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A SEARCH FOR ϕ MESON NUCLEUS BOUND STATE USING ANTIPROTON ANNIHILATION ON NUCLEUS*

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The mass shift of the vector mesons in nuclei is known to be a powerful tool for investigating the mechanism of generating hadron mass from the QCD vacuum. The mechanism is known to be the spontaneous breaking of chiral symmetry. One of the approach to investigate spontaneous breaking of chiral symmetry in nuclear media is formation of meson nucleus bound state and measurring energy level of the state which will be a direct connection to the $\langle\overline{q}q\rangle$ expectation value in nucleus. We propose the experiment to study in-medium mass modification of the ϕ meson using the formation of ϕ-meson bound state at J-PARC/Japan. We demonstrate that a clear missing-mass spectrum can be obtained efficiently by $(\overline{p}, \phi)$ spectroscopy together with the Λ tagging, using the primary reaction channel $\overline{p}p \to \phi\phi$. 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 $\phi(s\overline{s})$. This paper gives an overview of the physics motivation and the detector concept, and explains the direction of the initial research and development effort.

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1. Introduction

Since 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 $\langle\overline{q}q\rangle$ is non-zero due to the spontaneous chiral symmetry breaking of the vacuum, and this $\langle\overline{q}q\rangle$-condensation is the major source of masses of low-lying hadrons such as protons, neutrons, pions, *etc.* The $\langle\overline{q}q\rangle$ 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.

In the year 2007, KEK-PS E325 experiment reported about 3.4% mass reduction of the ϕ meson in medium-heavy nuclei (Cu) [1]. This result is pointing towards a possible partial restoration of the chiral symmetry in nuclear media, however, it is hard to make strong conclusions using only that data. On the other hand, recently ϕ meson and nucleon cross sections have been investigated at LEPS at SPring-8 [2] and CLAS at J-LAB [3] using gamma ray induced hadron production processes and unexpectedly large ϕ–N cross sections of > 20 mb have been presented, which can be interpreted as a huge broadening of ϕ-meson decay width in nuclear media, without mass shift of the ϕ meson. Similar results have been recently obtained at COSY in proton induced ϕ-meson production [4]. Therefore, the ϕ-meson mass shift phenomena in nuclear matter is still controversial.

To get definitive information about the possible ϕ-meson mass shift in nuclear media, we need to perform new generation experiments. There is the E16 experiment [5] at J-PARC in progress, which intends to measure di-electron spectra in p–A collisions precisely at J-PARC with 100 times more achieved in statistics than previous experiments at KEK-PS.

The proposed experiment instead starts form the 3.4% (= 35 MeV/c^2) possible mass reduction of the ϕ mass in nuclei measured by the KEK E325 experiment. We plan to confirm (or not) this shift by performing a much more precise experiment. Possible theoretical indications toward the existence of ϕ-mass shifts are related to the charged kaon behavior in nuclei. Reference [6] pointed out that mass of the K^- will be reduced in nuclear matter due to the strong attractive potential between K^- and nucleon. This theoretical prediction indicates that "mass reduction of ϕ meson in nucleus" will be directly connected with the possible existence of an attractive potential between ϕ meson and nucleus. The depth of the potential is expected to be in the same order of the mass reduction which have been measured. Therefore, we have examined an experimental approach to measure ϕ-meson properties in nuclear media using the formation of a ϕ-meson bound state.

Detail theoretical calculations about ϕ-meson bound state has been performed by authors of reference [7]. The article indicates that it is depending on the strength of the attractive potential between ϕ meson and nucleon, whether the formation of the ϕ-meson bound state will be possible or not.

The experiment [8] is to search for the ϕ-nucleus bound state and measure the binding energy of the system at J-PARC where a high intensity antiproton beam is available. The measurement must be done with different target nuclei to see the evolution of the binding energy of newly generated nuclear cluster, ϕ-nucleus bound state.

