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Mainz Microtron MAMI

Collaboration A1: "Virtual Photons"

Spokesperson: H. Merkel

Proposal for an Experiment

Coherent ϕ-meson electro-production on nuclear targets

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Abstract

We propose an experiment on ϕ-meson electro-production on nuclear targets with the 1.5 GeV electron beam at the Mainz Microtron MAMI. The associated production of K^+K^- pairs very close to threshold offers the unique possibility to study the interaction of strange mesons under quasi-stationary conditions in cold nuclei at normal nuclear density. For low momentum ϕ-mesons decaying inside a nucleus the K^+K^- invariant mass may be modified. We present a result of a simulation study on the yield of reconstructed ϕ-mesons using the Kaos spectrometer and Spectrometer B or C at the spectrometer facility of the A1 collaboration.

1 Introduction

For hadrons consisting only of light u and d quarks, the dominant part of their mass is generated dynamically by the quark interaction inside the hadron and the self-interaction among gluons. An important role is played by the spontaneous breaking of the chiral symmetry, which is related to a non-zero expectation value of the chiral condensate. Properties of hadrons embedded in a strongly interacting environment are therefore expected to reflect both hadronic many-body effects, like the coupling of mesons to resonance-hole states, and the coupling of the modified mesons to resonances, as well as the spontaneous and explicit breaking of the chiral symmetry. Although there is at present no direct relation between the quark condensate and the in-medium properties of hadrons, QCD sum rules [1] provide a link between the QCD picture and the hadron picture.

Therefore, the question of how properties of hadrons change once they are embedded in nuclei is of fundamental interest. In particular the ϕ-meson provides an appealing probe for this field. The ϕ-meson is the lowest bound state of $s\bar{s}$ quarks. Its properties in nuclei are intimately connected to the way kaons and anti-kaons are modified in a nuclear medium [2, 3, 4] and may provide information on the in-medium strange-quark condensate $\langle s\bar{s}\rangle$ [1]. ϕ-mesons decaying within nuclei can be studied via the e^+e^- as well as the K^+K^- decay channels. Electrons practically do not interact with the nuclear medium while the kaons interact strongly inside nuclei. Thus, studying ϕ decays under well defined conditions in cold nuclei at normal nuclear density may allow us to disentangle medium properties of the ϕ-meson on one hand and properties of kaons propagating within a nucleus on the other hand. Concerning the experimental side, the natural width of the ϕ is rather narrow (($\Gamma_\phi = 4.26\,\mathrm{MeV}/c^2$) and it is not masked by other neighbouring resonances. Consequently, even the small medium modifications of typically few percent expected for the ϕ mass at normal nuclear density [3, 5, 6, 7, 8] may be observable.

Although the present maximum beam energy of MAMI-C of 1500 MeV is not sufficient for the elementary production of ϕ-mesons or K^+K^- pairs on an individual nucleon at rest (threshold $E_\gamma = 1574.4\,\mathrm{MeV}$), the coherent or quasi-free production on systems with more than one nucleon is possible. The associated production of K^+K^- pairs very close to threshold offers the unique possibility to study the interaction of strange mesons under quasi-stationary conditions in cold nuclei at normal nuclear density. For low momentum ϕ-mesons decaying inside a nucleus both—medium properties of the ϕ-meson and the propagation of the kaons—may effect the kaon kinematics. As a consequence, the K^+K^- invariant mass of the ϕ may be modified.

We present a result of a simulation study on the coherent electro-production of ϕ-mesons coherently on nuclear targets with the 1.5 GeV electron beam at the Mainz Microtron MAMI and the subsequent decay $\phi \to K^-K^+$. The invariant mass of the ϕ-meson will be reconstructed by detecting K^- in Spectrometer C (SpekC) or Spectrometer B (SpekB) and K^+ in Kaos. SpekC or SpekB will be positioned opposite to Kaos with respect to the beam-pipe. A schematic drawing of a possible set-up for the experiment is presented in Fig. 1. The experiment makes only moderate demands on the detection system. Since the spectrometers are positioned at rather large laboratory angles, the background load is tolerable. Also, the required momentum resolution is not very demanding. Clearly, the measurement

