$, has been estimated as $35^{\pm17}_{\pm11}$ mb using the $A$-dependence of the $\phi$ 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 $\phi$ properties might change in the nuclear medium.

**Key words:**

**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 $\phi$ meson in the nuclear medium because of partial restoration of chiral symmetry [1] or the meson-nucleon interaction in the nuclear medium [2,3,4]. The mass shift of the $\phi$ 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 $\phi$-$N$ cross section, $\sigma_{\phi N}$, should be small since the $\phi$ 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 $\phi$ photo-production cross section from a nucleus, $\sigma_{\phi N}^{inc}$, is approximately proportional to the target mass number, $A$, since almost all the produced $\phi$ mesons are expected to go outside the nucleus without interacting with a nucleon. If $\sigma_{\phi N}$ becomes larger in the

---

*Email address: ishikawa@lns.tohoku.ac.jp (T. Ishikawa).*

1 Present address: Laboratory of Nuclear Science, Tohoku University, Sendai 982-0826, Japan
2 Present address: Research Center for Nuclear Physics, Osaka University, Ibaraki 567-0047, Japan
3 Present address: Department of Physics, Kyoto University, Kyoto 606-8502, Japan
4 Present address: Department of Applied Physics, National Defense Academy, Yokosuka 239-8686, Japan
5 Present address: Department of Physics and Astronomy, Ohio University, Ohio 45701, USA
6 Present address: Department of Physics, Liberal Arts and Sciences, Wakayama Medical University, Wakayama 641-8509, Japan
7 Present address: Department of Physics, Tohoku University, Sendai 980-8578, Japan
8 Present address: Japan Synchrotron Radiation Research Institute, Mikazuki 679-5198, Japan
9 Present address: National Superconducting Cyclotron Laboratory, Michigan State University, Michigan 48824, USA
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 sizeably deviates from \( \sigma_A \propto A^1 \).

Only one measurement of φ photo-production from various nuclei is reported at \( E_\gamma = 6.4–9.0 \text{ GeV} \) [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, \( d\sigma/dt|_{t=0} \), at \( E_\gamma = 4.6–6.7 \text{ GeV} \), where the energy dependence of the \( \gamma-\phi \) 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, \( d\sigma^\text{inc}/dt \), is described as a product of the φ photo-production cross section on the nucleon, \( d\sigma_N/dt \), and the effective nucleon number, \( A_{\text{eff}} \), 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 mm, 36 mm, 24 mm, 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 $4\sigma$ 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 mis-identification was 3% for 1 GeV/$c$ kaons. The $\phi$ 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 $\gamma\text{Cu} \rightarrow K^+K^-X$ 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 $\phi$ 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,

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

where $L(m_0, \Gamma_0; m')$ is the Breit-Wigner function and $\sigma_0$ is the width of the Gaussian resolution function.
where $\sigma_0$ 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 $\Gamma_0$. 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 $\gamma N \rightarrow K^+K^-N$. In the case that $\sigma_0$ is fixed to the values predicted by the MC simulation, the fitted mass $m_0$ and width $\Gamma_0$ of the $\phi$ meson are consistent with those in free space, where the fitting region was $1000–1060$ MeV/$c^2$. The mass and width of the $\phi$ meson would not change from its free-space values since almost all the $\phi$ mesons decay outside a nucleus ($\gtrsim 95\%$) in the momentum range from 1.0 to 2.2 GeV/$c$. In the case that the $\sigma_0$ for each target is treated as a free parameter instead of $\Gamma_0$, the fitted value of $\sigma_0$ is consistent with the value estimated by the MC simulation. The predicted $\sigma_0$ and the fitting results are summarized in Table 1.

Table 1
The summary of the invariant mass resolution $\sigma_0$ and the fitting results. (a) The invariant mass resolutions predicted by the Monte Carlo (MC) simulation. (b) The fitting results in the case that $\sigma_0$ is fixed to be the value estimated in the MC simulation. (c) The fitting results in the case that the width of the $\phi$ meson, $\Gamma_0$, for each target is fixed to be the same as that of the free $\phi$ meson (4.26 MeV/$c^2$ [13]).

| parameter (MeV/$c^2$) | Li   | C     | Al    | Cu    |
|------------------------|------|-------|-------|-------|
| (a) $\sigma_0$         | 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 |
| $\Gamma_0^{fit}$       | 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 |
| $\sigma_0^{fit}$       | 1.3 ± 0.4 | 2.0 ± 0.5 | 2.3 ± 0.4 | 2.4 ± 0.4 |

To determine the background subtracted $\phi$-yield normalized by incident photon numbers, first, the $\phi$ 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 $\phi$ peak region, $N_{BG}$, are estimated by

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

(2)

where $N_{tail}$ means the observed number of events in the tail region from 1050 to 1100 MeV/$c^2$. The $N_{MC}^{peak}$ and $N_{MC}^{tail}$ 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, \( N_{\text{tag}} \), the attenuation of the photon flux in the target material, \( \eta_{\text{att}} \), the number of target nuclei, \( N_{\tau} \), the live time of the data taking system, \( \eta_{\text{DAQ}} \), and the acceptance correction, \( \eta_{\text{acc}} \). The normalized number of events, \( Y \), is then written as

\[
Y = \frac{N_{KK} - N_{BG}}{N_{\text{tag}}N_{\tau}\eta_{\text{att}}\eta_{\text{DAQ}}\eta_{\text{acc}}}.
\]  

(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 target 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.

