Search for η'-meson bound nuclei using a GeV photon beam

In today's cold universe, two or three quarks are confined in a hadron such as a meson and a nucleon. The mass of a hadron composed of light quarks cannot be explained by the sum of bare quark masses, which are generated by the interaction of quarks with the Higgs field. For example, such a sum accounts for only about 1% of the nucleon mass. Thus, a dynamical mechanism of hadron-mass generation is widely believed in modern physics. In this mechanism, the quantum-mechanical vacuum changes its ground-state properties by the spontaneous breaking of chiral symmetry and interacts with quarks to provide a hadron mass, as the universe evolves from a high-temperature and high-density plasma of massless quarks, where all symmetries hold. Such a phenomenon is called the chiral phase transition, whose order parameter is the vacuum expectation value of quark condensates. This idea was proposed by Nambu, who was inspired by the theory of superconductivity. The generation of quark condensates and hadron masses correspond to the appearance of Cooper pairs and energy gaps.

Experimental efforts to prove mass generation by the spontaneous breaking of chiral symmetry have been actively attempted in the field of hadron physics. The partial restoration of the chiral symmetry is expected even inside the nucleus, which has an ultrahigh density of about 10^{14} g/cm^3, as a precursor phenomenon of the chiral phase transition. Therefore, the BGOegg experiment, running at SPring-8 **BL31LEP**, has searched for the signals of hadron-mass reduction inside a nucleus through the photoproduction of η' mesons [1]. The η' meson has attracted attention in recent years because its mass (958 MeV/c^2) is abnormally heavier than those of the other pseudoscalar mesons in the flavor SU(3) nonet owing to the $U_A(1)$ quantum anomaly. Studying the η'-meson properties in nuclei should provide a clue for exploring the relationship between the spontaneous breaking of chiral symmetry and the $U_A(1)$ anomaly, both of which should be taken into account at the Lagrangians of effective hadron models. Several models have predicted the η'-meson mass reduction at the nuclear density to be 40–150 MeV/c^2 [2].

The BGOegg experiment uses a photon beam produced at BL31LEP in the energy range of 1.3–2.4 GeV. A large acceptance electromagnetic calorimeter (Fig. 1) has been set up with several charged-particle detectors at the LEPS2 experimental building [3]. This calorimeter covers a polar angle range from 24° to 144° with 1320 $Bi_4Ge_3O_{12}$ (BGO) crystals, giving the world's best energy resolution of 1.3% for a 1 GeV γ-ray. For studies of the η'-meson mass in nuclei, a 20-mm-thick carbon target was adopted to search for nuclear bound states of η' mesons by missing mass spectroscopy with forward high-momentum protons. If the η' mass reduction is large, such a bound state can be formed with a corresponding attractive potential inside a nucleus [4].

A conceptual description of the experiment is shown in Fig. 2. The η' bound nuclei were searched by detecting a forward proton at the resistive plate chamber (RPC) wall located 12.5 m downstream of the carbon target with a polar angle coverage up to 6.8°. The time of flight of a charged particle was measured with a time resolution of 60–90 ps to determine its momentum, assuming that the detected particle is a proton. If η' bound signals exist, they must appear below the production threshold in the proton missing mass spectrum, which is calculated by solving the unknown mass of an η' bound nucleus under the 4-momentum conservation of the $\gamma+^{12}$**C** reaction. Because there remains much background in such a spectrum, the BGOegg experiment has, for the first time, required the simultaneous detection of a conversion signal by the bound η' meson and a spectator proton (**p**), namely, the reaction η'**p**$\to\eta$**p**, followed by the $\eta\to\gamma\gamma$ decay.

Black dots in Fig. 3 show the excitation energies $E_{ex}-E_0$ (missing masses relative to the η' production threshold or the sum of boron-nucleus and η'-meson masses in a vacuum) and η emission angles cos(η) (polar angles in the Lab frame) of the real data events after the detection of an η meson, decaying into $\gamma\gamma$, and a slow proton (p_s) at the calorimeter. Unfortunately,

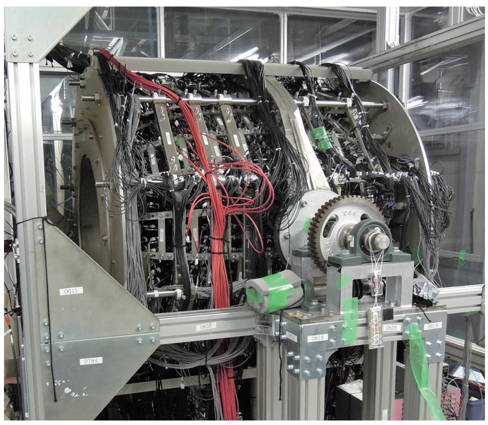

Fig.1. Photograph of the BGOegg calorimeter, assembled with 1320 BGO crystals.