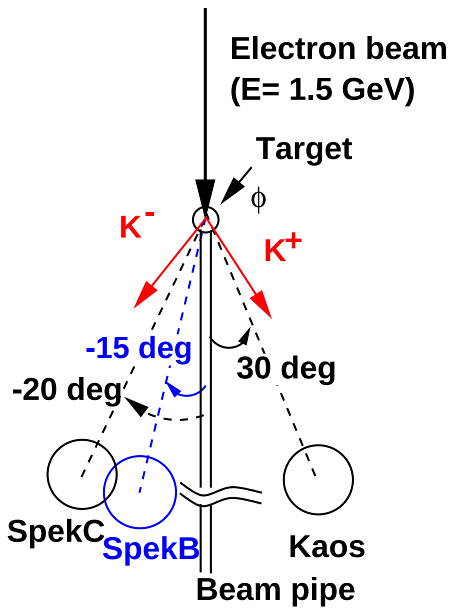

Figure 1: A possible set-up (top view) of the two spectrometers KAOS and SpekB or SpekC. Since the minimum angle of SpekC is $\vartheta_{C,min} = -37°$, the configuration of $\vartheta_C = -20°$ is possible only if SpekB is moved to $\vartheta_B \sim +90°$ on the other side of the beam-pipe. The minimum angle of SpekB is $\vartheta_{B,min} = -15.5°$.

has to be performed with different target materials.

2 State of knowledge

The mass distributions of ϕ-mesons produced in 12 GeV p + C and p + Cu reactions were recently measured in the $\phi \to e^+e^-$ and $\phi \to K^+K^-$ decay channels by the KEK-PS E325 Collaboration [13, 14]. In the ϕ momentum region $\beta\gamma > 1.25$ none of the decay channels revealed signs of a shape modification in the invariant mass distributions. On the other hand, for ϕ momenta less than 1.25 GeV/c the e^+e^- invariant mass distribution showed a significant excess on the low-mass side of the ϕ peak in case of the copper target [13] (see Fig. 2 (left)). This tail was interpreted as a decrease of the pole mass of the ϕ-resonance by 3.4% at normal nuclear density. If no broadening of the ϕ decay width is introduced, the expected fraction of in-nucleus decays would correspond to about 6% for the ϕ momentum range with $\beta\gamma$ <1.25. The fact that the yield in this enhancement corresponds to about 22% of all observed ϕ decays can be interpreted as an increase of Γ_ϕ^{ee} by a factor of 3.6 [13].

In case of the K^+K^- decay channel the experimental invariant mass resolution was about 2 MeV/c^2 in the KEK-E325 experiment [14]. Unfortunately, the statistics in the ϕ momentum region with $\beta\gamma$ <1.25 was very limited and no information on the shape of the ϕ resonance could be deduced.

Previously, the E-802 Collaboration measured the ϕ production in ^{28}Si + ^{196}Au at 14.6 AGeV/c in the K^+K^- decay mode with a mass resolution of about 3 MeV/c^2 [15]. In this experiment the position and the width of the peak were found to be consistent with those for a free ϕ-meson.