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, \( N_{\text{tag}} \): the tagged photon flux, \( \eta_{\text{att}} \): the attenuation of the photon flux in the target material, \( N_{\tau} \): the number of target nuclei, \( \eta_{\text{DAQ}} \): the live time of the data taking system, and \( \eta_{\text{acc}} \): 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 |
| \( N_{\text{tag}} \times 10^{-10} \) | 7.15 | 6.97 | 9.76 | 23.31 |
| \( N_{\tau} \times 10^{-23} \) | 4.63 | 3.12 | 1.45 | 0.254 |
| \( \eta_{\text{att}} \) | 0.976 | 0.948 | 0.906 | 0.926 |
| \( \eta_{\text{DAQ}} \) | 0.922 | 0.899 | 0.874 | 0.911 |
| \( \eta_{\text{acc}} \times 10^2 \) | 5.84 ± 0.06 | 5.74 ± 0.06 | 5.79 ± 0.07 | 6.12 ± 0.07 |

The measured momentum-transfer square \( |t| \) ranges up to 0.6 GeV\(^2\)/c\(^2\). Fig. 2 (a) shows the \( \tilde{t} = |t| - |t|_{\text{min}} \) distribution for C, where \( |t|_{\text{min}} \) 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 pro-
Fig. 2. (a) The $\tilde{t} = |t| - |t|_{\text{min}}$ 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 $\phi$ meson photo-production from nuclei. The data points are fitted with the parameterization $A^{0.63}$.

In order to determine $\sigma_{\phi N}$ from the $A$-dependence of the $\phi$ 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, $d\sigma_{\text{inc}}^A / dt$, is described as

$$\frac{d\sigma_{\text{inc}}^A}{dt} = A_{\text{eff}} \frac{d\sigma_N}{dt},$$

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

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

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

where $\sigma_{\gamma N}$ stands for the total photon-nucleon cross section, $\vec{b}$ denotes the impact vector of the incident photon, and $\rho$ is the nucleon density of the target nucleus. The effect of quasi-elastic collision between a $\phi$ meson and a nucleon in the nucleus is not included in Eq. (4) since the direction and energy change of the outgoing $\phi$ meson is small because of the small direct $\phi NN$ 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 $\phi$ photo-production cross sections. In this case, the absolute values of $d\sigma_A/dt$ are not necessary. The $\sigma_{\gamma N}$ is fixed to be $140\ \mu$b in the energy range from 1.5 to 2.4 GeV [13]. The nucleon density is given by normalizing the charge density distribution [15], 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 $\phi$ mesons decay outside the nucleus. The value of $\sigma_{\phi N}$ is estimated to be $71^{+32}_{-19}$ mb from the $A$-dependence of the number of all the $\phi$ events. This value is much larger than other meson-nucleon total cross sections. This is attributed to the coherent production contribution as described below.

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

$$E_x = m_X - m_A,$$  

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. 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 $\phi$ photo-production concentrates at 0 MeV within the experimental resolution, and that of incoherent production 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 $\phi$ 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 [17],

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

where $q$ is the three dimensional momentum-transfer. The coherent contribution is evaluated by integrating $d\sigma/dq$ over the kinematically allowed region
Fig. 3. (a) The missing energy spectrum of $\phi$ 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 $\phi$ photo-production from nuclei after the contribution of coherent production is subtracted. The data points are fitted with the parameterization $A^{0.72}$.

of $q$. The number of $\phi$ mesons produced coherently is then estimated to be $72.9 \pm 11.4$, $30.9 \pm 4.8$, and $30.4 \pm 4.7$ 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), from which $\sigma_{\phi N}$ is deduced, and is found to be $35_{-11}^{+17}$ mb. 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, $\sigma_A$ is proportional to $A^{0.73 \pm 0.07}$, and $\sigma_{\phi N}$ is estimated to be $34_{-11}^{+17}$ 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, $\sigma_A \propto A^{0.74 \pm 0.06}$ and $\sigma_{\phi N} = 30_{-8}^{+12}$ 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 $\sigma_{\phi N}$ in free space, indicating the modification of the $\phi$-$N$ scattering amplitude in the nuclear medium.

