Letter of Intent for J-PARC

A new approach to study the in-medium $\phi(1020)$-meson mass

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Abstract

A feasibility study to detect the in-medium mass modification of the ϕ-meson is discussed. We demonstrate that a completely background-free missing-mass spectrum can be obtained efficiently by $(\bar{p}, \phi)$ spectroscopy together with the $K^+\Lambda$ tagging, using the primary reaction channel $\bar{p}p \to \phi\phi$. From both missing mass and invariant mass study of the sub-threshold energy region, one can independently deduce the mass shift information. A systematic study over several nuclear targets will yield a unique, definitive and precise determination of the in-medium mass modification of the vector meson $\phi(s\bar{s})$.

1 Introduction

Because in-medium meson properties are fundamentally related to chiral symmetry breaking and its restoration in the nuclear medium, there is currently great experimental interest. It is widely accepted that the vacuum expectation value of $\langle\bar{q}q\rangle$ is non zero due to the spontaneous chiral symmetry breaking of the vacuum, and this $\langle\bar{q}q\rangle$-condensation is the major source of masses of low lying hadrons such as protons, neutrons, pions, *etc.* The $\langle\bar{q}q\rangle$ expectation value (chiral order parameter) is a function of temperature and chemical potential (density), so that various experimental studies have been performed to detect the restoration of the chiral symmetry.

One milestone of the study using mesons is the observation of deeply-bound pionic atom states in nuclei [1]. In the pionic atom case, the Bohr radius of the pion in heavy nuclei lies within the nucleus, but the s-wave strong interaction of the pion is repulsive so the major part of the wave function is pushed away from the nucleus, and the pions are bound to the nuclear surface by the Coulomb force. Through the study of the energy shift and width of the state, there is an indication of chiral symmetry restoration through the in-medium modification of the pion decay constant, f_π, leading to a proposed systematic study at RIBF (RIKEN Nishina Center).

Kaonic nuclear bound states provide another channel for the study of chiral symmetry. A recent hot topic concerns the possible existence of a deeply bound kaonic nuclear state. In this case, the $\overline{K}N$ interaction is expected to be strongly attractive, so the change in properties of the medium itself, and not just the meson, could be studied. There are several experimental searches of the state [2, 3, 4], although clear and definitive experimental evidence is still missing. An experimental study, J-PARC E15, is now being prepared to search for the simplest system, "K^-pp", by the in-flight (K^-, n) method.

Vector mesons in the nuclear medium have also been extensively studied experimentally. There are two outstanding features of the study 1) the mass (or energy) shift of the meson in the nuclear medium can be calculated from the QCD sum-rule and it is predicted to be about $1.5 \sim 3$ % of the rest mass [5], and 2) the formation and the decay can be obtained by an invariant mass study [6, 7]. It is inconclusive whether the mass shift has been observed in invariant mass spectra, however the corresponding peaks such as ρ and ϕ have low energy tails on peaks at the free mass. The simple model calculation for the ϕ given in [7] shows that the tail formation results from about a 3 % mass reduction in the nuclear medium, which is consistent with the calculated value given by the QCD sum-rule. An experimental study, J-PARC E16 [8], is planning to accumulate much higher statistics to obtain a more conclusive result using the dispersion relation between the total energy and the momentum.

2 Previous Experimental Study at KEK

For the case of ρ and ω mesons in hot or dense matter, several experiments reported evidence of the mass modification in a medium [9, 10, 11, 12, 13, 14]. On the other hand, experimental information on the ϕ meson modification is very limited compared to ρ and ω mesons. Recently, the invariant mass spectrum of $\phi \rightarrow e^+e^-$ was observed using $p+A$ reactions with 12 GeV protons by the KEK-PS experiment E325 [7], which has an extremely interesting energy dependence. Figure 1 shows the invariant mass spectrum of $\phi \rightarrow e^+e^-$, and an excess on the low-mass side of the ϕ meson peak was observed in the low $\beta\gamma$ ($\equiv p/m$) region of ϕ mesons ($\beta\gamma < 1.25$) with copper targets. However, in the high $\beta\gamma$ region ($\beta\gamma > 1.25$), spectral shapes of ϕ mesons were consistent with the Breit-Wigner shape, *i.e.*, spectrum shape in vacuum. Since the mass modification of the ϕ mesons in a target nucleus is expected to be visible only for slow ϕ mesons produced in a heavy target nucleus, they concluded that the excess is considered to be the signal of the mass modification of the ϕ mesons in a target nucleus.

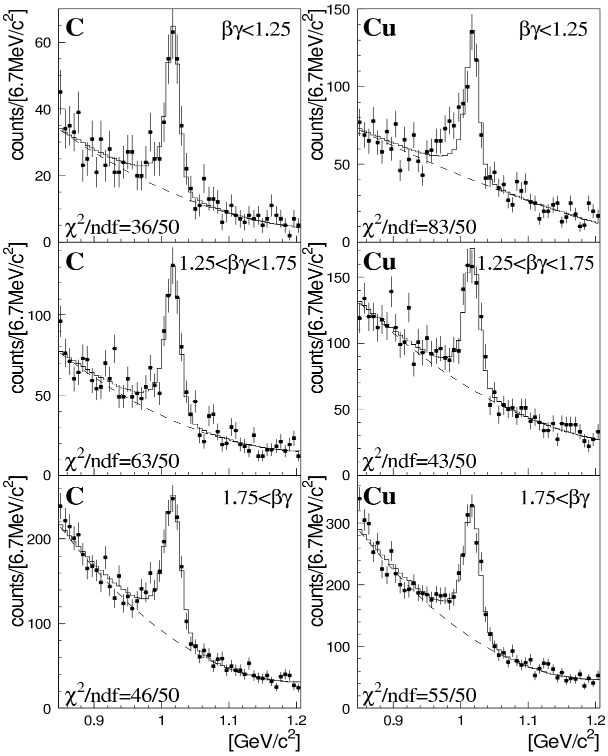

Figure 1: The invariant mass spectra of $\phi \to e^+e^-$ at KEK-PS E325 [7].

To interpret the invariant mass spectra of ϕ mesons measured in the E325 experiment, the simplest approach is to assume that the spectrum shape of ϕ meson is modified in the nuclear medium. This allows us to compare the spectrum directly to the theoretical predictions. There are a number of predictions about the mass shift of ϕ mesons in nuclei, from QCD calculations such as the Brown-Rho scaling [15], the QCD sum-rule [5, 16], the effective chiral Lagrangian [17], the renormalization of the kaon [18], *etc.* The comparison based on a simple model calculation gives about 3 % mass reduction and 3.4 times width broadening of the ϕ in nuclear media [7]. On the other hand, there is criticism of such a straightforward comparison of the invariant mass [19]. Therefore the conclusion that properties of the in-medium ϕ meson have been modified is still controversial.

3 A New Exclusive Experimental Approach

Is there any method to study the property of vector mesons in nuclei other than invariant mass? Let us discuss the energy eigenstate of the ϕ in nuclei, and discuss a possible new combined experimental approach using missing-mass spectroscopy and invariant mass study of the decay channel, by specifying the intermediate state and the final state at the same time.

3.1 The ϕ in nuclei

What can one expect when a ϕ is in a nucleus? As described, the in-medium mass shift of the ϕ is predicted to be $\Delta m_\phi/m_\phi = 1.5 \sim 2.6\%$ by the QCD sum rule as shown in figure 2 (left) [16]. The width broadening is naturally expected because several decay channels are open in a nucleus. There are several theoretical predictions and the predicted widths are quite narrow. Klingl-Waas-Weise predicted that the width is below $\Gamma_\phi < 10$ MeV [20], while Oset-Ramos reported that the width can be bigger, $\Gamma_\phi < 16$ MeV (for $\Delta m_\phi \sim 30$ MeV/c^2), taking into account Σ^* and the vertex correction in the chiral unitary model [21] (figure 2 (right)). All the currently available theoretical predictions give a quite narrow natural decay width of the ϕ even in the nuclear medium.

On the other hand, experimental ϕ invariant mass studies in the pA reaction reported that the ϕ mass shift in medium-heavy nuclei (Cu) is about 3 % and the natural width broadening of $\Gamma_\phi/\Gamma_\phi^{free} \approx 3.4$ [7]. These numbers are in quite good agreement with theoretical predictions, except for the strength of the attraction of the chiral unitary model.[1] Therefore, let us take the mass shift and width from the previous experiment reported in reference [7].

This means that a nucleus is nothing more than an energy pocket for the ϕ meson of about $\Delta m_\phi \sim 30$ MeV at the relative distance r below the nuclear radius R_0 ($\propto A^{1/3}$). Another feature is that this spatial energy pocket (a nucleus) is absorptive, but the strength is quite weak. The situation is illustrated in figure 3. A weak absorptive interaction makes the ϕ a bit unstable, which broadens the width, but one can expect that the width would be less than 16 MeV. Therefore, the ϕ will form a meta-stable, though still discrete, bound state in nuclei. Only the free decay channel remains outside the nucleus, while all decay channels realized in nuclear media are closed.

The situation is almost analogous to the case of Λ hypernuclei. The Δm_ϕ is almost the same as the potential depth of the Λ, whose mass, 1115 MeV/c^2, is almost the same as that of the ϕ. Systematic study of Λ hypernuclei is giving us another remarkable insight for the in-medium study of the ϕ meson. The study shows that the Λ behaves as if it is a free particle inside nuclei, because the Pauli principle does not contribute. Therefore, the Λ binding energy (B_Λ) has a clear A dependence, as shown in figure 4. For the Λ ground state,

$$B_\Lambda \approx V_\Lambda \left(1 - \left(\frac{A}{A_\Lambda^0}\right)^{-\frac{2}{3}}\right) \qquad (1)$$

[1] The interaction obtained by Oset-Ramos is attractive [21], but much weaker than what one can expect from reference [16].