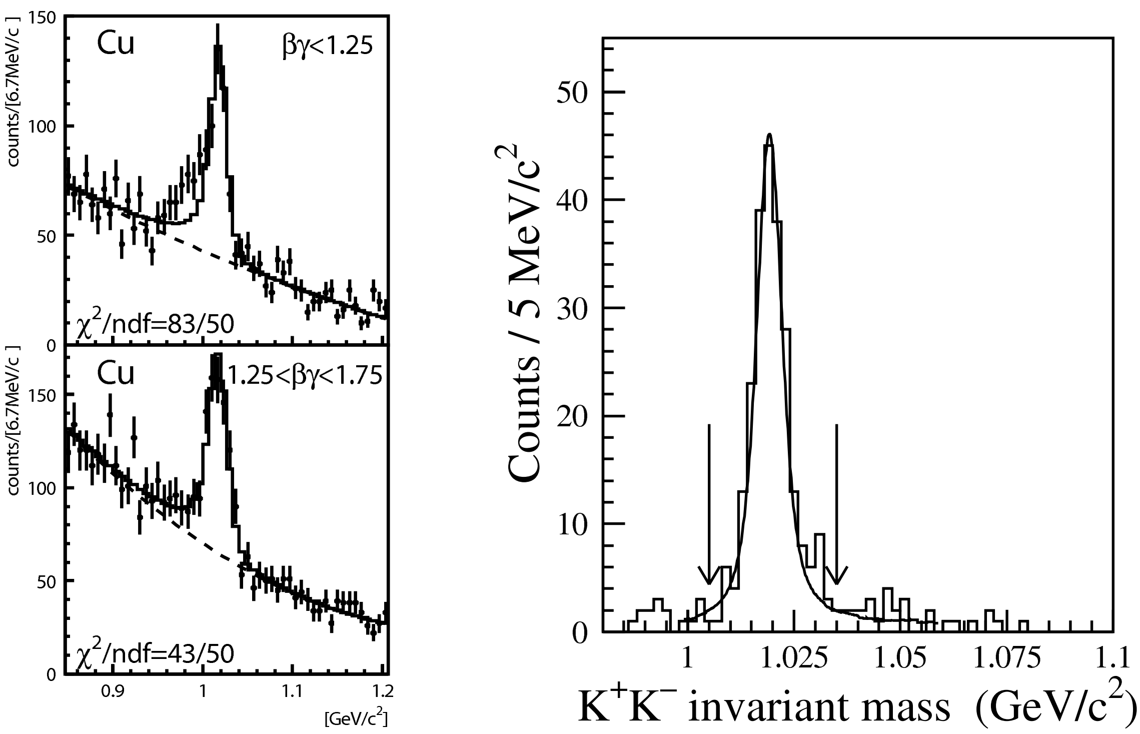

Figure 2: Left: The e^+e^- invariant mass spectrum measured in 12 GeV p + Cu interactions for two different ϕ momentum bins [13]. The width of the peaks reflects the mass resolution of 10.7 MeV/c^2. Right: The K^+K^- invariant mass spectrum measured for the γ + Cu $\rightarrow K^+K^- + X$ reaction at E_γ = 1.5–2.4 GeV [16].

At LEPS, Ishikawa *et al.* measured the photo-production of ϕ-mesons from various targets (Li, C, Al, Cu) at forward angles for γ energies between 1.5 and 2.4 GeV [16]. The ϕ-mesons were reconstructed from the K^+K^- invariant mass with a mass resolution of about 2.1 MeV/c^2. Fig. 2 (right) shows, as an example, the mass spectrum for the copper target. The observed mass and width of the ϕ-resonance observed was found to be consistent with those of the free meson for all nuclear targets. Because of the larger average momenta of the produced ϕ-mesons of 1.8 GeV/c, only 4% are expected to decay within the Cu nucleus. While the structure visible at M_x =0.99 GeV/c^2 in Fig. 2 may, on first sight, be compatible with such a number ($N \leq 9$ counts compared to 238 counts in the dominant peak) one has to keep in mind that due to the strong absorption of K^- the detection of K^+K^- pairs from in-nucleus decays are strongly suppressed (see discussion below). Thus, also in this experiment, the limited statistics does not allow further conclusions on in-nucleus decays.

As shown in Fig. 4, the differential cross section ($d\sigma/dt$) on the proton is given by in a form of $C \cdot \exp(-b \cdot t)$. Then the total cross section can be expressed as

$$\sigma_{tot} = \int_{|t|_{\min}=0.05}^{|t|_{\max}=\infty} C \cdot \exp(-b \cdot t) dt \,, \tag{1}$$

where the quantities C and b can be determined by experimental data. The values $|t|_{\min}$ and $|t|_{\max}$ are the minimum and maximum four-momentum transfers.

Very limited experimental information on coherent ϕ production at low photon energies is available. Recently, the CLAS collaboration published first data

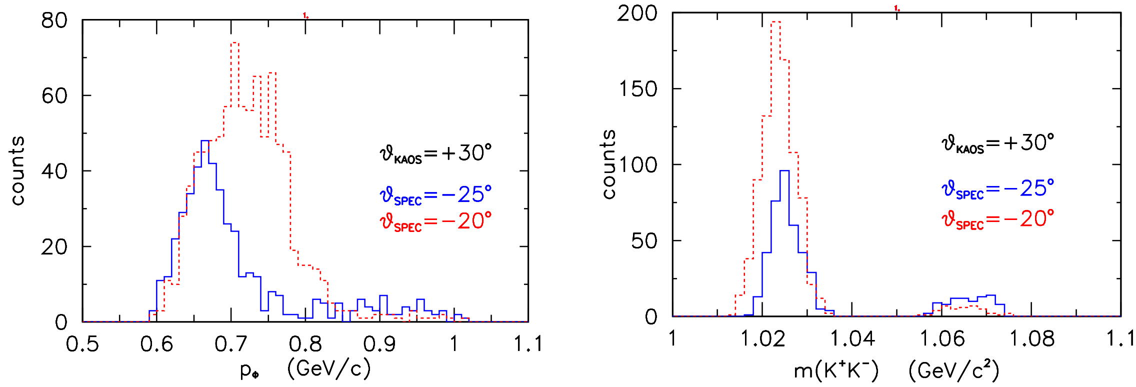

Figure 3: Left: Momentum distribution of ϕ-mesons reconstructed in Kaos and SpekC via the K^+K^- decay channel. Kaos is positioned at an in-plane angle $\vartheta = 30°$ and SpekC on the opposite side of the beam at $\vartheta_C = -20°$ (dashed histogram) and -25° (solid histogram), respectively. Right: Reconstructed K^+K^- invariant mass.

