Direct measurement of the in-medium η' mass spectrum in a γ+C reaction

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論 文 内 容 要 旨

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氏　　名	松村 裕二	提出年	令和　元年
学位論文の題　　名	Direct measurement of the in-medium η' mass spectrum in a γ +C reaction (γ +C 反応を用いた核媒質中での η' 質量スペクトルの直接測定)		

The hadron mass is known to be generated by the spontaneous breaking of chiral symmetry in quantum chromodynamics (QCD) vacuum. The chiral symmetry is expected to be restored under the condition such as high temperatures or high densities. Therefore, possible modification of hadron properties under the condition has been explored both theoretically and experimentally. A nucleus has often been used as a laboratory for the high-density environment. Thus, some experiments have been carried out to measure the mass or decay width of hadrons, especially for mesons, in a nucleus. However, the results are controversial. Therefore, more experimental data are mandatory to obtain reliable information about the meson properties in a nucleus.

The property of the η' meson, which is one of the ground states of pseudoscalar mesons in flavor SU(3), in a nucleus is a crucial research subject that has attracted a great deal of attention to date. The η' meson has larger mass than other pseudoscalar mesons due to the axial U(1) anomaly effect. The anomaly effect is expected to have close relation with the degree of chiral symmetry. Thus, various theoretical models have predicted significant decreasing of η' mass in nuclear medium due to partial restoration of chiral symmetry in a nucleus.

In this thesis, the mass spectrum of η' mesons in nuclear medium is studied in a γ+C reaction via the $\eta' \to \gamma\gamma$ decay mode with an electro-magnetic calorimeter. This is the first direct measurement of in-medium η' mass spectrum.

The experiment was carried out at the SPring-8/LEPS2 beamline. Hadrons, including η' mesons, are produced in a γ+C reaction with incident photon beam energies up to 2.4 GeV. Decay products, mainly photons, from photoproduced hadrons are detected by an electromagnetic calorimeter (BGOegg). The BGOegg consists of 1320 BGO crystals covering polar angles from 24 to 144 degrees and the whole azimuthal angles. Neutral or charged particles are distinguished by using inner scintillator hodoscopes installed inside the BGOegg.

Mesons decaying into photons are identified in the invariant mass spectrum reconstructed from energies and hit positions at the BGOegg. The energy calibration process was carried out using π^0 mass information in the $\gamma\gamma$ invariant mass distribution. Finally, the η' mass resolution is achieved to be 18.8 MeV/c^2 in the $\gamma\gamma$ invariant mass spectrum, and the independence of the reconstructed mass on the total energies and the emission angles of produced mesons was confirmed.

The η' mass spectrum reconstructed via the $\gamma\gamma$ decay mode was fitted in two cases of spectral functions: namely, by a sum of signal and background functions or only by a background function. The background is assumed to consist of the following three sources; the quasi-free η' peak, the background originated by ω mesons, and the multi-meson background. The quasi-free η' peak is represented by a Gaussian function with a fixed width based on the experimental mass resolution. The background distribution from ω mesons was obtained by a realistic Monte Carlo (MC) simulation. The multi-meson production, such as $\pi^0\pi^0, \pi^0\pi^0\pi^0, \pi^0\eta$, will also be a major significant background for the measurement. Their relative contribution was determined by fitting the simulated spectra of these processes to the real data. It has been confirmed that a simple and smooth function with a few parameters well describes the multi-meson background spectrum around the η' mass. Finally, the signal distribution of the in-medium η' decay was generated by MC simulation, where two parameters corresponding to mass reduction and width broadening in nuclear media were introduced.

The significance of the signals was evaluated by comparing the χ^2 values of fits with and without the signal function. The significance is defined for each mass and width parameters. The event sample was divided into two ranges of $\gamma\gamma$ momenta below and above 1 GeV/c. The high-momentum sample is used as a reference without in-medium signals because most of η' mesons are expected to decay outside a carbon nucleus due to a long decay length. η' photoproduction events from a proton target, which were collected in a

different experimental period, were also analyzed as another reference.

The significance of signals was scanned in the two-parameter space of in-medium mass and width modification. Relatively higher significance was observed for the low-momentum sample of the carbon target, while there was no significance appeared for the high-momentum sample in the carbon target data and the overall-momentum sample in the proton target data. The maximum significance reaches 3.7σ for the parameter corresponding to the mass reduction of $\Delta m = 57$ MeV/c^2. The favored region of mass reduction was determined as an area within 1σ from the maximum value of significance. On the other hand, there was no significant difference among width parameters of $\Delta\Gamma < 100$ MeV. The result indicates the possible modification of η' mass spectrum in the nuclear medium.

別　紙

論文審査の結果の要旨

「陽子や中性子に代表されるハドロンの質量はどのように獲得されるのか？」という問いは、ハドロン物理学における重要な問題の一つである。その主たる要因は、「強い力を記述する量子色力学（QCD）の真空で起こっているカイラル対称性の自発的な破れ（χ_{SB}）」であると理論的に解釈されている。しかし、このχ_{SB}がハドロン質量の起源である明確な実験証拠は得られていない。

松村祐二氏は、χ_{SB}により作り出される真空の期待値$\langle q^{bar}q\rangle$がQCDにおける量子異常の一つ$U_A(1)$アノーマリーと結びつくことにより非常に重い質量を持つη’中間子に注目し、原子核中で崩壊するη’中間子の質量分布（スペクトル関数）が真空中のものから変化する事を直接測定し、ハドロン質量とχ_{SB}の相互関係を明らかにすることを目的として研究を推進した。

松村氏は、最終的な実験結果導出のため、1320チャンネルからなる電磁カロリーメーターのエネルギースケール校正作業を緻密行ったことに加え、標的上流からの背景事象の除去、検出器反応の一様性の確認など、全てを一貫して行った。また、データ内に含まれる本研究の主題であるη’→γγ反応以外の背景事象過程をしらみ潰しにあたり、取得したスペクトル全体像を解釈するまで理解を進めた。これら解析の大部分は本学博士課程後期在学中に行なったものである。

松村氏は、得られたデータをη’中間子の崩壊確率が大きい低運動量成分と、η’中間子がほぼ真空中で崩壊する高運動量成分に分けた解析を行なった。その結果、低運動量成分に於いて、我々の理解を超えるη’スペクトル関数の変化を導出した。これは、原子核中で真空では破れているカイラル対称性が部分的に回復している可能性を示唆する非常に重要な成果である。更に、松村氏は、観測したスペクトル関数の変化を説明するため、原子核中でη’中間子の質量が軽くなるというシンプルなモデルを使い、スペクトル関数変化に関する定量的な評価を与えた。本博士論文に記載されている結果は、世界初の研究成果であるだけでなく、ハドロン物理に大きな貢献となる成果である。

以上、博士論文に記載されている、研究の学術的背景・データ解析・成果の導出・議論は、自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって，松村裕二提出の博士論文は，博士（理学）の学位論文として合格と認める。