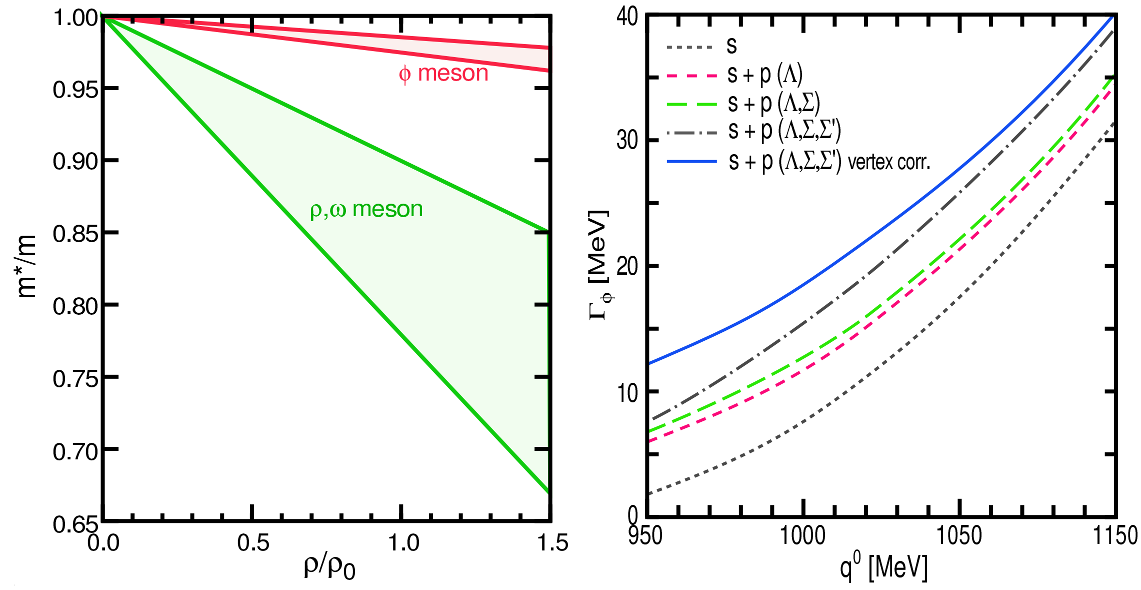

Figure 2: Theoretical calculation of the in-medium mass shift of the ϕ by the QCD sum rule (left) [16], and the in-medium decay width by using the chiral unitary model (right) [21].

and the averaged kinetic energy term $\langle T_\Lambda \rangle$ is as,

$$\langle T_\Lambda \rangle \approx V_\Lambda \left(\frac{A}{A^0_\Lambda} \right)^{-\frac{2}{3}}, \tag{2}$$

where $\langle T_\Lambda \rangle$ is the mean Λ kinetic energy, V_Λ is the real part of the Λ potential strength, and A^0_Λ is the critical mass number for the Λ to bind ($A^0_\Lambda \sim 3$). The A dependence is quite easy to understand from the uncertainty principle $\Delta p \cdot \Delta x \sim \hbar$, and the Λ hypernuclei should have a size proportional to $A^{-\frac{1}{3}}$. As shown in figure 4, the simple $A^{-\frac{2}{3}}$ rule does not hold precisely, especially for large A. It is not clear whether the problem locates in the experimental data of the heavy nuclear targets or in the A dependence itself. Thus, one need more detailed theoretical study of the A dependence, which can also be experimentally deduced by a systematic study by replacing the constant to a fitting parameter.

Analogous to the Λ state in hypernuclei, the ϕ binding energy (B_ϕ) of the ground states should have clear mass number dependence again, which can be given as,

$$B_\phi \approx \Delta m_\phi \left(1 - \left(\frac{A}{A^0_\phi} \right)^{-\alpha_\phi} \right). \tag{3}$$

where α_ϕ represents the coefficient in the case of the ϕ meson bound state, and A^0_ϕ is the critical mass number for the ϕ to be bound which should be around $A^0_\phi \sim (A^0_\Lambda - 1 \approx 4)$.

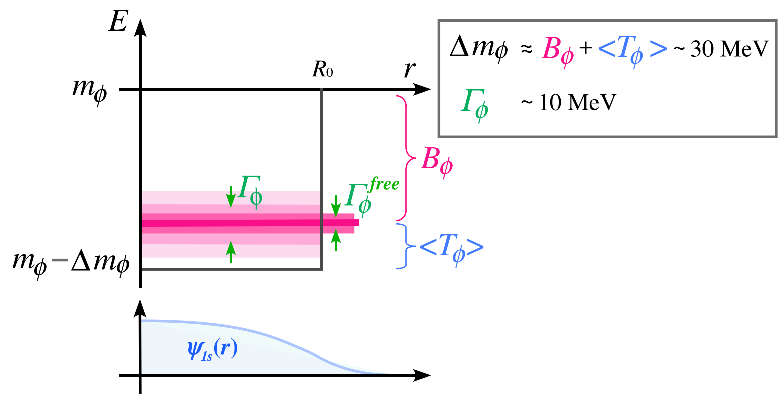

Figure 3: A cartoon of the bound state formation trapped in an energy pocket caused by the in-medium mass shift of the ϕ.

The formation of the ϕ meson bound state could be observed in the energy spectrum as a discreet peak for the case of $A > A^0_\phi$.

Note that the kinetic energy $\langle T_\phi \rangle$ is not a good quantum number, having a finite width in a finite nucleus. Even if the total energy is defined, the ϕ momentum should have a distribution in a nucleus, which is simply the square of the wave function of ϕ in a momentum representation. Actually, this is one of the key reasons for the criticism given by Yamazaki-Akaishi [19]. The invariant mass is not a good quantum number because it is a kind of operator to give residual energy (called rest mass) by subtracting the kinetic energy from its total energy $\langle T_\phi \rangle$, namely,

$$M_{inv}(\phi) = E_\phi - \langle T_\phi \rangle \,, \tag{4}$$

and the kinetic energy should have a size-dependent width in finite nuclei. Therefore, the invariant mass should distribute around $m_\phi - \Delta m_\phi$, even without considering its decay. When the ϕ is in a highly excited state, the central value and the width of the invariant mass could be moved and broadened by the core excitation of the residual nucleus, so instead they called the quantity the "*quasi-invariant mass*" in their paper.

It is clear that one can resolve the situation by specifically identifying the ϕ-meson nuclear bound state, which enables us to be free from the criticism described above.

3.2 Missing mass approach

Experimentally, the calculation of the missing mass is also quite simple. Let us discuss the reaction ${}^A_Z\mathrm{X}(B, C)$, namely

$$B +^{A'}_{Z'} \mathrm{X}' \rightarrow \{\phi \; {}^A_Z\mathrm{X}\} + C, \tag{5}$$

where B and C can be any particle, and $\{\phi \; {}^A_Z\mathrm{X}\}$ represents a ϕ mesonic nucleus. If we measure the momenta of B and C, then the square of the missing mass for $\{\phi \; {}^A_Z\mathrm{X}\}$

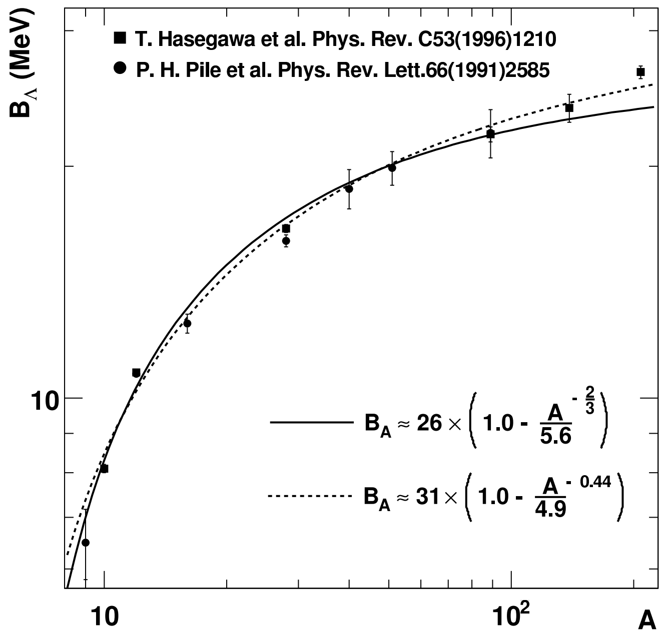

Figure 4: The mass number dependence of the binding energy ground states of Λ hypernuclei. The simple $A^{-\frac{2}{3}}$ rule does not hold, especially for large A.

can be given as

$$M_{missing} = \sqrt{(p_B + p_{^{A'}_{Z'}\mathrm{X}'} - p_C)^2}, \tag{6}$$

where p_B, $p_{^{A'}_{Z'}\mathrm{X}'}$ and p_C are the four momenta of each particle. The missing mass can also be given as

$$M_{missing} = M_{^A_Z\mathrm{X}} + m_\phi - B_\phi, \tag{7}$$

where $M_{^A_Z\mathrm{X}}$ is the mass of the residual (spectator) nucleus $^A_Z\mathrm{X}$. If $\{\phi\ ^A_Z\mathrm{X}\}$ is formed, the missing mass $M_{missing}$ should be located below the threshold energy $M_{^A_Z\mathrm{X}} + m_\phi$. Of course in a real experiment, the situation is not that simple, because C can be generated in other channels even without producing a ϕ in the reaction. The strong interaction cross section is the order of 10 mb, while the ϕ production is the order of 10 μb, so that the background is expected to be about 10^3 times higher.

However, if one can efficiently select the reaction (5) exclusively, and drastically improve the signal-to-noise ratio (S/N) at the same time, then the ϕ must decay inside the nucleus and the signal can be observed in the sub-threshold energy region. This is one of the remarkable points of missing mass spectroscopy.

3.3 Invariant mass approach

What happens if a ϕ is in a nucleus? One can naturally expect that six $\phi N \to KY$ channels will open. Table 1 shows a summary of possible decay / reaction channels. In the table, the binding energy of the proton ("p") and neutron ("n") in a nucleus is expressed as B_p and B_n, respectively. Because the partial decay widths to each KY channel are not given in reference [21], we computed the branching ratio from the given partial widths of $K\Lambda$ and $K\Sigma$ channels, by assuming the isospin relation 1 : 2 between $K^0\Sigma^0$ and $K^+\Sigma^-$ channels, and that ϕp and ϕn have the same coupling strength.

initial channel	decay/KY channel	free BR	branching ratio (%) $^{(*)}$	Q-value (MeV)	suppression
ϕ	$e^+ e^-$	3×10^{-4}	–	1018	EM
	$\mu^+ \mu^-$	3×10^{-4}	–	808	EM
	$K^+ K^-$	0.49	–	32	OZI
	$K^0 \overline{K}^0$	0.33	–	32	OZI
ϕ "p"	$K^+ \Lambda$	–	37	$348 - B_\phi - B_p$	none
	$K^+ \Sigma^0$	–	1	$271 - B_\phi - B_p$	none
	$K^0 \Sigma^+$	–	2	$275 - B_\phi - B_p$	none
	$K\ \Sigma^*$ *etc.*	–	10	–	-
ϕ "n"	$K^0 \Lambda$	–	37	$346 - B_\phi - B_n$	none
	$K^0 \Sigma^0$	–	1	$269 - B_\phi - B_n$	none
	$K^+ \Sigma^-$	–	2	$268 - B_\phi - B_n$	none
	$K\ \Sigma^*$ *etc.*	–	10	–	-

Table 1: Decay / reaction channels of the ϕ in nuclei. (∗): The decay branch is calculated from the theoretical partial widths contributed from $K\Lambda$ and $K\Sigma$ channels given in reference [21].