In order to experimentally search for the ϕ-meson bound nuclear state, we are focusing on the elementary process $\overline{p}p \to \phi\phi$ around the production threshold. The advantage for this elementary process are (a) relatively low momentum ϕ meson, which is around a few 100 MeV/c, can be produced by the reaction, and (b) it is found experimentally that in the case of double strangeness pair production in $\overline{p}p$ annihilation for this energy, $\phi\phi$ production appears as the dominant production branch. The production of four kaons or ϕKK are highly suppressed [9].

The concept for the experiment is shown in figure 1. Double ϕ mesons are produced by $\overline{p}p \to \phi\phi$ on one of the protons in the nucleus. The forward going ϕ meson is detected and identified by its decay products of K^+ and K^-. The other ϕ mesons, which will be moving in backward direction in the CM frame of the $\overline{p}p$ reaction, will be trapped in nucleus and a ϕ-meson bound state will be formed. It should be noted that if we choose an incident $\overline{p}$ momentum of about 1.1 GeV/c, the momentum of the backward ϕ meson in laboratory frame will be about 240 MeV/c, which is comparable with the Fermi momentum of the nucleons in the nucleus if we select the heavy nucleus as a target. The sticking probability of the ϕ meson to a nucleus, like carbon, is expected to be $\approx 11\%$. Finally, the ϕ meson which is trapped in the nucleus will disappear because of ϕ–N interaction. The decay products from the ϕ–N interaction is expected to be $K^+ + \Lambda$ and $K^0_\mathrm{s} + \Lambda$ for ϕ–proton and ϕ–neutron interaction, respectively.

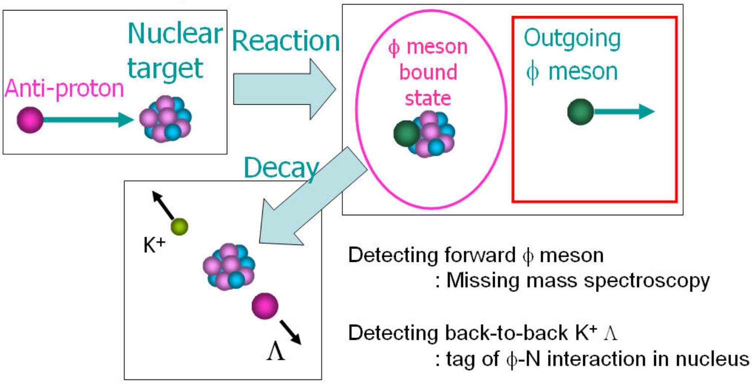

Fig. 1. The concept for the proposed experiment.

The identification of the ϕ-meson bound state will be done as follows. First of all, the missing mass of the reaction using the forward going ϕ meson is analyzed. However, due to a huge number of background events expected from other reaction channels, such as $\bar{p}p \rightarrow \phi\pi\pi$ and $\bar{p}p \rightarrow K^+K^-\pi^+\pi^-$, the signal coming from possible bound state formation will not appear cleanly only in the missing mass spectroscopy. As a second step, we will require kaon and/or Λ in coincidence to the existence of a forward going ϕ meson. The requirement of a kaon or Λ together with a ϕ meson is essentially selecting events with double strangeness pair production. The double ϕ-meson production is the dominant process for double strangeness pair production in $\bar{p}p$ annihilation at the energy region we are interested, thus, this requirement will reject almost all background events. The rejection power and expected signal and background will be discussed in the next section.

Therefore, the measurement can be explained as the missing mass spectroscopy using a forward going ϕ meson together with Λ production as a tag of double strangeness production.

2. Conceptual design for the spectrometer

2.1. Setup for the experiment

The detector is designed to detect forward going ϕ mesons efficiently together with large acceptance for decay particles from ϕ-meson bound state.

The conceptual design for the spectrometer is shown in figure 2. The target is placed in the center of the dipole magnet. A cylindrical drift chamber (CDC) is surrounding the target to maximize the acceptance for the decay particles, namely K^+ and/or Λ. Moreover, the CDC will also be working perfectly for forward going kaons from the ϕ meson decay.