On the basis of the $\phi$ self-energy in the nuclear medium, Cabrera et al. presents the $A$-dependence of the $\phi$ photo-production cross section from nuclei in terms of the variable $P_{\text{out}} = \sigma_A/(A\sigma_N)$, which represents the probability of a photo-produced $\phi$ meson going out a nucleus [16]. The $P_{\text{out}}$ is deduced by using $Y$ described in Eq. (3) and the normalized number of events for $\phi$ photo-production on the nucleon, $Y_0$, which is deduced from the present data by using a Glauber-type multiple scattering theory. Fig. 4 (a) shows the obtained $P_{\text{out}}$ in the experiment and theoretical predictions given by Cabrera et al.
Fig. 4. (a) The probability $P_{\text{out}} = \sigma_A/(A\sigma_N)$. 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 $\phi$ meson scattering angle in the laboratory frame of $0^\circ$, respectively. (b) The ratio $P_{\text{out}}/P_{\text{out}}(\text{Li})$. The solid and dashed curves show the theoretical calculations same as (a).

As a function of $A$. It is noted that the averaged momentum of $\phi$ mesons in the present experiment is $\langle P_\phi \rangle = 1.8 \text{ GeV}/c$, while theoretical predictions are made for $P_\phi = 2.0 \text{ GeV}/c$. The obtained $P_{\text{out}}$ are smaller than the theoretical predictions. The $\phi$ meson flux obtained in the experiment is almost half of the theoretical predictions. The absolute value of $P_{\text{out}}$ obtained in the experiment depends on an applied model to deduce $Y_0$. However, the ratio of $P_{\text{out}}/P_{\text{out}}(\text{Li})$ 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 $\phi$ meson flux in the nucleus. This discrepancy implies that the $\phi$-$N$ interaction is stronger than theoretical estimations due to the modification of the $\phi$ properties in the nuclear medium.

In summary, the photo-production of $\phi$ 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 $\phi$ meson observed in the $K^+K^-$ invariant mass spectrum are consistent with those of the free $\phi$ 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 $\phi$ meson for the high momenta of the measured $\phi$ mesons (1.0–2.2 GeV/$c$).

The $A$-dependence of the $\phi$ photo-production yields for $|t| \leq 0.6 \text{ GeV}^2/c^2$ is found to be proportional to $A^{0.63 \pm 0.05}$. After subtracting the coherent contribution evaluated from the nuclear form factor, the yields are found to have the $A$-dependence of $A^{0.72 \pm 0.07}$. The total cross section of the $\phi$-nucleon inter-
action, $\sigma_{\phi N}$, 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 $\phi$ 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.

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.

References

[1] T. Hatsuda, S.H. Lee, Phys. Rev. C 46 (1992) 34; G.E. Brown, M. Rho, Phys. Rept. 269 (1996) 333-380; G.E. Brown, M. Rho, Phys. Rev. Lett. 66 (1991) 2720; K. Saito, A.W. Thomas, Phys. Rev. C 51 (1995) 2757.

[2] E. Oset, M.J. Vicente Vacas, H. Toki, A. Ramos, Phys. Lett. B 508 (2001) 237; E. Oset, A. Ramos, Nucl. Phys. A 679 (2001) 616.

[3] D. Cabrera and M.J. Vicente Vacas, Phys. Rev. C 67 (2003) 045203.

[4] P. Mühlich, T. Falter, C. Greiner, J. Lehr, M. Post, U. Mosel, Phys. Rev. C 67 (2003) 024605.

[5] H. En’yo, et al., Nucl. Phys. A 670 (2000) 182c; H. En’yo, et al., Prog. Theor. Phys. Suppl. 149 (2003) 49; K. Ozawa, et al., Phys. Rev. Lett. 86 (2001) 5019.

[6] E-802 Collaboration, Y. Akiba, et al., Phys. Rev. Lett. 76 (1996) 2021.

[7] G. McClellan, et al., Phys. Rev. Lett. 25 (1971) 1593.

[8] H.-J. Behrend, et al., Phys. Lett. 56 B (1975) 408.

[9] H.J. Lipkin, Phys. Rev. Lett. 16 (1966) 1015.

[10] T.H. Bauer, R.D. Spital, D.R. Yannie, F.M. Pipkin, Rev. Mod. Phys. 50 (1978) 261, and references therein; M. Effenberger and A. Sibirtsev, Nucl. Phys. A 632 (1998) 99.
[11] K.S. Köbbing and B. Margolis, Nucl. Phys. B 6 (1968) 85;
    B. Margolis, Phys. Lett. 26 B (1968) 524.

[12] T. Nakano, et al., Nucl. Phys. A 684 (2001) 71c;
    T. Nakano, Nucl. Phys. A 721 (2003) 112c;
    T. Nakano, et al., Phys. Rev. Lett. 91 (2003) 012002;
    R.G.T. Zegers, et al., Phys. Rev. Lett. 91 (2003) 092001.

[13] K. Hagiwara, et al., Phys. Rev. D 66 (2002) 010001.

[14] T. Mibe, Doctor thesis, Osaka University (2004).

[15] H. de Vries, et al., Atom. Data Nucl. Data Tabl. 36 (1987) 495.

[16] D. Cabrera, L. Roca, E. Oset, H. Toki, M.J. Vicente Vacas, Nucl. Phys. A733
    (2004) 130.

[17] E. Oset, D. Cabrera, L. Roca, M.J. Vicente Vacas, private communication.