The free-space decay channel is easy to analyze using the quasi-invariant mass, but it is difficult to observe. The di-lepton channel has a quite small branching ratio $\sim 10^{-4}$. Because of the small Q value, the $K\overline{K}$ channel is also difficult to observe if the ϕ is produced near or below the threshold. At the threshold, the $K\overline{K}$-pair produced at around 126 MeV/c can easily stop around the target.

Therefore, let us focus on the KY decay channel of the ϕ mesonic nuclei, ignoring the effect of the final state interaction (FSI) for simplicity. Especially, the $K^+ - \Lambda$ channel is quite promising, not only because of its large branching ratio but also because of the large $p\pi^-$ decay branch (as much as 60%) of the Λ. This means that a large fraction of the channel can be reconstructed by measuring only charged particles. Unfortunately, observation of the $K^+\Sigma$ channel is difficult not only from its small branching ratio, but also because 1) the $\Sigma\Lambda$ conversion is known to be quite strong and 2) most of the charged-Σ decays emit neutral particles.

In a nucleus, the K^+–Λ channel can be observed as

$$\{\phi\ {}^{A}_{Z}\mathrm{X}\} \to K^+ + \Lambda + {}^{A-1}_{Z-1}\mathrm{X}'', \tag{8}$$

in which a ΛK^+ pair is produced by the simple quark re-configuration as

$$\phi(s\bar{s}) + \text{“}p\text{”}(uud) \to K^+(u\bar{s}) + \Lambda(uds). \tag{9}$$

If the ϕ is in a bound state or low momentum region (roughly below proton Fermi motion), then the ΛK^+ pair should be produced in a *back-to-back* direction at the center-of-mass (CM) of the $\{\phi\ {}^{A}_{Z}X\}$ system, because the kinetic energy of the ϕ is well below the Q-value. If we neglect the kinetic energy carried out by residual nuclei, then the invariant mass should be given as

$$m_{inv}(\Lambda K^+) \approx \sqrt{(m_\phi - \Delta m_\phi)^2 + \mathbf{p}^2_{cm'}} + \sqrt{m_p^{\mathrm{eff}\,2} + \mathbf{p}^2_{cm'}} \tag{10}$$

where m_ϕ and m_p are the mass of the ϕ and proton, respectively, $\mathbf{p}_{cm'}$ is the three-momentum of the ϕ (or proton) in the center of mass of the ϕ-p sub-system in $\{\phi\ {}^{A}_{Z}\mathrm{X}\}$, $\Delta m(\phi)$ is the mass shift, and m_p^{eff} is the effective mass of the proton. If $p_{cm'}$ is small, it can be simplified as

$$m_{inv}(\Lambda K^+) \approx m_\phi + m_p - \Delta m_\phi - V_p + \langle \frac{m_\phi + m_p}{2 m_\phi m_p} \mathbf{p}^2_{cm'} \rangle, \tag{11}$$

where V_p is the real part of the optical potential of the proton.

Very unfortunately, there is no good way to deduce $\mathbf{p}_{cm'}$ experimentally. Thus, the invariant mass study of the ΛK^+-pair is even more difficult than that of the free decay mode of the ϕ. The invariant mass will be smeared out not only from the imaginary part, but by the internal kinetic term which is roughly 40 MeV, if we assume $|\mathbf{p}_{cm'}|$ is of the order of the Fermi-motion ~ 270 MeV/c. However this invariant mass is useful for defining an energy window to identify the ϕ production in the reaction using a rather wide window to cover the smearing effect.

3.4 Q-value approach

Is there any other way to be free from the hidden ambiguity in the invariant mass caused by other effects, such as finite size, core excitation? If one knows the rest frame of the ϕ mesonic nucleus, and if it decays to three bodies $\{\phi\ {}^{A}_{Z}\mathrm{X}\} \to \Lambda + K^+ + {}^{A-1}_{Z-1}\mathrm{X}''$, then the Q-value can be given as

$$\begin{aligned} Q &= (m_\phi - B_\phi) + (m_p - B_p) - (m_{K^+} + m_\Lambda) \\ &= T_\Lambda + T_{K^+} + T_{{}^{A-1}_{Z-1}\mathrm{X}''}, \end{aligned} \tag{12}$$

so thus

$$\begin{aligned} Q + m_{K^+} + m_\Lambda &= E^{rf}_\Lambda + E^{rf}_{K^+} + \frac{\mathbf{p}^2_{\Lambda K^+}}{2 M_{{}^{A-1}_{Z-1}\mathrm{X}''}} \\ &= m_\phi + m_p - B_\phi - B_p, \end{aligned} \tag{13}$$

where $\langle T_\phi \rangle$ and $\langle T_{^{A-1}_{Z-1}\mathrm{X}''} \rangle$ are the kinetic energy of the ϕ and the residual nucleus (with proton hole), respectively, $M_{^{A-1}_{Z-1}\mathrm{X}}$ is the mass of the residual nucleus, E^{rf}_Λ and $E^{rf}_{K^+}$ are the total energy of Λ and K^+ in the rest frame of $\{\phi\ ^A_Z\mathrm{X}\}$, and $\mathbf{p}_{\Lambda K^+}$ is the three-momentum of the ΛK^+-pair in the rest frame. All the quantities used to compute E_{rest} can be observed experimentally, thus this is an extremely interesting quantity for deducing B_ϕ, if one can define the frame by knowing the production channel. Note that formula (13) is obtained simply from energy conservation. In contrast to the invariant mass formulation, there is no ambiguity in this representation except for the possible core excitation energy of the residual nucleus.

3.5 The combined approach

None of the approaches described above are simply enough to deduce the mass shift directly. However, the problem can be solved by selecting the simplest event by observing the formation and the decay reaction at the same time.

As discussed, both Λ and K^+ are tagged with strangeness, thus with a loose cut for ΛK^+ invariant mass and by requiring *back-to-back* Λ and K^+ emission, we can expect a clear missing mass spectrum. From the missing mass, one can also select events which correspond to a specific ϕ-bound-state formation. It is also possible to extend the study further, using formula (7) and (13) to check the consistency of the resultant binding energy. Namely, from a missing mass study of the ground state of the ϕ,

$$B_\phi = -\left(M_{missing} - M_{^A_Z\mathrm{X}} - m_\phi\right), \tag{14}$$

and from the energy conservation rule in the rest frame of $\{\phi\ ^A_Z\mathrm{X}\}$,

$$B_\phi = -\left(E^{rf}_\Lambda + E^{rf}_{K^+} + \frac{\mathbf{p}^2_{\Lambda K^+}}{2M_{^{A-1}_{Z-1}\mathrm{X}''}} - m_\phi - m_p + B_p\right), \tag{15}$$

where $^A_Z\mathrm{X}$ is the core nucleus of the ϕ mesonic nucleus $\{\phi\ ^A_Z\mathrm{X}\}$, and $^{A-1}_{Z-1}\mathrm{X}''$ is the residual nucleus of the decay. Note that the mass $M_{^A_Z\mathrm{X}}$ and the proton binding energy B_p are not unique, but can be assigned if the width broadening of the ϕ bound state is relatively small. As described, one can deduce the mass shift of the ϕ meson in the nuclear medium by a systematic study of the ϕ bound states as

$$\Delta m_\phi = \left(1 - \left(\frac{A}{A^0_\phi}\right)^{-\alpha_\phi}\right)^{-1} B_\phi. \tag{16}$$

There are several remarkable points, which can be summarized as,

- decay channel, Λ and K^+, open only when ϕ is in a nucleus,
- both Λ and K^+ are labeled by strangeness coming from the $s\bar{s}$-pair of the ϕ,

- all charged final states in $\Lambda \to p\pi^+$ and K^+ makes for efficient detection,
- FSI effect should be minimized for the *back-to-back* condition,
- background-free missing-mass spectrum is expected, and
- ϕ mass shift can be detected by two independent methods.

Even if the branching ratio for the decay mode of $K^+\Sigma^0$ is small, there is a question whether the $K^+\Sigma^0$ channel could arise in the event if one could not detect the γ-ray emission of the Σ^0 decay $\Sigma^0 \to \gamma\Lambda$ ($BR \sim 100\%$). It should be noted that $K^+\Lambda$ invariant mass spectrum will be shifted by 70 MeV for the events from $K^+\Sigma^0$ if experimental detector is not sensitive to the neutral particles, *i.e.* missing γ ray from Σ^0 decay. However, if the overall energy resolution for the detector is better than 70 MeV, we can separate the $K^+\Sigma^0$ events from the $K^+\Lambda$ direct decay events.

4 Possible Production Channels

To form a ϕ bound state, the momentum transfer of the production reaction should be small. In reaction $B +^{A'}_{Z'} \mathrm{X}' \to \{\phi\ ^{A}_{Z}\mathrm{X}\} + C$, the minimum momentum transfer (recoilless condition) can be realized when the mass difference between C and B is bigger than the mass of the ϕ. Unfortunately, there is no ideal reaction channel to fit this condition.

The pair annihilation is an alternative solution to achieve minimum momentum transfer. In this sense, the most interesting formation channel is $\overline{p} + p \to \phi + \phi$. Among the ϕ production channels in which the $s\overline{s}$-pair can be produced in the residual nucleus, the threshold energy of this channel is practically the lowest, because the lower threshold channel $\overline{p} + p \to K + \overline{K} + \phi$ has a much smaller production cross section compared to the $\phi + \phi$ final state at around the threshold energy ($\overline{p}$ below 1.4 GeV/c). Therefore, $(\overline{p}, \phi)$ spectroscopy could be possible without any background process. The momentum transfer to the backward ϕ is much smaller compared to the Fermi motion, which is below 200 MeV/c.

Other promising formation channels close to the condition are $\pi + N' \to \phi + N$ reactions or $\gamma + N \to \phi + N$ reactions. In the case of (π, N) reactions, which can be realized at J-PARC, the experiment will be limited by the incident pion beam rate. In the case of (γ, N) reactions, which can be realized *e.g.* at SPring-8, it will be limited by its small cross section and the small incident γ ray yield. For both cases, one can expect good S/N ratio by applying $K^+\Lambda$ tagging. In both cases, the momentum transfers ($300 \sim 400$ MeV/c) are much larger than that of $\overline{p}p$ cannel, and also the Fermi motion of the ϕ bound states, if they exist.

In this section, we focus on $(\overline{p}, \phi)$ reaction channels for the feasibility study and describe (π, N) channel in an appendix.