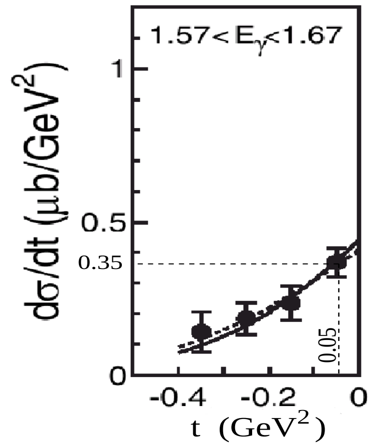

Figure 4: Differential cross section with respect to the momentum transfer, t=(P_γ-P_ϕ)^2, in $\gamma p \to \phi p$ reaction with hydrogen target [22].

of coherent ϕ-meson photo-production on deuterium for E$_\gamma$ between 1.6 and 3.6 GeV [22]. As predicted [18], the t-distribution close to t_{min} signals a t-slope of $b \geq 6\,(\mathrm{GeV}/c)^{-2}$ [20, 22] which is significantly larger than for diffractive ϕ production on the proton where a slope parameter $b = 4\,(\mathrm{GeV}/c)^{-2}$ was observed [23]. The cross section at t_{min} is in the range of $d\sigma/dt(t = |t|_{min}) \sim 0.02$–$0.05\,\mu\mathrm{b/GeV}^2$. A similar value is obtained from the diffractive data [23] using dependence on the deuteron form factor [18]. The data of Ref. [16] indicate only a moderate A^α-dependence of the coherent production with $\alpha \sim 0.4$. The slope parameters, b, for Li, C, Al and Cu in the region t =0.0–0.5 GeV^2 were obtained by LEPS collaboration [16], those parameters are consistent with ϕ photo-production on proton within statistical uncertainty. Using C=0.35 μb, b=3.38 (GeV/c)$^{-2}$, $|t|_{\mathrm{min}}$=0.05 GeV^2 [22], and assuming a mass number dependence of the cross section as $(A/2)^{2/3}$, the total cross section of coherent production of ϕ-meson in a copper target was found to be 900 nb. Here we considered "coherent production" as production on two-nucleon clusters.

3 Goals and methods

We propose to study the coherent production of K^+K^- pairs at the maximum energy of MAMI-C. With the beam energy being so close to threshold, the production of K^+K^- pairs will be dominated by intermediate ϕ-meson production [9, 17]. Because of the small momentum of the ϕ ($\langle p \rangle \approx 800\,\mathrm{MeV}/c$) and in view of the small transverse momentum transfer, the two kaons are kinematically constrained. Despite the small energy available for the decay in the rest frame of the ϕ ($E_{decay} = 32\,\mathrm{MeV}$ corresponding to $p_{decay} = 127\,\mathrm{MeV}/c$), the relative azimuth angle of the two kaons peaks at 180°. The experiment takes advantage of this correlation and of the large solid angle of the KAOS spectrometer. Positive kaons will be detected in the KAOS spectrometer centred at an in-plane angle of $\vartheta = +30°$. Negative kaons will be detected in one of the other spectrometers (SpekB or SpekC) on the opposite side of the beam direction at an angle around -20 to $-25°$. The typical kaon momenta are $p \simeq 400\,\mathrm{MeV}/c$. The momenta are shared rather equally. Even with a rather pessimistic momentum resolution of 1% we will obtain a mass resolution of better than $1\,\mathrm{MeV}/c^2$.

In order to explore the feasibility of the measurement we performed a *schematic* Monte Carlo study assuming coherent production on a deuteron. For heavier targets, the contribution of the coherent process depends on the nuclear form factor [9, 16, 18]. However, the kinematics of the produced particles does not change significantly. ϕ-meson events were weighted by the virtual photon flux [19] and the four-momentum transfer to the ϕ-meson [18, 20]. In order to illustrate the possible sensitivity to the kaon potentials, we ignored a possible mass shift or broadening of the ϕ in medium. The decay probability of the ϕ-meson was considered as $1 - \exp(-r_0/c\tau_\phi\beta\gamma)$. In here, a nuclear radius r_0 of 4 fm was assumed, and $c\tau_\phi$ is given by $hc/\Gamma_\phi = 46\,\mathrm{fm}$. The ϕ-mesons decays were simulated with the free-space lifetime and were assumed to be isotropic. An anisotropic distribution [21] has no significant influence on the numbers presented here. Kaons resulting from decays within the nucleus were propagated as described in [4]. The escaping probabilities of K^-, K^+ and ϕ-mesons were expressed as $P = \exp(-\sigma\rho\langle R\rangle)$, where the average path of particles inside a nucleus was assumed to be $\langle R \rangle = 3\,\mathrm{fm}$, and ρ denotes normal nuclear density of $0.16\,\mathrm{fm}^{-3}$. Using a total cross-section for K^-N of 12 mb [29], for K^+N of 60 mb [28], and for ϕN of 20 mb [27], escaping probabilities of $P_{K^-} = 0.56$, $P_{K^+} = 0.06$, and $P_\phi = 0.38$ were estimated.