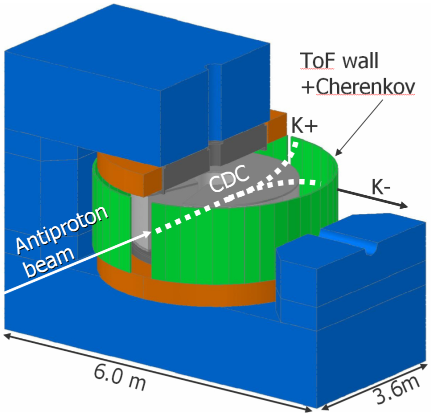

Fig. 2. The conceptual design for the spectrometer.

A Time-of-Flight (ToF) wall will be installed just outside the CDC for trigger and particle identification (PID). To achieve more than 2 σ separation of pions and kaons up to 700 MeV$/c$ momentum, the time resolution of the ToF wall must be less than 100 ps. Moreover, part of the ToF detector system is going to be in the region where magnetic field is present. To have such high timing resolution under the magnetic field condition, we selected Resistive Plate Chamber (RPC) as a candidate of our detector. R&D project for the ToF wall is also in progress.

Segmented Cherenkov counters (CRK) will be installed just after the ToF wall to reject pions which are mainly coming from multi-pion production in the $\bar{p}p$ annihilation processes. The Cherenkov radiator for the CRK counter is chosen to be very efficient in rejecting pions, without killing the kaons from our signal. One of the candidates satisfying the request to reject pions but not affect kaons for the experiment is the recently developed high density silica aerogel which has a refraction index (n) of approximately $n = 1.2$. Another possibility is using water, which has a refraction index of 1.33. The actual design of the Cherenkov counter is under way.

3. Yield estimation

To evaluate the number of expected event candidates, all factors, acceptance of the spectrometer, decay rate and sticking probability *etc.* are evaluated using Geant4 based detector simulation. The experiment is planning to perform at K1.8BR beam line at J-PARC. The beam intensity of 1.1 GeV$/c$ antiproton available at K1.8BR beam line is $\sim 10^6/3.5$ s. A target thickness of 2.0 g/cm^2 will be used for all materials.

Another quantities we need to consider are the momentum transfer and the ratio of the bound state formation, *i.e.* sticking probability P_{sticking}. A rough estimation is that $P_{\mathrm{sticking}} \sim \exp(-\boldsymbol{q}^2/{p_F}^2)$, where $\boldsymbol{q}$ is the momentum transfer to the ϕ meson in the reaction. The formula represents the overlap integral between a plane wave of ϕ at the momentum of $\boldsymbol{q}$, and the ϕ-wave function in the sub-threshold region. The P_{sticking} of the produced ϕ meson to a nucleus is estimated to be 11% of the produced ϕ meson.

The branching ratio of $\phi \rightarrow K^+K^-$, ~ 48.9 %, is also taken into account in the acceptance calculation. For the decay from bound state side, we took a branching ratio for (ϕ–N) goes to at least single Λ, of 76% [10]. The reason that we just take a single Λ is as follows. The signal we are looking for is double strangeness pair production in a nucleus. For the measurement, a single pair of strangeness is tagged by the forward ϕ meson. If we also tag another strangeness pair in the backward region, namely K^+ and Λ or K^0_{s} and Λ, we can collect pure double strangeness pairs produced event, efficiently. However, it is also true, that only single strangeness, either, Kaon or Λ will give us a good tagging for the "effective" double strangeness production, because single $s\bar{s}$ pair have already been identified via detecting $\phi \rightarrow K^+K^-$. Therefore, for the measurement, we just use a single Λ tag to clean the signal of bound state formation from the background. The final number of the detector acceptance including decay of particles is found to be 4.8×10^{-3}.