4.1 The ϕ meson production via ($\overline{p}$, ϕ) reactions

To search for gluonic matter and exotic quark-gluon formations, intensive studies have been performed at the CERN/LEAR facility for the "OZI-forbidden" formation reaction of the type $\overline{p}p \to M_1 M_2$, where M_1 and M_2 are vector mesons. One striking result is the rather large $\phi\phi$ production cross section near the production threshold (~ 0.9 GeV/c), namely incident $\overline{p}$ momentum at around $1.3 \sim 1.4$ GeV/c. Figure 5 (left) shows the production cross section for double ϕ meson production as a function of incident momentum for $\overline{p}$ together with direct production of $\phi\, K^+K^-$ and $K^+K^-K^+K^-$ (non-resonant $K\overline{K}$ pairs).

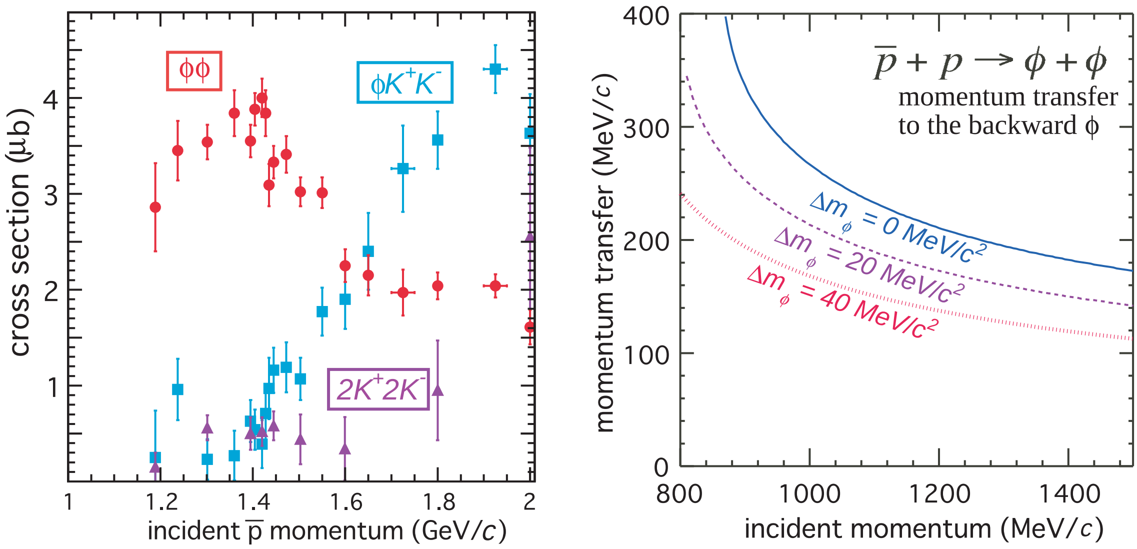

Figure 5: Left panel shows the cross section for double ϕ meson production around the production threshold [22]. Right panel shows the momentum transfer for backward ϕ production as a function of the incident $\overline{p}$ momentum.

Let us focus on the double-ϕ elementary reaction channel. In this reaction, one can use the backward ϕ as the source of the quasi-recoilless ϕ meson production channel, and the forward ϕ as a spectroscopic analyzer of the missing mass of the backward ϕ-mesonic nuclei. The cross section of the double-ϕ channel has a peak at around a $\overline{p}$ momentum of $1.3 \sim 1.4$ GeV/c. In this momentum region, other kaon associated reactions, ϕK^+K^- and $K^+K^-K^+K^-$, have considerably lower cross sections (~ 10 %) as shown in figure 5 (left), in spite of their lower Q-values. The incident ($\overline{p}$, ϕ) reaction can be written as,

$$\overline{p} + {}^{A+1}_{Z+1}\mathrm{X}' \to \{\phi\ {}^{A}_{Z}\mathrm{X}\} + \phi. \tag{17}$$

For these channels, the missing masses of the ϕ mesonic nuclei $\{\phi\ {}^{A}_{Z}X\}$ and their rest frames can be obtained by the forward ϕ meson momentum using $\phi \to K^+K^-$ decay.

The momentum transfer of the reaction is shown in figure 5 (right). As shown in the figure, the momentum transfer to the backward ϕ is below 200 MeV/c at around 1.3 $\sim$ 1.4 GeV/c, where the double-ϕ cross section is maximum. The momentum transfer is below the Fermi motion, so the ϕ bound-state formation rate would be larger than the case of the (π, N) reaction channel, where the momentum transfer of the reaction is the order of 400 MeV (see appendix in detail).

Let us consider how to ensure that the backward ϕ is in a nucleus. As discussed, we can tag the events which have *back-to-back* ΛK^+-pair production at the momentum region around 200 $\sim$ 600 MeV/c for both Λ and K^+, whose quasi-invariant mass is in the region of interest. By this tagging, we can select the cascade reactions $\overline{p} + {}^{A+1}_{Z+1}\mathrm{X}' \rightarrow \{\phi\ {}^{A}_{Z}\mathrm{X}\} + \phi$ and $\{\phi\ {}^{A}_{Z}\mathrm{X}\} \rightarrow {}^{A-1}_{Z}\mathrm{X}'' + \Lambda + K^+$.

The most distinguishable feature of this reaction channel is its *fully background-free* nature. The yield of the kaon-associated ϕ production channel, ϕK^+K^- and $K^+K^-K^+K^-$, is much smaller than the double ϕ production channel for the incident $\overline{p}$ momentum below 1.4 GeV/c, and those events can be discriminated by the invariant mass analysis so no background processes exist in the primary reaction. Another unique feature is that all the particles we shall observe, including forward $\phi \rightarrow K^+K^-$ decay, are labeled with strangeness so the discrimination from other processes is quite clear, which ensures that it is free from any accidental background formation.

However, the hardware trigger for these events is difficult. Figure 6 shows cross sections of possible hardware trigger sources as a function of incident $\overline{p}$ momentum. For this experiment, the forward ϕ meson can be detected with a K^+K^- pair. Therefore the forward K^+K^- is a requirement of the experiment. As we can see in figure 6, it suppresses many of major hardware trigger sources like multi-pion production. Therefore, leftover hardware trigger sources are the $K^+K^-\pi^+\pi^-$ channels, if we simply require at least one charged particle around the target region in the hardware trigger level(note that the $\overline{p}p\pi^+\pi^-$ channel is open only when the incident $\overline{p}$ momentum is above 1.5 GeV/c). Therefore, one needs a second level trigger to identify a positive kaon track around the target region.[2]

4.2 Possible experimental setup for $(\overline{p}, \phi)$ spectroscopy

As shown in figure 5 (right), one can realize a quasi-recoilless condition (below typical Fermi motion in nuclei) for the incident $\overline{p}$ momentum at around 1.3 $\sim$ 1.4 GeV/c, where the cross section of the elementary double-ϕ production channel is maximum. This momentum region is suitable to minimize the background source, *i.e.* ϕK^+K^- and $K^+K^-K^+K^-$. However, protons in a nucleus have Fermi motion which smears the CM energy of the primary reaction, so the initial $\overline{p}$ momentum should be lower than 1.4 GeV/c. Therefore, we choose the momentum for the incident $\overline{p}$ to be 1.3

[2]If the event rate is acceptable for requiring a single K^+ track in the tracking detector around the target, then one can extend the purpose of the experiment to include a di-lepton invariant mass study.

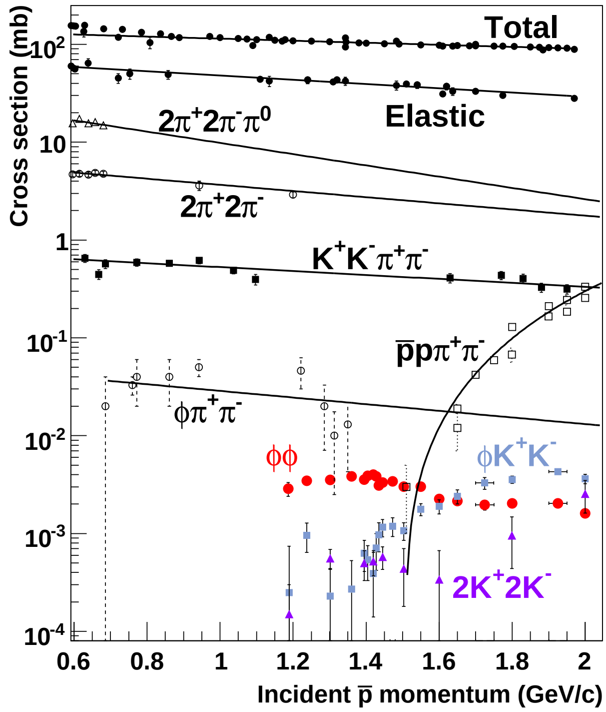

Figure 6: Cross section of various $\bar{p}p$ reaction branches as a function of incident momentum of $\bar{p}$.

GeV/c. Note that even if we cannot remove those events at the hardware level, they can be removed by *back-to-back* requirement of the $K^+\Lambda$ pair.

The momentum of the ϕ from the double ϕ production for a proton target is plotted in figure 7 (left). In the case of nuclear target, only extremely forward ϕ production events, having momentum around 1.1 GeV/c, contribute to the ϕ meson bound state formation by the backward ϕ. This is different from the proton target case, in which ϕ momentum is quite sensitive to the production angle as shown in figure 7 (left). The decay K^+K^- which form this forward ϕ have momenta around 550 MeV/c as shown in figure 7 (right). The opening angles from the beam axis of the charged kaons are rather large - about 0.25 rad.