The in-medium modification due to the kaon potential was realized by using a set of dispersion relations [4]. The momenta of kaons in a nucleus satisfied the following conditions:

$$(E_{K^+} - V_{K^+})^2 = (M_{K^+} + U_{K^+})^2 + {P_{K^+}}^2 \quad \text{for } K^+\,, \tag{2}$$

$$(E_{K^-} - V_{K^-})^2 = (M_{K^-} + U_{K^-})^2 + {P_{K^-}}^2 \quad \text{for } K^-\,, \tag{3}$$

where $E_{K^\pm}$ denotes the total energy of the outgoing particle, $M_{K^\pm}$ the kaon mass, and $P_{K^\pm}$ the kaon momentum. For simplicity, we used momentum independent scalar and vector potentials of $U_{K^+} = -30\,\mathrm{MeV}$, $V_{K^+} = +50\,\mathrm{MeV}$, and $U_{K^-} = -30\,\mathrm{MeV}$, $V_{K^-} = -50\,\mathrm{MeV}$. From impulse approximation, the KN scattering length is related to the kaon potential by $U_{K^+} = 2\pi/M_K(1 + M_K/M_N)a_{K^-N}\rho$, where $a_{K^-N} \simeq -0.255\,\mathrm{fm}$ is the isospin-averaged KN scattering length in free space, and $\rho = 0.16\,\mathrm{fm}^{-3}$ is the normal nuclear matter density [26]. In order to gain information on the nuclear medium effects a more detailed consideration of the coherent

ϕ production (see e.g. [9]) below threshold is needed. Since the absorption and scattering of kaons in nuclei are momentum dependent (see e.g. [10]), the schematic calculations that model the ϕ and kaon potentials as well as the ϕ and kaon propagation in nuclei needs also further improvements (see e.g. [11, 12] and references therein).

In the left part of Fig. 3 we present the momentum distribution of the produced ϕ-mesons which can be detected with this set-up. As expected, the experimental conditions at MAMI-C allow the detection ϕ-mesons with rather low average momentum of approximately 0.75 GeV/c.

The right part of Fig. 3 shows the reconstructed K^+K^- invariant mass for the Kaos spectrometer positioned at an in-plane angle $\vartheta = 30°$ and spectrometer C at at $-20°$ (dashed) and $-25°$ (solid histogram). The statistics correspond to approximately one day of running under the conditions mentioned above. The two peaks correspond to ϕ decays inside (right) and outside (left) of the nucleus. The shift of the left peaks with respect to the free ϕ mass of 1.019 GeV/c^2 reflects a bias caused by the finite momentum and angular acceptances for the kaons. Comparing the dashed and solid histograms, one recognizes that by changing the positions of the two spectrometer the in-nucleus decays can be enhanced relative to decays outside of the nucleus. Note, that an additional shift of the ϕ mass in medium will also shift the right invariant mass peak.

To describe the Kaos spectrometer, we used the GEANT4 package [24]. For the magnetic field of SpekB and SpekC, we have employed existing field functions [25]. Prepared event data files were fed into the GEANT4 package through an event recorder, the HepMC [30] interface. In order to reduce calculation time, the event data were prepared with pre-acceptance cuts. The decay of kaons was independently considered after the simulation with a kaon survival probability of $\exp(-L/(c\tau_K\beta\gamma))$, where $c\tau_K$ is 3.7 m. L denotes mean path-length through each spectrometer (8.53 m for SpekC, 12 m for SpekB, 6 m for Kaos).

Fig. 5 shows the decay angle of K^+ and K^- for the produced ϕ-meson. It is shown that the K^-K^+ yield would be maximised at $-15°$ for SpekC or SpekB and 15° for Kaos side. Fig. 6 presents distribution of momentum for K^+ and K^- after acceptance cut, where central momentum of the Kaos is found to be 300 MeV/c while 400 MeV/c for the SpekC and SpekB.

