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PHOTOPRODUCTION OF η' MESONS AT SPring-8/LEPS2*

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An experiment for η'-meson photoproduction has been conducted at SPring-8 by utilizing a 2.4 GeV laser-electron photon beam at the LEPS2 beamline. This is an attempt to measure the spectral function of η' mesons propagating in the nuclear medium. For this purpose, an electromagnetic calorimeter, BGOegg, is employed to detect η' decaying into $\gamma\gamma$ in a nucleus. BGOegg consisting of 1320 BGO crystals exhibits excellent calorimeter performance both in the energy and mass resolutions.

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1. Introduction

The Standard Model describes nature very well. However, it leaves several intrinsic questions unanswered on the framework itself of the model. We need to explore a new field beyond the Standard Model, say many physicists, as if they had a satisfactory understanding of nature within the framework of the model. We basically agree, but at the same time, we know the non-perturbative regime of QCD in the Standard Model is still not well-understood because of a complicated situation brought in by the gauge boson–gluon — that carries a color charge by itself. Thus, the first line of this introduction would be a little bit misleading statement. We have two big questions in QCD, on confinements and mass generation of hadrons, to be solved in the framework of the Standard Model. In such a hard environment surrounding non-perturbative QCD, low-energy chiral effective theories including no gluon fields have been working well, especially for the subject of hadron mass generation. We focus on this subject by studying η' mesons in a nucleus.

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2. Chiral symmetry and axial U(1) anomaly

It is widely accepted way of understanding that chiral symmetry is one of the most fundamental properties of QCD and is spontaneously broken in our real world due to $\langle\bar{q}q\rangle \neq 0$, the non-zero vacuum expectation value of quark–antiquark condensate. The $\langle\bar{q}q\rangle$ value is thought to mainly determine hadron masses. This scenario encourages experiments trying to find the effect of changes in hadron properties in a nucleus since the vacuum expectation value $|\langle\bar{q}q\rangle|$ is expected to go down in the nuclear medium, leading to partial restoration of chiral symmetry.

Here is another issue, that is axial U(1) anomaly, to be discussed in connection to the η' meson being mostly the singlet η_0. The classical QCD Lagrangian for three quark flavors satisfies $\mathrm{U(3)_L} \otimes \mathrm{U(3)_R}$ chiral symmetry, which is decomposed as

$$\mathrm{U(3)_L} \otimes \mathrm{U(3)_R} \simeq \mathrm{U(1)_V} \otimes \mathrm{U(1)_A} \otimes \mathrm{SU(3)_L} \otimes \mathrm{SU(3)_R}\,. \tag{1}$$

All the Noether currents corresponding to the individual symmetries are conserved in classical fields in the chiral limit. But when we come to quantum fields, the singlet axial current due to the axial U(1) symmetry ($\mathrm{U(1)_A}$ symmetry) is not conserved any more because of topological charge density operators, which originate from the quantum effect of gluon fields. The other currents remain conserved even in the quantum fields. Thus, the topological charge density operators give rise to the axial U(1) anomaly.

The QCD Lagrangian has now $\mathrm{SU(3)_L} \otimes \mathrm{SU(3)_R} \otimes \mathrm{U(1)_V}$ symmetry. Then $\mathrm{SU(3)_L} \otimes \mathrm{SU(3)_R}$ chiral symmetry is spontaneously broken. To get the effect of the axial U(1) anomaly into effective theories based on the Nambu–Jona-Lasinio (NJL) model that includes no gluon fields, Kobayashi–Maskawa–'t Hooft (KMT) interactions are introduced. An extended NJL model taking into account the KMT interactions predicts a large in-medium mass reduction of the η' meson by about 150 MeV at the normal nuclear density [1]. According to the prediction for three quark flavors, the η' mass goes down and gets degenerate with the η mass when the nuclear density goes up if a density-independent coupling constant is employed for the KMT term representing six-quark interactions. Consequently, a bound state of the η' and a nucleus might come about, depending on the η'-nucleus potential, which shows an attractive force due to the in-medium η'-mass reduction. Although no exact predictions are given for the real and imaginary parts of the η'-nucleus optical potential, the logic described here might lead to an idea of axial U(1) symmetry restoration driven by chiral restoration.

A simple question arises here. Does chiral symmetry restoration really affect axial U(1) symmetry? The axial U(1) anomaly originates from the quantization of gluon fields. And the KMT term is introduced into effective theories just to break down axial U(1) symmetry. The relation between the topological charge of gluon fields and the KMT term is not straightforward. However, we may give an answer to the question from the point of view of "symmetry arguments" [2]. The QCD Lagrangian for three quark flavors has $\mathrm{SU(3)_L} \otimes \mathrm{SU(3)_R}$ chiral symmetry, which is approximately equivalent to $\mathrm{SU(3)_V} \otimes \mathrm{SU(3)_A}$ symmetry and is, therefore, invariant under the octet axial transformations generated by octet axial charges Q_5^b. Now, octet scalars S^a in $q\bar{q}$ meson states are transformed as

$$\theta_5^b \left[iQ_5^b, S^a \right] = d^{abc} \theta_5^b P^c - \tfrac{2}{3} \theta_5^a P_0 \tag{2}$$

being mixed with octet P^c and singlet P_0 pseudoscalars, where θ_5^b are transformation parameters and d^{abc} denote the d-coefficients of anticommutation relations of SU(3) generators. As a consequence, when the spontaneously broken chiral symmetry is restored, the singlet $\eta_0 = P_0$ and octet $\eta_8 \in P^c$ must get degenerate in mass, irrespective of axial U(1) anomaly. However, this does not necessarily mean axial U(1) symmetry restoration [2].