The experimental setup must be designed to detect these forward K^+K^- efficiently. One good example is the LEPS experimental setup at Spring-8. A schematic view of the experimental setup similar to the LEPS is shown in figure 8. The setup consists of a cylindrical detector system (CDS) and the dipole type double-arm spectrometer, which is conventional for this type of experiment. There are several difficulties with this configuration. To achieve large acceptance for the forward ϕ, the pole gap of the double-arm spectrometer should be quite large. For the configuration of the setup

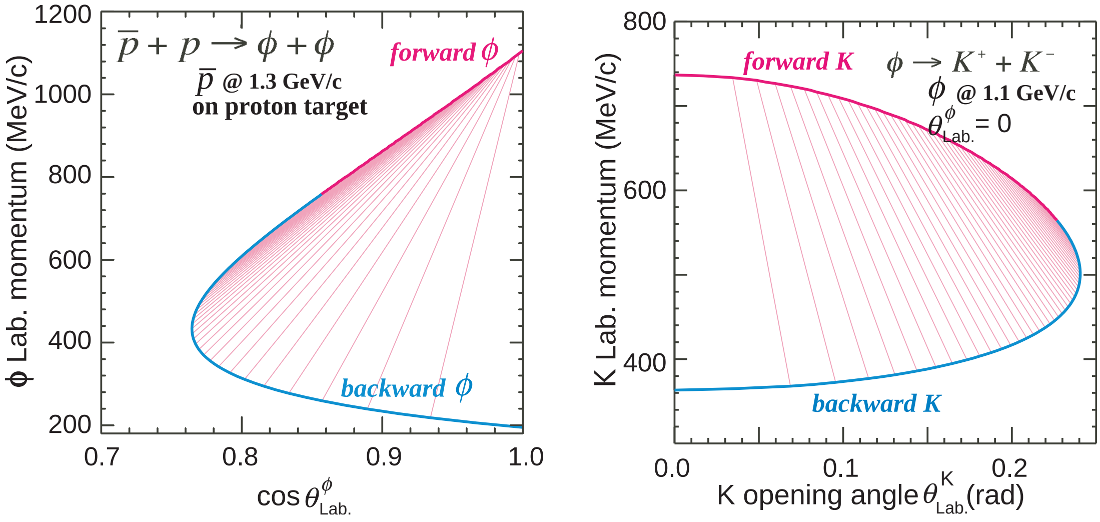

Figure 7: Left panel shows the momentum transfer to ϕ in the case of a proton target as a function of ϕ production angle. Right panel shows the momentum of a kaon from forward ϕ decay ($\theta^{\phi} = 0$ at 1.1 GeV/c) as a function of opening angle from the beam. Thin lines in both figures are plotted with a step of $\Delta\cos\theta_{CM} = 0.02$.

shown in figure 8, one needs as large as a $\sim$ 50 cm gap to avoid scraping $\phi \to K^+K^-$ decay in the vertical direction. The resulting large field leakage from the magnet might also be a serious problem. Another difficulty is how to handle the $\bar{p}$ beam without conflicting with the kaon tracking device. The other problem is that we cannot apply a large magnetic field to the double-arm spectrometer to achieve a wide momentum range (350 $\sim$ 700 MeV/c). In the setup shown in figure 8, the bending power is about 0.7 Tm. Tracks on the low momentum side have a large deflection angle which is not suitable for tracking, while the bending power for the high side is insufficient. This limits the momentum resolution of the missing mass spectroscopy. On the other hand, the particle identification detectors (PID) for the forward kaons are easy to operate, because they are placed in the free space.

One extreme design to overcome the above difficulties is the cylindrical setup both for the forward ϕ spectroscopy and for the decay particle analysis as shown in figure 9. This is similar to the idea of the spectrometer discussed in μ-e conversion search experiments or the TWIST experiment measuring the Michel parameters at TRIUMF. The conceptual design for the detector is shown in figure 9. In this setup, all detectors are installed in a long and large solenoidal magnetic field (3 m long and 1 m in diameter at 2 T magnetic field in this example). The Cylindrical Drift Chamber (CDC), which is the main tracker for the decay particle from the bound state (i.e. K^+ and Λ), is located around the target. For the forward direction, tracking detectors are placed to measure forward going K^+ and K^- pairs from the ϕ decay. The schematic event topology of the decay is given in the figure 9. In the x-y view of the figure 9, trajectories of the

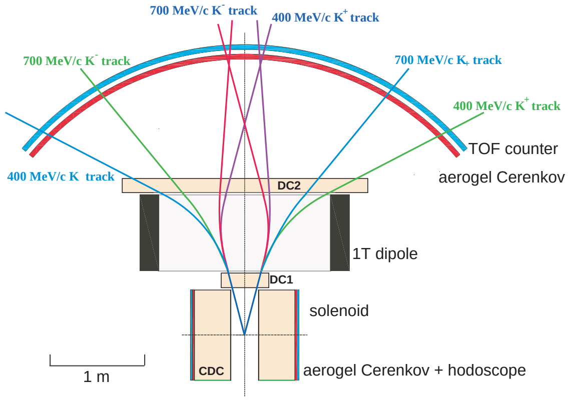

Figure 8: Conceptual design of the conventional experimental setup.

forward and backward K^+K^- pairs ($K^{\pm}_{fw}$ and $K^{\pm}_{bw}$) are plotted for several CM angles from the decay axis of the forward ϕ in steps of $\Delta\cos\theta_{CM} = 0.1$. In the side view of the figure, radial distance from the beam axis of these forward (R_{fw}) and backward (R_{bw}) trajectories are plotted.

The CDC for the decay particle analysis can be similar to the conventional one. For the forward ϕ spectroscopy, one needs a high field to confine the kaon within a reasonable size for the tracking as shown in the figure 9. To achieve good momentum resolution for the kaons, one also needs a long distance to measure several layers of planar chambers for tracking. Kaon identification devices are also needed both for the forward spectrometer and around the CDC (not shown in the figure).

The good features of this cylindrical setup are 1) wide momentum range for $K^{\pm}$ and good resolution can be achieve at the same time, 2) $\overline{p}$ handling is quite easy because most of the kaons (~ 85 %) have an opening angle of more than 100 mrad as shown in figure 7 (right : note that the thin lines in the figure are plotted for each $\Delta\cos\theta_{CM} = 0.02$), which is well separated from the $\overline{p}$ beam axis. On the other hand, the operation of an experimental device for the PID in the high magnetic field is much more difficult. For this purpose, one may employ an aerogel Čerenkov counter with readout using GEM-equipped photocathodes presently under development. It is also true that the cost of the setup will be more expensive than the conventional one.

In both configurations, the acceptance of the forward ϕ is limited by the hole size of the CDC at the downstream endplate. If we have a 30 cm diameter CDC hole at 50 cm down stream from the target, one can achieve a forward ϕ solid angle of ~ 120 msr in both examples shown in figures 8 and 9.

4.3 Event rate estimation for the $(\overline{p}, \phi)$ reaction

The $(\overline{p}, \phi)$ experiment is limited by the incident beam rate, even at J-PARC. The maximum $\overline{p}$ intensity is expected to be about $I_{\overline{p}} = 2 \times 10^6$ per *spill* (*spill* $= 0.7$ sec)

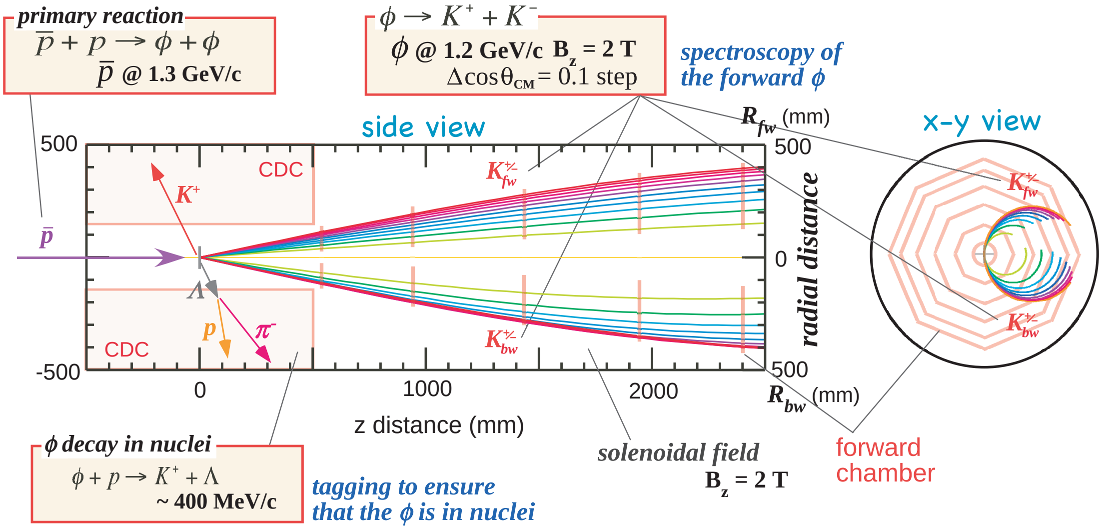

Figure 9: Conceptual design of the cylindrical experimental setup. The complete detector is placed inside a large solenoidal magnet.

at 30 GeV operation of the proton synchrotron.[3] At this beam rate, it is feasible to measure the beam momentum by using current experimental techniques with high rate chambers. Operating at 50 GeV, one can expect a higher intensity of $I_{\overline{p}} = 1 \times 10^7$ per *spill*, but the realization of the beam momentum measurement at this rate poses a quite severe technical challenge, and one also needs to wait for 50 GeV operation of the J-PARC proton synchrotron.

To estimate the event rate of the ϕ-meson ground-state formation via the $(\overline{p}, \phi)$ reaction, let us base the calculation on the hypernuclear formation rate obtained at KEK-SKS ($\sim$ twenty ${}^{12}_{\Lambda}$C ground state events per 1×10^9 π^+ on a 1 g/cm^2 target after corrections for the decay loss of the K^+ and detector efficiency), focusing on the difference with the (π^+, K^+) hypernuclear experiment.

The primary reaction rate can be evaluated from the following quantities.

- $\overline{p}$ beam intensity of $I_\pi = 2.0 \times 10^6$ per *spill* at 1.3 GeV/c,
- elementary cross section at CM $\sigma^{CM}_{\overline{p}p\rightarrow\phi\phi} = 4$ μb,
- uniform angular distribution in CM boosted with γ-factor, $\gamma_{\overline{p}p\rightarrow\phi\phi} = 1.16$, and
- target thickness of 2 g/cm^2.

Here we assume a uniform angular distribution in the CM frame. Because of the symmetrical reaction products, this assumption will be good enough for the event rate

[3]J-PARC proton synchrotron (50 GeV-PS) will be operated at a repetition rate of 3.52 seconds, providing a slow extraction period of 0.7 sec (*spill*).

evaluation. A thick target (2 g/cm^2) can be used without loosing the energy resolution by separating the target into several layers along the beam axis.

Another quantities we need to consider are the momentum transfer and the ratio of the bound state formation $R_{capture}$ difference between formation of hypernucleus and ϕ meson bound states. A rough estimation is that $R_{capture} \sim \exp(-\mathbf{q}^2/{p_F}^2)$, where $\mathbf{q}$ is the momentum transfer to the ϕ meson. The formula represents the overlap integral between a plane wave of ϕ at the momentum of $\mathbf{q}$, and the ϕ wave function in the sub-threshold region. If we assume $|\mathbf{q}| \sim 200$ MeV/c, then the ratio would be about 0.58 at $p_F \sim 270$ MeV/c,[4] so we have

- relative capture rate $R_{capture} \sim \exp(-\mathbf{q}^2/{p_F}^2) = 0.58$.

The other quantities are defined by the experimental setup assume to be

- CDS solid angle $\Omega_{CDS} = 4\pi \cdot 60$ %,
- $K^+\Lambda$ decay branch $R_{K^+\Lambda} = 37\%$ and $R_{\Lambda\to\pi^-p} = 60$ %,
- forward spectrometer with an acceptance $\Omega_{FS} = 120$ msr, and
- ϕ decay branch $R_{\phi\to K^+K^-} = 49$ %.