this sample was still dominated by background mainly due to η photoproduction, where the secondary interactions of primary products generated additional slow protons. Therefore, we further developed kinematical conditions to select events with a back-to-back behavior of the η–p_s pair and to exclude events having boosted kinematics with a very forward production of either η or p_s. These conditions were optimized without examining the predetermined signal region, indicated by the red shaded area in Fig. 3. Finally, only events shown by blue circles survived after applying the kinematical conditions. No events were observed in the signal region. We obtained an upper limit for the production of η' bound nuclei with η–p_s pairs of 2.2 nb/sr (90% confidence level) at the opening angles $\cos(\eta p_s) < -0.9$.

We compared this upper limit of the production cross section with the results of a theoretical calculation using the distorted wave impulse approximation (DWIA) and a few assumed optical-potential values [4]. In the comparison process, we normalized the theoretical calculation by the observed amount of quasi-free η' photoproduction events, which were not affected by the mass reduction. This normalization was essential to remove ambiguities in the DWIA calculation. As a result, we have concluded that a branching fraction of the process where the one-nucleon (1N) absorption of the bound η' meson occurs with conversion to a pair of an η meson and a nucleon is constrained to be lower than 24% (the 90% confidence level) in the case of optical potential $V_0 = -100$ MeV, indicating that such a large V_0 value or a large mass reduction is not favored.

In the BGOegg experiment, a complementary analysis to study the η' mass at the nuclear density is carried out concurrently. In this method, the mass spectrum of η' mesons decaying into $\gamma\gamma$ inside a nucleus is directly measured by reconstructing the invariant mass with the selection of low-momentum η' mesons. This analysis mode has a higher sensitivity in the case of a smaller mass reduction. On the basis of the results of the above two analyses, we plan the second-phase experiment with an upgraded detector setup to observe firm evidence of the partial restoration of chiral symmetry in nuclei.

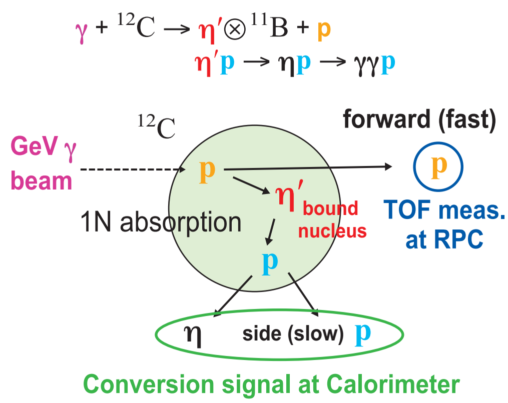

Fig. 2. Conceptual description of the search for η'-meson bound nuclei by the BGOegg experiment at BL31LEP.

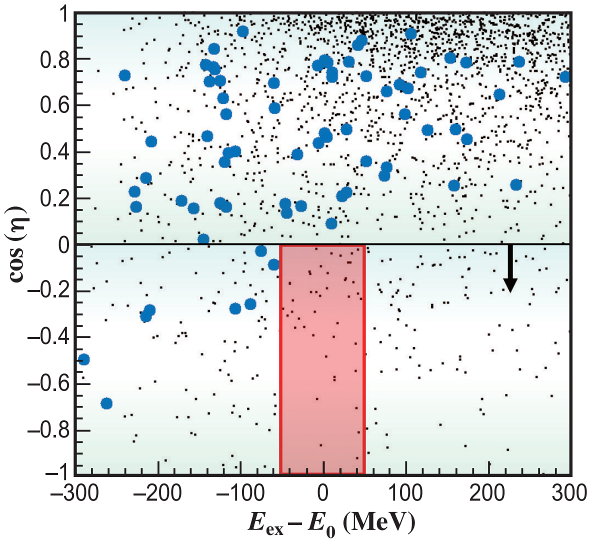

Fig. 3. Two-dimensional plot of the η polar angle versus the excitation energy for signal samples of the η' bound nuclei search. The kinematical region of $\cos(\eta) < 0$ was selected to reduce background. The red shaded area indicates the signal search region.

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