The optimum value of magnetic field in those momentum regions was estimated to be B =0.6 T for Kaos and B =0.95 T for SpekB, respectively. Fig. 7 displays single arm counting rates of Kaos and SpekB as a function of magnetic induction of the spectrometers.

4 Results

The production rate of ϕ-meson can be calculated by using following relation

$$Y_\phi = N_e \rho L_{target} \frac{N_a}{A} \Delta\sigma(\Omega, t) \tag{4}$$

For a beam current 10 μA the number of beam particles per second, N_e, is given by 6×10^{13}/s. For a 1 mm thick Cu target, $\rho \times L_{target} \approx 1\,\mathrm{g/cm^2}$, and A= 63 for Cu,

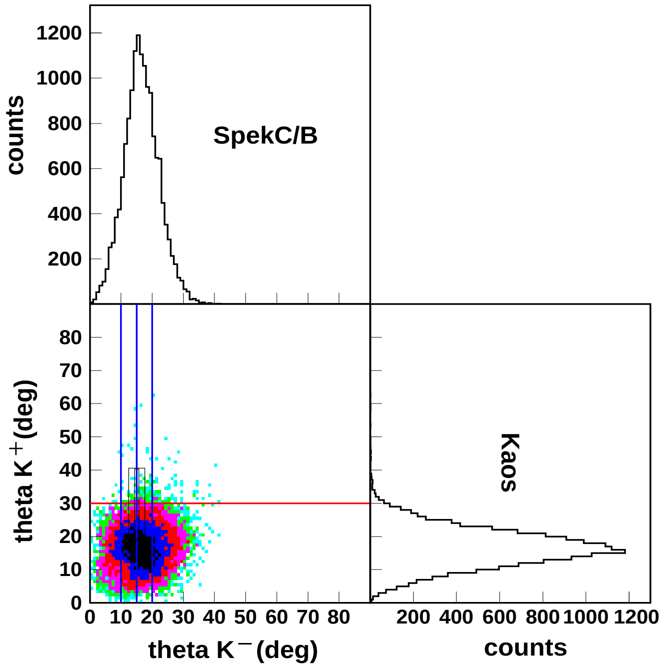

Figure 5: Angular distribution of K^- and K^+ from decaying ϕ-mesons. The lines indicate the angles of the spectrometers in the simulation. It is shown that the yield of K^-K^+ coincidences would be maximum at -15° for SpekC or SpekB side and 15° for KAOS side. Indicated boxes represents the acceptance of SpekB (inner small box) and SpekC (outer box).

the relation (4) can be rewritten as

$$Y_\phi \simeq 600 \times \Delta\sigma(\Omega, t) \ [1/\text{nb}] \tag{5}$$

For a 1 g/cm^2 thick copper target and a typical beam current of 10 μA one obtains a total initial ϕ production rate of $\sim$50 000 s^{-1}. Of course the absorption of the ϕ-meson and of the two kaons, in case of in-nucleus decays, will reduce the number of observable K^+K^- pairs significantly [12]. The number of observable decays of ϕ-mesons outside of the nucleus are reduced by $\approx$ 50–80% while in-nucleus decays will be reduced by about a factor of 20 due to the strong K^- absorbtion.

The net contribution of the cross section due to the limited acceptance of spectrometers $\Delta\sigma(\Omega, t)$ can be expressed as

$$\Delta\sigma(\Omega, t) = \sigma_{tot} \times (N^{KK}_{\text{coin}}/N^{\phi}_{\text{gen}}), \tag{6}$$

where N^{KK}_{coin} is the number of coincidence events for K^- K^+ pairs, and N^{ϕ}_{gen} is the number of generated events in the simulation. If we assume that angular dependence of ϕ-production cross section is not significantly large, i.e. $\Delta\sigma(\Omega, t) \simeq \Delta\sigma(\Omega)$, the yield of the $\phi \to K^-K^+$ channel can be expressed as

$$Y_\phi = 600 \times 900 \times (N^{KK}_{\text{coin}}/N^{\phi}_{\text{gen}}) \times Br \times wt \times P_{KK} \times \eta_{\text{eff}}/\text{s}. \tag{7}$$

Here $(N^{KK}_{\text{coin}}/N^{\phi}_{\text{gen}})$ denotes fraction of coincidence events with respect to the initially generated ϕ-mesons in the simulation. The symbol Br represents the branching ratio for the K^-K^+ channel which is 0.49, and the symbol wt is a weighting factor