For a more precise yield estimation, one also needs to take into account the angular momentum of the proton hole formed in the primary reaction. For the case of hypernucleus formation on carbon target, the ground state formation rate is enhanced by the momentum transfer (feeding ground state from p-shell nucleon). Because the present reaction has moderate momentum transfer, the effect will not be much different in the two cases. In the present estimation, we ignored the effect for simplicity.

The required numbers for the estimation and the resultant event numbers are tabulated in table 2. As shown in the table, we can expect to observe ~ 240 events of the ϕ meson ground state formation within one month at $\overline{p}$ intensity of 2×10^6 / *spill*. Thanks to the lower momentum transfer (quasi-recoilless condition) of the $(\overline{p}, \phi)$ reaction, we obtained an excellent formation rate despite the lower cross section.[5] The ground state yield would be reduced by a severe requirement for the *back-to-back* $K^+\Lambda$ pair tagging, because of the FSI.[6]

As described, there is no chance to have backgrounds including accidentals, because all the particles to be observed are clearly labeled with the strangeness. Therefore, it is feasible to perform the systematic study even with a heavier target at the lower formation rate of the ground state.

[4]In this estimation, we used a larger Fermi momentum for the heavier targets than is used for light nuclei (*cf.* $p_F \sim 220$ MeV/c for carbon). This results in a conservative estimate by factor four.

[5]In this estimation, we haven't taken into account the ϕ mass reduction, namely we assumed the momentum transfer to be 200 MeV/c. As shown in figure 5 (right), the momentum transfer becomes smaller than that. This is again a more conservative yield estimation.

[6]In the case of the weak decay of the Λ hypernuclei, $\Lambda N \to NN$, the FSI effect is known to be ~ 50 %. In the case of $K^+\Lambda$ pair production, the effect won't be much different from hypernuclear weak decay, although the Q-value is different.

	${}^{12}_{\Lambda}C$	${}^{11}_{\phi}$ B
elementary reaction	$n(\pi^+, K^+)\Lambda$	$p(\overline{p}, \phi)\phi$
beam momentum	1.0 GeV/c	1.3 GeV/c
momentum transfer	500 MeV/c	200 MeV/c
$\overline{p}$ intensity	-	2×10^6 / *spill*
number of incident particles (π^+ or $\overline{p}$)	1×10^9 $^{(*)}$	$1{,}440\times10^9$/month
target thickness	1.0 g/cm^2 $^{(*)}$	2.0 g/cm^2
$d\sigma_{CM}/d\Omega$	104 μb/sr	0.3 μb/sr
γ factor	1.17	1.16
relative capture rate ($R_{capture}$)	0.032	0.58
ΛK^+ tagging efficiency ($\Omega_{CDS} R_{K^+\Lambda} R_{\Lambda\to\pi^- p}$)	12.6 ($\equiv 4\pi$) sr $^{(*)}$	1.7 sr
forward detector efficiency ($\Omega_{FS} R_{\phi\to K^+K^-}$)	100 msr $^{(*)}$ (SKS)	59 msr
expected yield of the ground state	$\sim$ 20 ev. $^{(*)}$	$\sim$ 240 ev. / month

Table 2: The event rate of the $(\overline{p}, \phi)$ reaction based on the ground state formation rate of the Λ hypernuclear study. The numbers with $(*)$ represent the reference based on the SKS experiments at KEK.

4.4 A competitive experimental setup

The experiment could be realized as a part of the experimental programs of the Panda experiment at GSI. They are now in the preparation phase of the future FAIR (Facility for the Antiproton and Ion Research). The Panda experiment and its collaboration is aiming at wide variety of physics, namely, glueballs, charm in nuclei, hypernuclei, *etc*, which makes the setup multi-purpose, composed of a huge and complex detector system as it is shown in figure 10. It is not clear whether one can add another physics

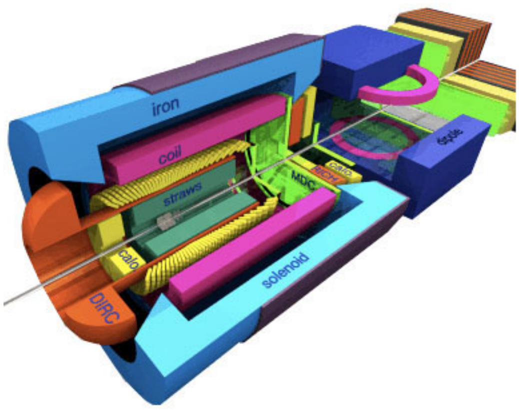

Figure 10: Planned design of the Panda experimental setup [23].

program easily to measure the momentum of the forward K^+K^- pair at large opening angle precisely without interfering with other complicated detector systems.

5 Discussion and Conclusion

Measurement of the in-medium mass modification of the vector-meson is an extremely interesting subject. A search for the ϕ-meson bound state itself is already quite interesting, although it seems to be natural that the ϕ forms a stable nuclear bound state.

Compared to other vector-meson studies, the ϕ is quite interesting due to its narrow width. Since the ϕ barely interacts with surrounding nucleons, it is natural to have a narrow width even in nuclei. In fact, the width broadening in nuclear media is reported to be only 3.4 times that of free space [6]. This fact makes the discrete peak observation in the missing mass feasible and allows simple analysis of the mass shift from the systematic study of the binding energies over several nuclei.

In this paper, we examined a new experimental approach to measure ϕ meson properties in nuclear media, and presented a feasibility study for the $(\bar{p}, \phi)$ reaction. For comparison, we also performed a feasibility study for the (π^-, n) reaction, which is given in the appendix. We haven't discussed (γ, N) spectroscopy in detail, because of the limitation of the information on the backward ϕ production cross section, and of the unavailability of a γ beam at J-PARC.

We demonstrated that the $K^+\Lambda$ tagging provides a clean missing mass spectrum. We also pointed out that one can deduce the mass shift information by two independent methods. A systematic study over several nuclear targets will lead to a unique, definitive and precise determination of the in-medium mass modification of the vector meson $\phi(s\bar{s})$.

The ideal completely background-free experiment can be done by $(\bar{p}, \phi)$ spectroscopy, in which all the particles to be measured are labeled with strangeness. In spite of the lower cross section of $p(\bar{p}, \phi)\phi$, we can expect an excellent ground-state formation event rate of 240 per month using the $\bar{p}$ beam of 2×10^6 per *spill* on a carbon target at J-PARC.

We presented two different conceptual designs to achieve these experiment. To finalize the design, we need more detailed study including detector development. As described in the paper, this experiment is feasible using present experimental techniques, although there are some difficulties to be resolved.

Another quite interesting study one may perform in this experiment is forward double K^+ observation. Although the elementary cross section is small as shown in figure 5 (left), the two K^-s in the backward direction will be produced in a quasi-recoilless condition. Therefore, one may have a chance to detect double kaonic nuclei, if they exist with a relatively narrow width.

This experiment requires at least the full capability of the J-PARC at 30 GeV operation to obtain $\bar{p}$ beam intensity of 2×10^6 per *spill*. Even at this rate, we need a relatively long beam time for the systematic study of the ϕ meson properties in the nuclear medium over several nuclei. The preparation of an experiment of this size is expected to be quite long, and we wish to start the preparation as soon as possible to be competitive with the Panda project in FAIR at GSI.

Appendix

A.1 The ϕ meson production via (π, N) reactions

The incident (π, N) reactions can be written as

$$\pi^- +^{A+1}_{Z+1} \mathrm{X}' \rightarrow \{\phi \ ^A_Z\mathrm{X}\} + n, \tag{18}$$

or

$$\pi^+ +^{A+1}_{Z} \mathrm{X} \rightarrow \{\phi \ ^A_Z\mathrm{X}\} + p. \tag{19}$$

For these channels, missing mass spectroscopy will be possible using the forward nucleon from the reaction. From this missing mass spectroscopy, one can define the rest frame of $\{\phi \ ^A_Z X\}$.

Let us start with the elementary cross section of the ϕ meson. Experimental measurements of the total cross section of the ϕ meson production around the production threshold energy have been studied intensively since the early 1970's to 1980's. Figure 11 (left) shows the measured total cross section as a function of the incident pion beam momentum. The production cross section of ϕ mesons has a maximum around the threshold energy where the cross section is about 20 μb and decreases monotonically as a function of beam momentum. Therefore, the optimum choice of beam momentum for the proposed experiment will be around the production threshold energy, *i.e.,* $\sim$ 2 GeV/c, to maximize the event rate.

The momentum transfer of the (π^-, N) reaction is shown in figure 11 (right). Because of the mass relation, the recoilless condition cannot be realized. If one chooses the incident π beam momentum as 2 GeV/c, where we expect the ϕ meson production cross section is maximum, the momentum transfer of the reaction is $\sim$ 400 MeV/c. It is larger than the nucleon Fermi-motion, but within a reasonable range for the ϕ bound state formation. The situation is similar to Λ hypernuclear production in the in-flight (π^+, K^+) reaction. Note that a series of experimental studies has been performed producing Λ hypernuclei with the in-flight (π^+, K^+) reaction where the momentum transfer for the reaction is about 360 $\sim$ 380 MeV/c. It is almost comparable to the case of ϕ bound state formation.

However, the above discussion is only valid when there is a finite backward ϕ production cross section, *i.e.*, the produced ϕ's are emitted in the opposite direction with respect to the incident π beam. The production angle distribution for ϕ mesons in the CM frame has also been measured by [24, 25] and results are shown as figure 12-(a)

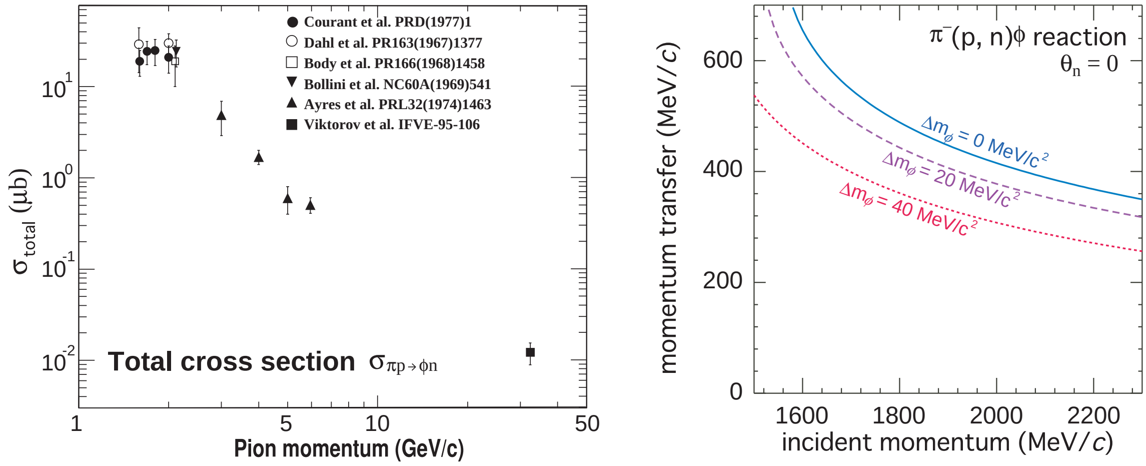

Figure 11: Left panel shows the elementary cross section of $\pi^- p \to \phi n$. The cross section has a maximum near the production threshold given in [24, 25]. Right panel shows the momentum transfer to the backward ϕ as a function of the incident pion momentum.

and (b). Both results support isotropic ϕ meson production at around the threshold energy.[7]

Let us focus on the decay reaction around the target region. By selecting *back-to-back* ΛK^+-pair production in the momentum region around $200 \sim 600$ MeV/c for both Λ and K^+, the quasi-invariant mass will be in the region of interest. Using a crude window for the quasi-invariant mass, the missing mass spectrum for forward nucleons N will be background free. This is because there is no primary process which produces energetic neutrons in the forward direction together with ΛK^+-pair production back-to-back from the target, at least in the single step reaction. In reality, it is not perfectly background free. More detailed discussion of the background will be given in following section.

