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| 学位(専攻分野) | 博士(理学) |
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| 学 位 論 文 題 目 | Dark photon search via $D^{*0} \rightarrow D^0 A'$ at Belle experiment |
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（様式３）

# 博士論文の要旨

氏　　名　　金道　玄樹

論文題目　　Dark photon search via $D^{*0} \to D^0 A'$ at Belle experiment

The existence of Dark Matter, invisible matter which interacts matters through gravity, is predicted from astronomical observations. For example, V. C. Rubin and her colleagues studied the relation between the velocities of stars and the distance from galactic center. The velocity should decrease as the distance increases, if the source of gravity is only from visible stars and interstellar gases. But the velocities showed flat distributions.

The observations can be explained by a hypothesis that there are invisible and massive matters broadly in galaxies, which dominate the mass of galaxies. This invisible and massive matter is called Dark Matter, and it is one of the major problems in astronomy and physics.

After the hypothesis is proposed, many experiments have tried to observe the Dark Matter. Some of them tried to find the Dark Matter from the missing energy or daughter particles of its decay in colliders like LHCb and BaBar experiments. Others tried through the elastic scattering of Dark Matter of nuclei like DAMA, XENON, and CDMS experiments. Despite of these efforts, the Dark Matter is not observed yet.

The search regions of previous experiments are focusing on GeV and TeV order due to the collider energy and the mass of nuclei.

In this thesis, I focus on Dark Matter in MeV scale with the electromagnetic interaction which is called Dark Photon, a part of Dark Matter model called Hidden Sector hypothesis, and predicted to have mixing with Standard Model photon. For this purpose, the decay of $D^{*0} \to D^0 A'$ in data accumulated by Belle experiment is a good prove because of 10 -100 MeV order energy.

I use $D^{*0} \to D^0 A'$ decay to search for the Dark Photon in this analysis.

The branching fraction of $D^{*0} \to D^0 \pi^0$ is 64.7% and $D^{*0} \to D^0 \gamma$ is 35.3%. A process $D^{*0} \to D^0 A'$ may occur by a mixing between $\gamma$ and $A'$ in $D^{*0} \to D^0 \gamma$. The mass difference $\Delta m \equiv m_{D^{*0}} - m_{D^0}$ is 142 MeV, so this is suitable to search for MeV scale Dark Photon.

Using the $D^{*0} \to D^0 \gamma$ decay as the normalization mode, the target variable to be determined is the ratio R between $D^{*0} \to D^0 \gamma$ and $D^{*0} \to D^0 A'$ written as

$$R = \frac{B(D^{*0} \to D^0 A')}{B(D^{*0} \to D^0 \gamma)}$$

The branching fractions of signal and normalization mode can be written as

$$B(D^{*0} \to D^0 A') = \frac{N_{sig}}{N_{D^{*0}} e_{sig}} = \frac{N_{sig}}{2L\sigma_{D^{*0}} \mathcal{B} e_{sig}}$$

$$B(D^{*0} \to D^0\gamma) = \frac{N_{D^*\gamma}}{N_{D^{*0}} e_{D^*\gamma}} = \frac{N_{D^*\gamma}}{2L\sigma_{D^{*0}}\mathcal{B} e_{D^*\gamma}}$$

where $N$ and $e$ are yield and efficiency of signal and normalization mode, respectively. Taking the ratio, the ratio can be written as

$$R = \frac{N_{sig}}{N_{D^*\gamma}} \frac{e_{D^*\gamma}}{e_{sig}}$$

The efficiencies are estimated from the simulation in advance and the yields are determined by the data.

$D^{*0} \to D^0 A'$ is produced in the hadronization of $c\bar{c}$ pair. The data taken in Belle experiment on $\Upsilon(4S)$ resonance is 711 $fb^{-1}$ and includes $1.9 \times 10^9$ $c\bar{c}$ events with $B\overline{B}$ and the other continuum processes.

To reconstruct the events of $D^{*0} \to D^0 A'$ and $D^{*0} \to D^0\gamma$ from the data of Belle, I used three decay modes of $D^0$; $D^0 \to K^-\pi^+$ (branching fraction is 4%), $D^0 \to K^-\pi^+\pi^0$ (14%), and $D^0 \to K^-\pi^+\pi^-\pi^0$ (8%). The $D^0$ meson is reconstructed from final state particles detected by Belle spectrometer with criterion to distinguish the signal events from the backgrounds using the mass of $D^0$. Then, the $D^0$ meson is combined to a pair of electron and positron or $\gamma$ to reconstruct $D^{*0}$ with the criteria by the mass difference $\Delta m \equiv m_{D^{*0}} - m_{D^0}$, and the momentum of $D^{*0}$.