The summary of all numbers together with final expected number of events are listed in Table I. It should be noted that for this experiment deuteron is used for quasi-free nucleon target as a reference for carbon and copper target. The number of event for the deuteron target represents just the number of double ϕ-meson production.

Here, we assumed 1000 [spill/hour] and 7 [hours/shift] for the effective running time. The number of expected ϕ meson nucleus bound state candidates for three months of beam time are, ~ 160, ~ 200, for copper and carbon, respectively.

TABLE I

Expected event rate.

Target	Cu	Carbon	Deuteron
Mass number	64.0	12.0	2.0
Charge number	29	6	1
Target thickness [g/cm^2]	2.0	2.0	1.35
Cross section $(Z^{2/3} \times \sigma_{\overline{p}p})$ [μb]	23.	7.9	2.4
$\overline{p}$ intensity (/spill)	10^6	10^6	10^6
Number of target nucleus (/cm^2)	0.19×10^{23}	1.0×10^{23}	4.1×10^{23}
Acceptance for decay particles	4.8×10^{-3}	4.8×10^{-3}	1.45×10^{-3}
Averaged Sticking probability	0.11	0.11	(N/A)
Analysis and DAQ efficiency	0.7	0.7	0.7
Expected yield/spill	1.6×10^{-4}	2.9×10^{-4}	$24. \times 10^{-4}$

4. Expected signal

The signal of ϕ-meson bound state production on a carbon nucleus together with possible major sources of the background, $\overline{p}p \to K^+K^-\pi^+\pi^-$ and $\overline{p}p \to \phi\pi^+\pi^-$ processes have been analyzed. For the ϕ-meson bound state signal, the values of 3.4% mass reduction and 3.6 times width broadening in the nucleus, which is the experimental result by KEK-PS E325 experiment, have been used. Event samples of ϕ-bound state formation and relevant background channels have been generated by simulation studies. The resulting missing mass distributions with the condition of a reconstructed Λ in the final state are shown in figure 3. The result shows that in

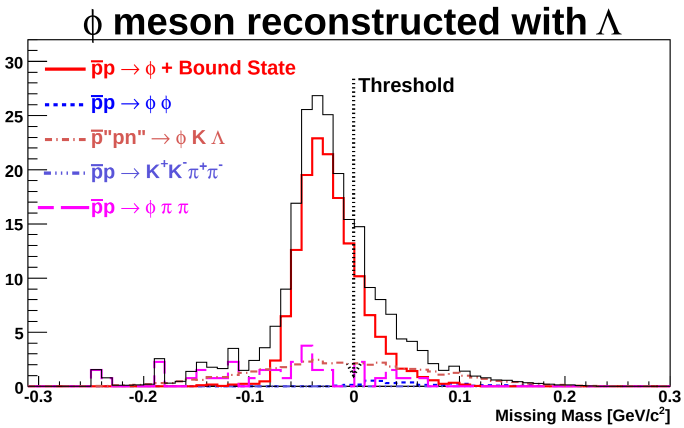

Fig. 3. Missing mass spectra for signals from bound state formation with possible background sources.

spite of such an even such a huge background expected from the $\phi\pi\pi$ and $KK\pi\pi$ processes, requiring a Λ in the final state is really suppressing the background efficiently. It should be noted that in the simulation we also include events from two nucleon absorption, *i.e.* $\overline{p}$ − "pn" $\rightarrow \phi K\Lambda$. There are no experimental data nor theoretical estimations of the fraction of such an event. Therefore, we assumed 10% double strangeness production in a nucleus are coming from those type of event.

5. Summary

An experiment to search for a ϕ-meson bound state has been discussed. We demonstrate that a rather background-free missing-mass spectrum can be obtained efficiently by $(\overline{p}, \phi)$ spectroscopy together with the Λ tagging, using the primary reaction channel $\overline{p}p \rightarrow \phi\phi$. 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 $\phi(s\overline{s})$.

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