3. Measurements of $\eta' \to \gamma\gamma$ decay in the nuclear medium

It is very important to have better information on the fundamental properties of the η' meson in free space in the study of η' in the nuclear medium. Precise measurements have recently been made at COSY for the total width of η' [3] and the η'-nucleon scattering length [4], which may yield information on η' scattering processes in the nuclear medium. The CBELSA/TAPS Collaboration provides the most relevant information on the η'-nucleus potential, the real part of which is found to be $-(37 \pm 10_{\mathrm{stat}} \pm 10_{\mathrm{syst}})$ MeV [5], showing an attractive force. The experimental result is just the same as the predicted value given by a Quark Meson Coupling model with the η–η' mixing angle of -20° [6].

The natural width of the η' meson is about 200 keV [3], which is too narrow for experiments detecting η' decaying inside a nucleus. Nevertheless, we are trying to measure the spectral function of η' mesons propagating in the nucleus through the $\eta' \to \gamma\gamma$ decay channel, the partial width of which in free space is 4.4 keV corresponding to the known branching ratio of 2.2% to the $\gamma\gamma$ channel. According to the CBELSA/TAPS experimental results, the η'-nucleus optical potential shows a small imaginary part of $-(10 \pm 2.5)$ MeV, which corresponds to the in-medium width of η' to be about 20 MeV at the normal nuclear density [5]. In the nuclear medium, the $\gamma\gamma$ partial decay width would not change so much, while the large total width of η', ~ 20 MeV, brings about a strong suppression of η' decay outside for η' having a low momentum. Thus, it may be possible to detect $\eta' \to \gamma\gamma$ decay inside the nucleus at the rate of several percent compared to the $\gamma\gamma$ decay outside.

4. Experiments at SPring-8/LEPS2

SPring-8 is the world's largest third-generation synchrotron radiation facility operating an 8 GeV electron storage ring, the circumference of which is 1436 m. Usually, SPring-8 provides X-rays of synchrotron radiation for mainly material science. LEPS (Laser-Electron Photons at SPring-8) and recently constructed LEPS2 beamlines are something special. We produce γ rays with an energy up to 2.9 GeV by means of the Compton backward scattering of laser light from circulating 8 GeV electrons in the storage ring [7]. A series of experiments has been conducted at LEPS2 beamline. The experimental layout is illustrated in Fig. 1. An electromagnetic calorimeter, BGOegg, was installed as the main detector assembly equipped with a cylindrical drift chamber (CDC) and an inner scintillator hodoscope. Forward-going charged particles can be detected with a time-of-flight (TOF) hodoscope made of resistive plate chambers (RPC) placed 12.5 m downstream of the target. The TOF resolution is found to be 80 ps, which corresponds to the energy resolution of $\sim$ 20 MeV for 2 GeV/c protons. A big solenoid magnet is not used in the current BGOegg experiments.

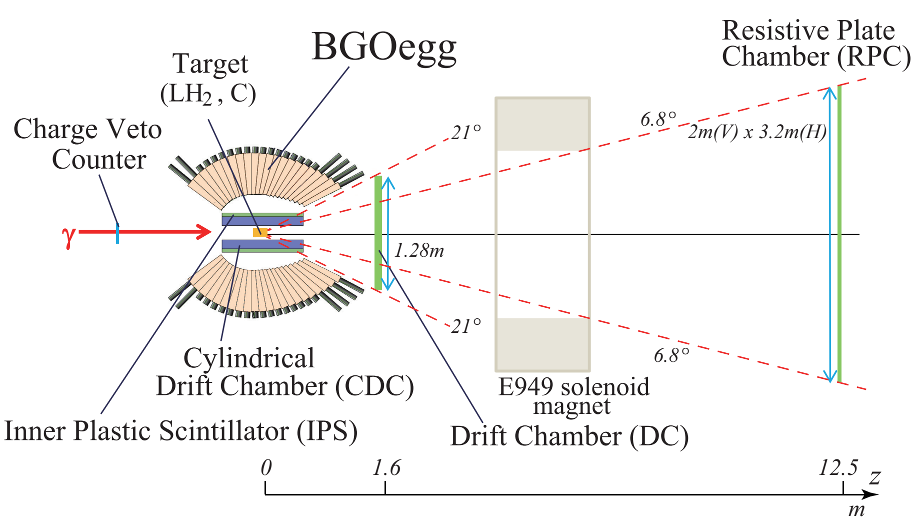

Fig. 1. Schematic view of an experimental setup for BGOegg experiments.