Note that $D^{*0} \to D^0 A'$ is not reconstructed directly, but after the reconstruction of $D^{*0}$ the invariant mass of the electron-positron pair is calculated as the mass of $A', m_{A'}$. If $A'$ exists, it should have a peak with finite mass.

For the normalization mode, as shown in Fig. A, the yields of normalization mode $N_{D^*\gamma}$ for each decay mode of $D^0$ are determined by the fit to $\Delta m \equiv m_{D^{*0}} - m_{D^0}$ distributions, independently of the signal modes. The distribution is modeled by a quadratic function for background and a Crystal Ball function for signal. The fit function for the normalization mode is

$$f_{D^*\gamma} = N_{D^*\gamma} f_{sig\gamma} + N_{bkg} f_{bkg\gamma}$$

with

$$f_{sig\gamma} = CB(x; \mu_\gamma, \sigma_\gamma, \alpha, n)$$
$$f_{bkg\gamma} = C_q(a_i)(1 + a_1 x + a_2 x^2)$$

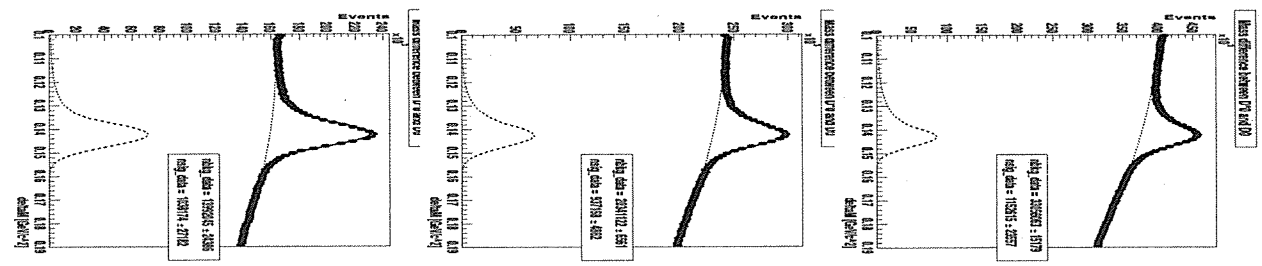

Fig.A The distributions of $\Delta m$ and the fit results. The dotted lines in the bottom show the signal components of the Crystal Ball functions.

where CB is a Crystal Ball function with the mean $\mu_\gamma$, width $\sigma_\gamma$, and tail factors $\alpha$ and n, and $C_q$ is a normalization depending on the coefficients $a_i$.

For the signal mode, the reconstructed $m_{A'}$ distributions are shown in Fig.B.
The background distributions are modeled by exponential and quartic functions and the signal component is modeled by the sum of a Gaussian and a bifurcated Gaussian function as

$$f = N_{sig}f_{sig} + N_{bkg}f_{bkg}$$

with

$$f_{sig} = C_{sig}G(\mu,\sigma) + (1 - C_{sig})G_b(\mu,\sigma_L,\sigma_R)$$

$$f_{bkg} = C_{bkg}C_e(a_0)\exp(a_0x) + (1 - C_{bkg})C_q(a_i)(1 + a_1x + a_2x^2 + a_3x^3 + a_4x^4)$$

For the signal component, $G(\mu,\sigma)$ is a gaussian with a mean $\mu$ and deviations $\sigma$, $G_b(\mu,\sigma_L,\sigma_R)$ is a bifurcated Gaussian with a mean $\mu$, left width $\sigma_L$ and right width $\sigma_R$, and $C_{sig}$ is a fraction of two Gaussians. For the background component, $C_e(a_0)$ and $C_q(a_i)$ are normalization factors for the exponential and quartic functions, respectively, and $C_{bkg}$ is the fraction of the two functions.
To combine the three decay modes of $D^0$, the signal yields in each mode $N_{sig}$ are treated as dependent variables on the ratio R as

$$N_{sig} = N_{D^*\gamma}\frac{e_{sig}}{e_{D^*\gamma}} \times R.$$

Finally, the $m_{A'}$ distributions of three $D^0$ decay modes are fitted simultaneously, using the ratio R as a common parameter. The fit results shown in Fig. B is assuming $m_{A'} =$ 17 MeV.
Since the mass of $A'$ is unknown, the other masses are also checked. However, there is no significant evidence of Dark Photon's existence and just upper limits are set to the ratio.
As a conclusion, Dark Photon is not observed in this analysis. But, a new upper limit is set to $D^{*0}$ mode, especially it is important that the charm quark is included as a mother of Dark Photon.