A.2 $K^+\Lambda$-background yield in (π, N) reactions

What's about the background? In the previous section, we neglected the background by focusing only on the primary reaction, but internal cascade reactions can possibly match to the $K^+\Lambda$-pair back-to-back production together with forward energetic nucleon emission. In the present rough estimation of the background, we evaluate only the dominant component.

Because we require the $K^+\Lambda$-pair in the final state, $s\bar{s}$ production is a must for the background process also, such as $\pi + N \to K^+ + Y$. This gives another big advantage

[7] This is not the case if incident beam momentum is away from the production threshold. For example, data with higher pion momentum, like 4-5 GeV/c, show more strength in the ϕ meson production in the forward direction (nucleon in backward) [26].

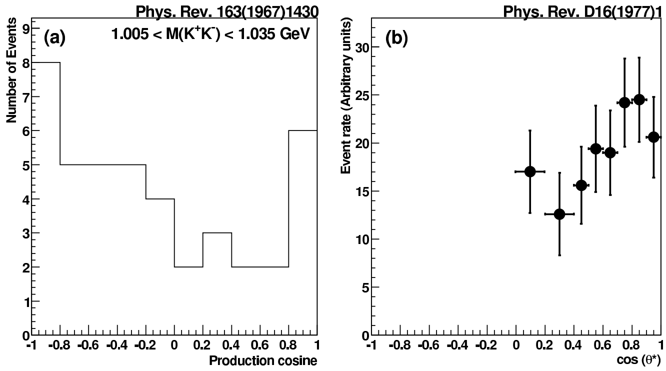

Figure 12: Angular distribution of the ϕ in the CM frame. The backward ϕ production seems to be slightly favored, but no strong angular dependence is seen in the ϕ production given in [24, 25].

to the tagging method. Most of the strong interaction channels have a total cross section of mb or more, while all those $K^+ + Y$ channels are $\sim 100\ \mu$b. The related cross sections are listed in table 3.

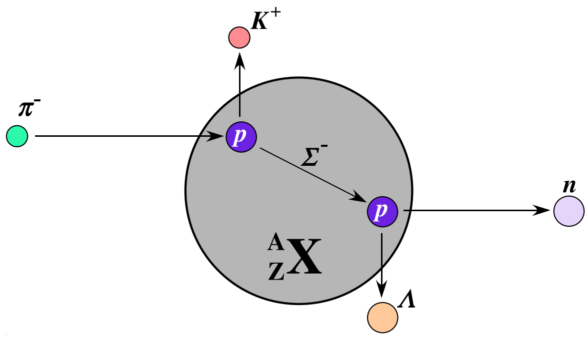

Figure 13: Illustration of the major background source caused by the cascade reaction of the primary $K^+\Sigma$ production and successive $\Sigma\Lambda$ conversion. In this example, two proton holes are generated.

Clearly the biggest background among these reactions will be the cascade reactions of $\pi + N \to K^+ + \Sigma$ and $\Sigma + N' \to \Lambda + N'$, as illustrated in figure 13. This is because the $\Sigma\Lambda$ conversion is known to be very large. The Σ-hypernuclear study using at-rest kaon absorption shows that the conversion strength of Σ to Λ within a nucleus is as much as 50 % at Σ momentum around 200 $\sim$ 300 MeV/c.

In the primary reaction of the cascade, the Σ is produced in the momentum range around 0.4 $\sim$ 2.1 GeV/c in the laboratory frame. The Σ forward production is required to generate low momentum K^+ with efficient generation of the high momentum

process (@ GeV/c)	channel	cross section	channel	cross section
$\pi^- p$ (2.0)	$\Sigma^- K^+$	87 μb	$\Sigma^-\pi^0 K^+$	52 μb
			$\Sigma^-\pi^+\pi^- K^+$	2.6 μb
			$\Sigma^+\pi^-\pi^- K^+$	3.2 μb
			$\Sigma^0\pi^- K^+$	67 μb
			$\Lambda\pi^- K^+$	152 μb
$\pi^- n$ (5.0)			$(\Lambda/\Sigma^0)\pi^-\pi^- K^+$	51 μb
$\pi^- n$ (2.3)			$\Sigma^-\pi^- K^+$	70 μb
$\pi^+ p$ (2.0)	$\Sigma^+ K^+$	290 μb	$\Sigma^+\pi^0 K^+$	170 μb
			$\Sigma^0\pi^+ K^+$	40 μb
			$\Lambda\pi^+ K^+$	120 μb
			$\Lambda\pi^+\pi^0 K^+$	15 μb
$\pi^+ n$ (2.5)	$\Sigma^0 K^+$	57 μb	$\Sigma^0\pi + \pi^- K^+$	140 μb
			$\Sigma^+\pi^- K^+$	96 μb
			$\Sigma^+\pi^0\pi^- K^+$	7 μb
			$\Sigma^-\pi^+ K^+$	34 μb
			$\Sigma^-\pi^0\pi^+ K^+$	10 μb
	ΛK^+	140 μb	$\Lambda\pi^0 K^+$	107 μb
			$\Lambda\pi^+\pi^- K^+$	61 μb
$\pi^- p$ (2.0)	nK^+K^-	39 μb	$n\pi^- K^0 K^+$	130 μb
$\pi^+ n$ (5.4)	pK^+K^-	137 μb		

Table 3: Background-related elementary $\pi^\pm N$ cross sections near 2.0 GeV/c with a K^+ in the final state

secondary nucleon in the forward direction, so that the Σ momentum should be in the range of 1.6 $\sim$ 2.1 GeV/c, thus 70 % of the $K^+\Sigma$ can be ignored. Naively, the $\Sigma\Lambda$ conversion strength in this momentum region should be much smaller, although let us conservatively assume that the strength will be unchanged because there is no reliable data on this strength. Although, the neutron yield within the energy window of interest is small, we assume the forward neutron will distribute uniformly over the wide momentum range of 1.6 $\sim$ 2.1 GeV/c. For the window as wide as 70 MeV ($\Delta p \sim$ 80 MeV/c), the forward neutron yield within the window is roughly 0.08 (ignoring backward neutrons).

To detect the resulting K^+ and Λ with detectors around the target, the reaction angle from the beam axis for the two successive reactions should be large. Therefore, the cross section should be smaller by at least twice the γ-factor $\gamma_{\pi p\to K\Sigma}\cdot\gamma_{\Sigma p\to\Lambda n} \sim 1.4\times$ 1.3 for large CM angles, even if we do not take the angular dependence into account. The optimal window for back-to-back coincidence of ΛK^+-pairs can be calculated from the smearing effect due to the Fermi motion of the ϕ and the nucleon by about $\Delta\cos\theta_{CM}$ $\sim$ 0.1, so that we need a 5 % window on the opening angle ($\cos\theta_{CM} < -0.9$).

To evaluate the S/N, one needs the signal production yield as well. One should take into account the $K^+\Lambda$ branch and its decay branch to the charged final state. Another quantity we need to consider is the sub-threshold production yield of the ϕ meson, in other words the ϕ-meson capture rate $R_{capture}$ on the nuclei. A rough estimate is $R_{capture} \sim \exp(-\mathbf{q}^2/{p_F}^2)$, where $\mathbf{q}$ is The momentum transfer to the ϕ meson. the formula represents the overlap integral between a plane wave of ϕ at the momentum of $\mathbf{q}$, and the ϕ wave function in the sub-threshold region. If we assume $|\mathbf{q}| \sim 400$ MeV/c, then the ratio would be about 0.11, at $p_F \sim 270$ MeV/c. To evaluate $R_{capture}$, we need to wait for a realistic calculation of the spectroscopic function.

A conservative estimate of the S/N is

$$\begin{aligned} S/N &\sim \frac{\sigma_{\phi N}}{\sigma_{K\Sigma}} \cdot \frac{0.4 \cdot 0.6}{1} \cdot \frac{0.11}{1} \cdot \frac{1}{0.5} \cdot \frac{1}{1-0.7} \cdot \frac{1}{0.07} \cdot \frac{1}{1/1.4 \cdot 1/1.3} \cdot \frac{1}{0.1/2} \\ &\sim 19 \qquad \Big(\text{for the } (\pi^-, n) \text{ formation channel}\Big)\,, \text{and} \qquad (20) \\ &\sim 6 \qquad \Big(\text{for the } (\pi^+, p) \text{ formation channel}\Big)\,. \qquad (21) \end{aligned}$$

To improve S/N, one can also require the balance of absolute three-momenta between the Λ and K^+ in the rest frame. One can require the energy balance between initial and final state, and/or $\sim 4\pi$ detector coverage of the target to veto any unfavorable particle production. If one focusses on the discreet peak in the missing mass spectrum, then the S/N will be even better.

Actually, some of these numbers are correlated so that the detailed simulation based on a realistic experimental setup is needed to obtain a more reliable number. Only the most serious background was discussed, so the sum of other contributions will further increase it. However, the estimated S/N is excellent and the contributions will not be significant.