The BGOegg calorimeter is an egg-shaped assembly of 1320 BGO crystals covering polar angles from 24° to 144° with a good segmentation of $\sim 6°$ both in the polar and azimuthal directions. Each crystal has a sufficient thickness of 220 mm corresponding to 20 radiation lengths. BGOegg has a self-supporting structure, like a Roman bridge, to hold the whole crystals of ~ 2 t in weight, having no insensitive area in between adjacent crystals. Consequently, BGOegg provides one of the world's best energy resolutions of 1.3% for 1 GeV photons. This resolution is not the maximum instantaneous value but is obtainable everywhere in BGOegg except for the edge regions.

The energy calibration of BGOegg is one of the most important jobs in the BGOegg experiments. By employing a huge number of $\pi^0 \to \gamma\gamma$ events, the calibration was made so as to get the π^0 mass to be the same as the PDG value. We achieved a very beautiful calibration so far as shown in Fig. 2 for a carbon target with a thickness of 20 mm. This is a kind of "overall" calibration with no momentum selection for $\gamma\gamma$ pairs. Nevertheless, we observe η and η' peaks just on the right places as indicated in Fig. 2. The overall $\gamma\gamma$ mass resolutions are preliminarily found to be 5.8, 12.9, and 19 MeV for π^0, η, and η', respectively. Thus, BGOegg provides excellent $\gamma\gamma$ mass resolutions ever made in meson photoproduction experiments. The obtained mass resolutions depend on the target thickness because of no vertex information for $\gamma\gamma$ events. We have no way to know the exact vertex point of each event in a target, if outgoing particles are all neutral. We assumed, therefore, all the events were generated at the center of the target.

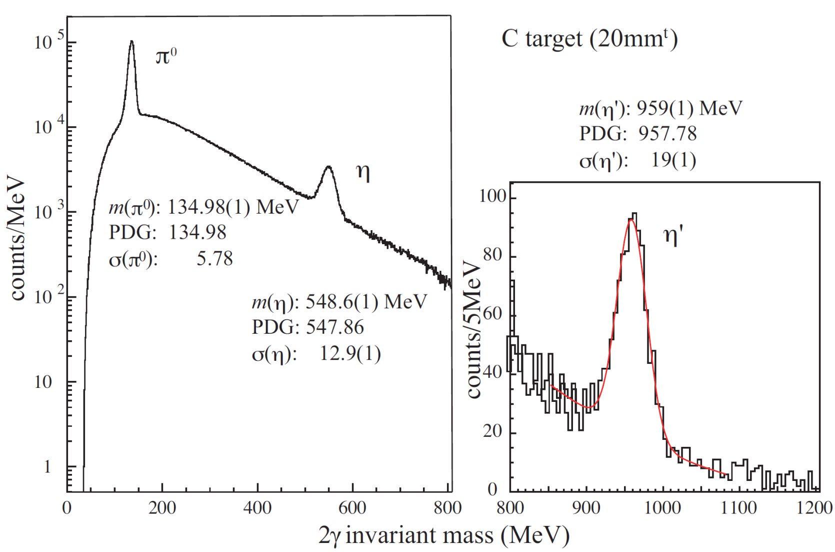

Fig. 2. Preliminary calibration results obtained with $\gamma\gamma$ events.

It is expected to have a better $\gamma\gamma$ mass resolution for η' with a thinner copper target. By employing a kinematical fit, a $\pi^0\pi^0\eta$ spectrum is obtained with a very good mass resolution as shown in Fig. 3. We are ready for measuring the spectral function of η' mesons propagating in the nuclear medium.

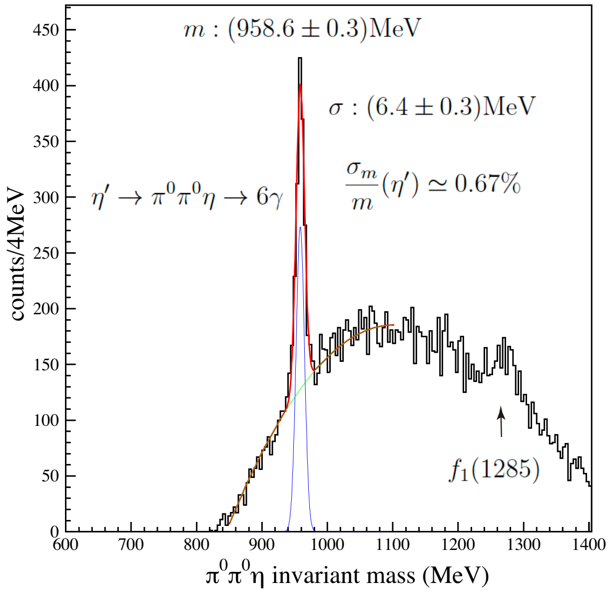

Fig. 3. $\pi^0\pi^0\eta$ invariant mass spectrum (preliminary).

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