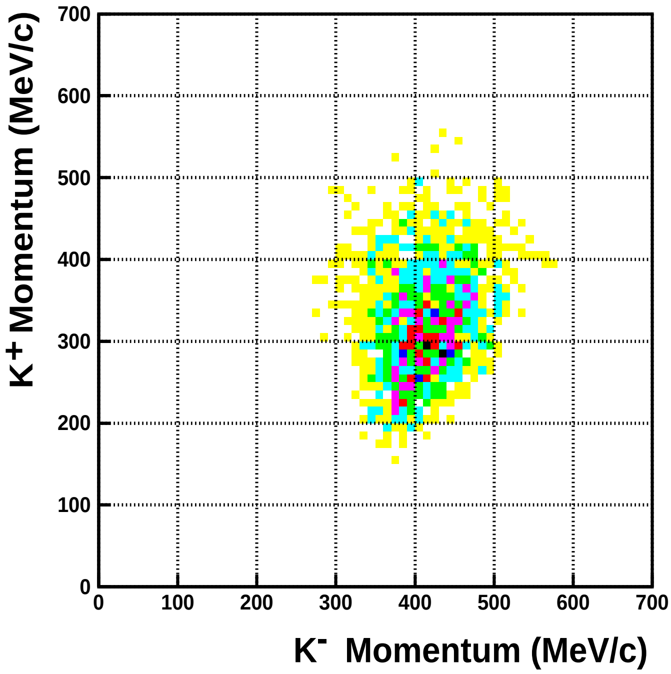

Figure 6: Momentum distribution for K^- and K^+ after acceptance cut of KAOS and SpekB. The in-plane angles of KAOS and SpekB were set to $+30°$ and $-25°$, respectively. Within the acceptance, the average K^+ momentum was found to be $300\,\mathrm{MeV}/c$ while for K^- it was $400\,\mathrm{MeV}/c$.

from the virtual photon flux with a value of 0.3. This factor was derived by using the relation $wt = \sum(\Gamma_i \times \exp(-b(|t| - |t|_{\min})))/\sum\Gamma_i$, where Γ_i denotes the virtual photon flux of i-th event. Note, that the obtained weighting factor of 0.3 is consistent with experimental analysis results wt=0.2∼0.5 [31] at Q^2=0.3 GeV^2 for the center-of-energy region 1.2–1.7 GeV. The quantity η_{eff} expresses an overall efficiency for DAQ and reconstruction of K^-K^+ pairs, and it was assumed to be 0.5.

The expected number of detected K^-K^+ pairs in two different experimental settings with KAOS at $+30°$ is summarized in Table 1. The resulting count rate for SpekB at $\vartheta_B = -15°$ and KAOS at $\vartheta = 30°$ is found to be 14 events in a day. If we use SpekC instead of SpekB, the K^-K^+-coincidence rate will be increased by a factor of 10.

The left panel of Fig. 8 displays the time-of-flight (TOF) vs. particle momenta for single arm events, the right panel shows K^-K^+-coincidence events between SpekB and KAOS. The events were generated by a different an event generator for photon-nucleon interactions [32].

5 Summary and Conclusion

We have estimated the detection rate of the $\phi \to K^+K^-$ decay channel for KAOS and a second spectrometer by using GEANT4-based Monte Carlo simulation. Calculated results suggest that approximately 15 events of $\phi \to K^+K^-$ events in a day with SpekB at $\vartheta_B = -15°$, and 180 events with SpekC at $\vartheta_C = -20°$ would be acceptable.