A.3 Possible experimental setup for (π, N) spectroscopy

As discussed, one promising channel which allows us to measure both the reaction and decay process of the product is the (π, N) reaction. For simplicity, let us think about the ${}^{A+1}_{Z+1}\mathrm{X}'$ (π^-, n) $\{\phi\ {}^{A}_{Z}\mathrm{X}\}$ channel.[8] The elementary reaction is

$$\pi^- + p \to \phi + n. \qquad (22)$$

As shown in figure 11 (right), it is impossible to choose an incident pion momentum to realize a zero momentum transfer in the elementary reaction, but the smaller momentum transfer is realized on the higher momentum side. On the other hand, as also shown in figure 11 (left), the production cross section of the ϕ meson shows a

[8] Although we haven't excluded the possibility of (π^+, p) channel, we will focus on this (π^-, n) channel in the present paper. For the case of (π^+, p), the forward proton production reaction would be extremely difficult, because one needs to detect the protons in a huge number of primary positive pions.

maximum around production threshold energy. To produce ϕ-meson bound states efficiently, momentum transfer of the reaction must be chosen to be, at least, the same order of magnitude as the Fermi momentum of nucleons in the nuclei. To maximize the ϕ meson production cross section and to realize a momentum transfer of the process as small as possible, we will choose the pion beam momentum as 2.0 GeV/c. Here, the momentum transfer to the ϕ is about 400 MeV/c. Thus, the forward neutrons to be measured are at around 1.6 GeV/c.

Unfortunately, it is not easy to tag the ϕ production events from only the neutron momentum. Because the cross section of the strong interaction is in the order of 10 mb, while the ϕ production is about 10 μb, we will have 10^3 times the background without 4π coverage of a decay particle detector surrounding the target.

The basic detector concepts for this measurement are summarized as follows.

- a beam line tracker for high intensity pions,
- a sweeping magnet to remove beam pions,
- a neutron counter, NC, at zero degrees, and
- a Cylindrical Detector System, CDS, to reconstruct K^+ and Λ.

As shown in table 1, the total background cross section associated with K^+ emission is a few hundred μb, which is already an acceptable level, although the present argument totally relies on the good particle identification of the charged particles detected in CDS. Therefore, the CDS should have enough PID capability to separate K^+ from π^+ at around 400 MeV/c. Another important point is that the detector resolution should be designed well below the energy width of the ϕ in nuclei, which is expected to be around 10 MeV.

A possible experimental setup for this measurement could be similar to that proposed for J-PARC E15 experiment [27], shown in figure 14. For this setup, a forward neutron counter is located 12 m away from the target. The missing mass resolution and solid angle for the neutron counter is estimated to be 25 MeV(FWHM) and 30 msr, respectively. If we are able to place a neutron counter 20 m from the target within the counter hall boundary, then missing mass resolution will be improved to 12 MeV(FWHM). However, the solid angle of the neutron counter is down to 10 msr for this setup.

A.4 Event rate estimation for the (π, N) reaction

The number of events expected in a month of beam time is estimated based on following assumptions.

- π^- beam intensity of $I_\pi = 1.0 \times 10^7$ per *spill* at 2.0 GeV/c,
- elementary ϕ production total cross section at CM $\sigma^{CM}_{\pi p \to \phi n} = 20$ μb,

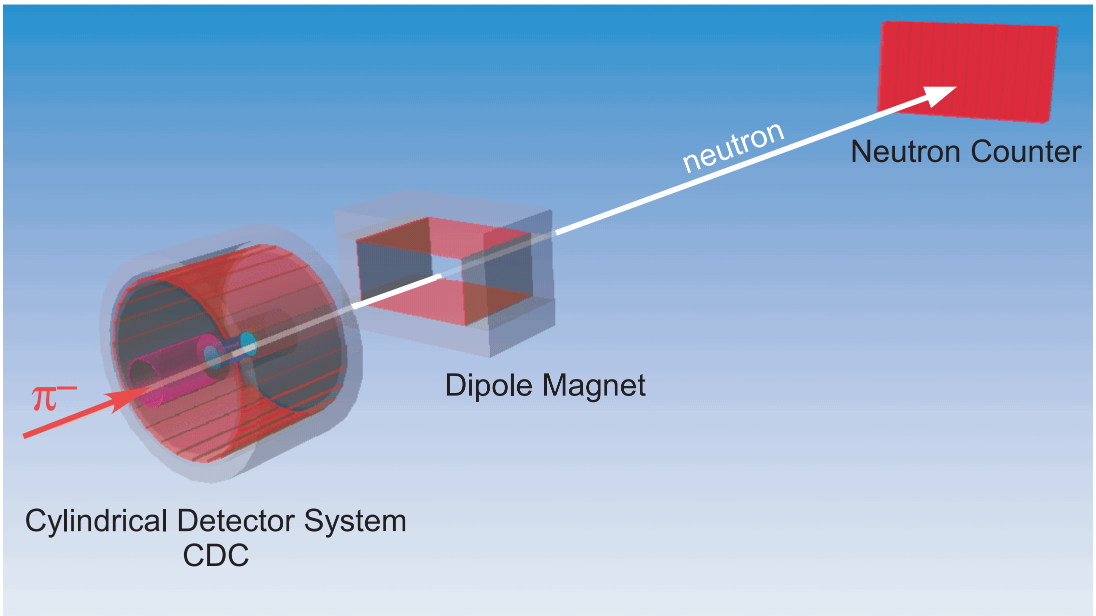

Figure 14: Conceptual design of the experimental setup.

- effective proton number in carbon $N^p_{\mathit{eff}} = 6$,
- forward cross section $\sigma_{\pi C\to\phi n} = N^p_{\mathit{eff}} \times \gamma_{\pi p\to K\Sigma} \times \sigma^{CM}_{\pi p\to\phi n}$, and
- carbon target of $T_C = 2$ g/cm^2 thickness in the direction of the beam axis.

Thus the number of the ϕ mesons produced per *spill* can be given as

$$N/spill = I_\pi \times \sigma_{\pi C\to\phi n} \times T_C \times \frac{N_A}{A} \quad (23)$$

$$= 120 \quad (24)$$

In total, 120 ϕ mesons will be produced per *spill*. Here the *spill* length of J-PARC 50 GeV PS slow extraction is assumed to be 3.52 s/*spill*, so the number of *spills* per month will be 720,000. Therefore, about 86 M ϕ mesons will be produced per month in 4π space. In addition, the following assumptions need to be added to the estimation.

- uniform CM angular distribution with the γ-factor $\gamma_{\pi p\to K\Sigma} = 1.4$,
- forward neutron counter with an acceptance $\Omega_{NC} = 20$ msr, and
- neutron counter efficiency $\epsilon_{NC} = 30$ % (*i.e.*, total thickness of 30 cm[9]).

[9]Nominally, high momentum neutrons have a reaction rate of ~ 1 % per g/cm^2 in plastic counters.

Therefore, the number of neutrons detected in NC coming from ϕ meson production will be

$$N_{detect}/month = N/day \times \gamma_{\pi p \to K\Lambda} \times \Omega_{NC} \times \epsilon_{NC} \quad (25)$$
$$= \sim 56,000. \quad (26)$$

In total, $\sim$ 56.0 K ϕ mesons per month will be detected by the neutron counter.

On the other hand, the number of neutrons produced in the strong interaction is about 10^3 times higher, so that the number of background high-momentum neutrons is about 400 per *spill*. We can safely operate the neutron counter at this background rate.

For the ΛK^+-pair detection, we also need to take into account

- $K^+\Lambda$ decay branch $R_{K^+\Lambda} = 37\%$ and $R_{\pi^- p} = 60$ %,
- CDS solid angle $\Omega_{CDS} = 4\pi \cdot 60$ %, and
- sub-threshold ϕ formation $R_{capture} \sim \exp(-\mathbf{q}^2/{p_F}^2) = 0.11$.

Taking into account these numbers, finally we get the number of events which can be seen in the sub-threshold (bound) region as $\sim$ 800 events per month. If we assume that 20% of the sub-threshold yield forms a ϕ-meson ground state, then total number of events expected will be about 160 per month. Note that this ground state formation ratio of 20 % is sufficiently pessimistic, even if we take into account the FSI effect for $K^+\Lambda$ pair branching. This is already quite acceptable, although there are still missing efficiencies such as analysis, DAQ, and so on.

To check the event rate estimation, let us compute it again from hypernuclear experimental data. In Sec. 3.1, we discussed the similarity between the ϕ meson bound state production and the hypernuclear formation via the (π^+, K^+) reaction in terms of the expected binding energy and momentum transfer of the reaction. As a first order approximation, the ground state formation rate of ϕ mesons can be obtained from the event rate seen in the hypernuclear experiment. A series of hypernuclear production experiments have been performed at KEK-PS/K6 beam line with the SKS spectrometer. We know from these experiments that about twenty ${}^{12}_{\Lambda}C$ ground state events will be produced with 1×10^9 π^+ on a 1 g/cm^2 target, after correcting for decay loss of K^+, detector efficiency and so on. For the proposed experiment, the beam intensity we will use is $1.0{\times}10^7$. Therefore, 7,200 G π^+ will hit the target per month. Now we need to take into account all the differing factors between hypernuclear production and ϕ meson bound state formation, like differences in the elementary cross section etc. These differences are summarized in table 4 and one can derive the expected yield to be about 140 events per month.

In summary, the expected number of ϕ-meson ground states events is $\sim$ 150 within a month of beam time with a $1.0 \times 10^7/spill$ π^- beam on 2 g/cm^2 carbon target. The number is evaluated two different ways and consistent results obtained.

	${}^{12}_{\Lambda}C$	${}^{11}_{\phi}$ B
elementary reaction	$n(\pi^+, K^+)\Lambda$	$p(\pi^-, n)\phi$
beam momentum	1.0 GeV/c	2.0 GeV/c
momentum transfer	500 MeV/c	400 MeV/c
π^+ intensity	-	1×10^7 / *spill*
number of incident $\pi^\pm$	1×10^9 $^{(*)}$	$7{,}200\times10^9$/month
target thickness	1.0 g/cm^2 $^{(*)}$	2.0 g/cm^2
$d\sigma_{CM}/d\Omega$	104 μb/sr	1.6 μb/sr
gamma factor	1.2	1.4
relative capture rate ($R_{capture}$)	0.032	0.11
ΛK^+ tagging efficiency ($\Omega_{CDS} R_{K^+\Lambda} R_{\pi^- p}$)	12.6 ($\equiv 4\pi$) sr $^{(*)}$	1.6 sr
forward detector acceptance	100 msr $^{(*)}$ (SKS)	20 msr (Ω_{NC})
neutron detection efficiency (ϵ_{NC})	1 $^{(*)}$	0.3
expected yield of the ground state	$\sim$ 20 ev. $^{(*)}$	$\sim$ 140 ev. / month

Table 4: The event rate of the (π^-, n) reaction based on a ground state formation rate of the Λ hypernuclear study. The $(*)$ indicates a reference number based on the SKS experiments at KEK.

The problem with this reaction channel is 1) how to handle an incident pion beam of $1.0 \times 10^7/spill$, 2) that the accidental neutron detection rate is not easy to evaluate precisely and might not be negligible at this incident beam rate, and 3) that good energy resolution is not easy to obtain.

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