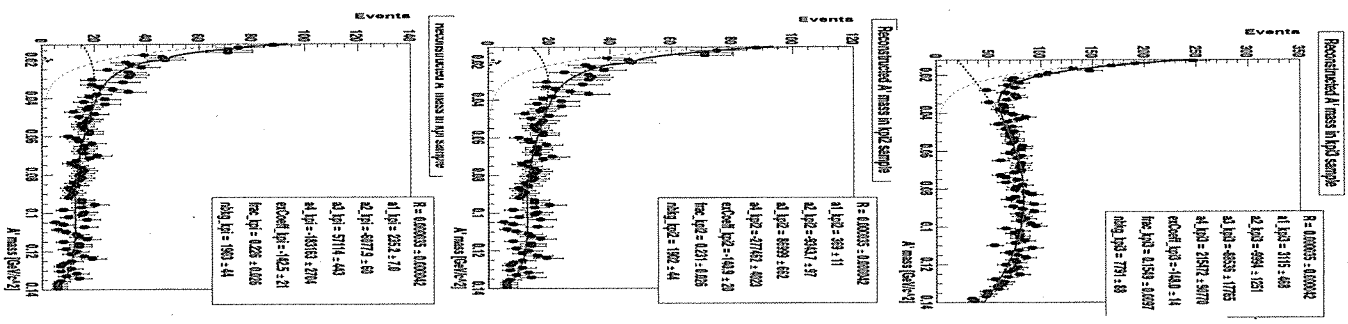

Fig.B The distributions of $m_{A'}$ and the result of simultaneous fit on $m_{A'}$ distribution assuming $m_{A'} = 17$ MeV.

Form8・Separate Sheet
（様式８・別紙１）

**Results of the doctoral thesis defense**

# 博士論文審査結果

Name in Full
氏　名　金道　玄樹

Title
論文題目　Dark photon search via $D^{*0} \rightarrow D^0A'$ at Belle experiment

本論文は、宇宙観測からその存在が必要とされる暗黒物質のモデルの有力候補のひとつである暗黒セクター仮説の手掛りとして、暗黒セクターと標準理論のポータルとして光子と混合する暗黒光子 $A'$を探索する研究である。ここでは、これまで探索されたことがなかった、$D^{*0}$中間子が $D^0$中間子に崩壊する時に $D^{*0}$と $D^0$の質量差である 140MeV/$c^2$より低い質量を持つ $A'$を放出し、電子・陽電子に崩壊する事象の探索を行った。

本論文では、Belle 実験のΥ(4S)共鳴の衝突エネルギーで収集した全データにおいて大量の $B$中間子対事象と同時に生成される大量の $D^{*0}$中間子を含むチャームクォーク対生成事象を用いた。測定手法として $D^{*0}$中間子が $D^0$中間子と光子に崩壊する過程との比を取ることにより、不定要素が少なく、系統誤差の小さい測定ができる。先行研究ではコライダー実験、固定標的実験、ビームダンプ実験、原子核実験などで幅広い質量領域での探索が行われてきた。本論文の探索領域に関しては NA48/2 実験の $K$中間子崩壊での探索および BaBar 実験の電子陽電子衝突での直接生成の探索がこれまで最も厳しい制限を与えている。また、ベリリウム８の励起状態を用いた実験では 17MeV/$c^2$の暗黒光子で説明可能なアノマリーが報告されており、この質量領域に注目が集まっている。

信号の終状態は $D^0$中間子と低エネルギーの電子陽電子対であり、背景事象の削減が重要な課題となる。探索研究における測定バイアスを避けるためにブラインド解析を行い、モンテカルロシミュレーションを用いた背景事象の削減のための最適化条件の決定および背景事象のフィットによる見積り方法の決定を経て、信号事象が存在する場合には正しく測定できることを示し、解析方法を確立した。実データを用いた解析では質量 17MeV/$c^2$を仮定した探索および 12-120MeV/$c^2$の質量領域をスキャンする探索を行い、結果は背景事象と無矛盾であり暗黒光子の信号は見つからなかったため、光子と暗黒光子との混合係数の上限値を与えた。得られた上限値は先行研究の結果を更新するものではなかったが、$D^{*0}$中間子を用いた探索が初めての試みであるためチャームクォークと暗黒光子が結合する場合としてはこの質量領域で初めての上限値であり、暗黒光子生成過程がフレーバーに依存する可能性も考えられるため、本論文の結果は重要な新しい知見である。この結果は Belle 実験グループとして学術論文に投稿する予定である。

この結果は学術的に十分な価値が認められるものであり、博士論文の内容として必要な水準を示しており、本論文が学位の授与に値すると判断した。