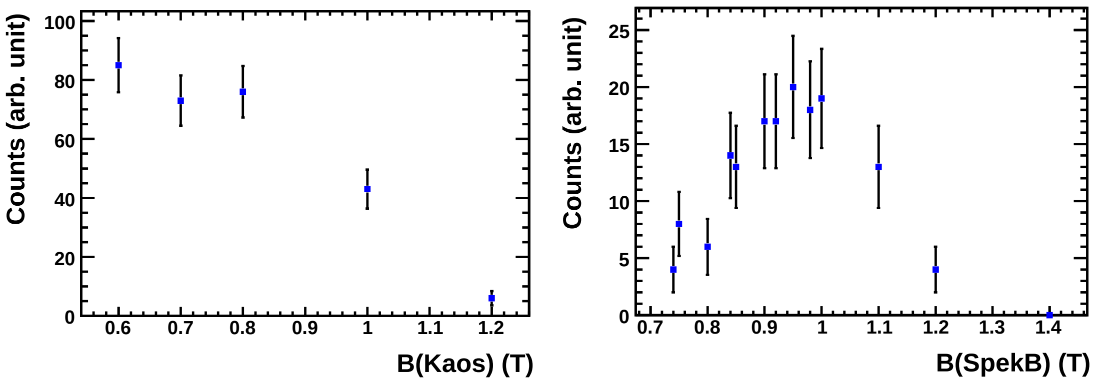

Figure 7: Left: count rate as a function of the magnetic field in KAOS at $\vartheta = +30°$. An optimum field is found to be at $B = 0.6\,\mathrm{T}$ to tag K^+ (momentum of $300\,\mathrm{MeV}/c$) from decayed ϕ-meson. Right: count rate as a function of the magnetic field of SpekB at $\vartheta_B = -15°$. The optimum field is found to be at $B = 0.95\,\mathrm{T}$ to tag K^- (momentum of $400\,\mathrm{MeV}/c$) from decayed ϕ-meson.

Table 1: Expected number of K^-K^+ pairs from ϕ-meson decay where KAOS was fixed at $\vartheta = 30°$, the fields were set to B(KAOS)$= 0.6\,\mathrm{T}$, and B(SpekB)$= 0.95\,\mathrm{T}$ and an overall efficiency, η_{eff}, was assumed to be 0.5.

	SpekB at -15°	SpekC at -20°
$\mathrm{N}^{\phi}_{\mathrm{gen}}$	2.4×10^7	2.0×10^7
$\mathrm{N}^{KK}_{\mathrm{coin}}$	54	282
$\mathrm{N}^{KK}_{\mathrm{coin}}/\mathrm{N}^{\phi}_{\mathrm{gen}}$	$23/10^7$	$127/10^7$
KK-survival probability	0.002	0.004
$Br(\phi \to K^+K^-)$	0.49	0.49
wt	0.3	0.3
η_{eff}	0.5	0.5
K^+K^- coincidence rate	0.6/hour	7/hour

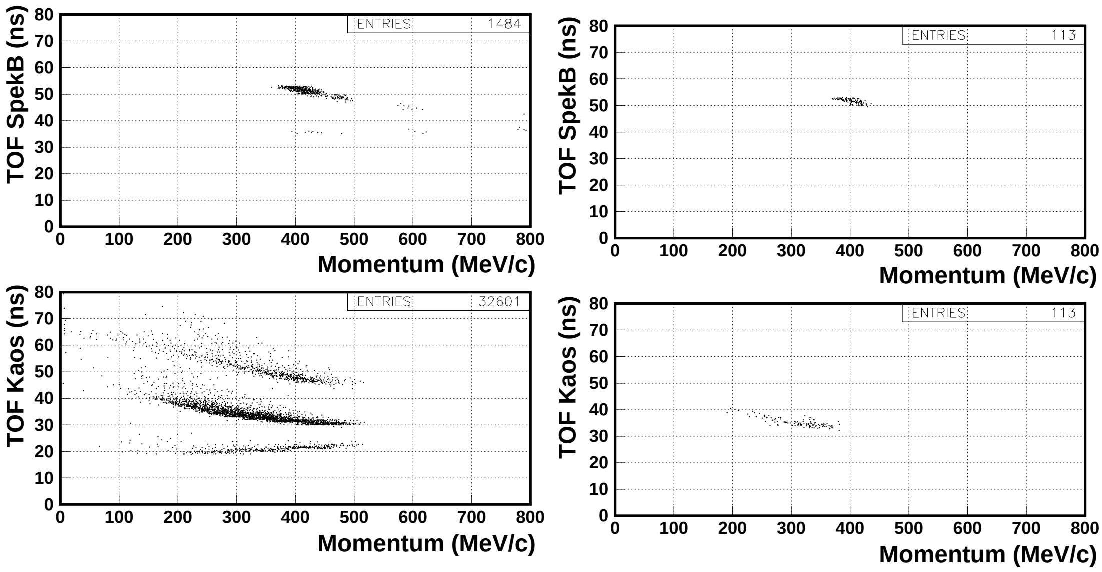

Figure 8: Left: Time-of-flight spectrum of SpekB at -15° (upper panel) and KAOS at 30° (bottom panel) in single arm events of the $\gamma + p \rightarrow \phi + p$ reaction. Right: Time-of-flight spectrum of SpekB at $\vartheta_B = -15°$ (upper panel) and KAOS at $\vartheta = +30°$ (bottom panel) in K^-K^+ coincidence events of the $\gamma + p \rightarrow \phi + p$ reaction.

The rate estimate shows that within a reasonable running time of typically two weeks the statistics of presently available data on low-momentum ϕ production in nuclei can be significantly improved. Thus, combining high statistics and good mass resolution for the first time the observation of in-nucleus decays via the K^+K^- channel in cold nuclei seems to be feasible.

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