Measurement of kaonic nitrogen X-ray lines using the gaseous target at DAΦNE

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Using CCDs to detect X-rays from kaonic nitrogen atoms formed in a cooled nitrogen gas target and negative kaons produced at the DAΦNE collider, we measured three sequential X-ray lines from kaonic nitrogen atoms, and their X-ray yields were obtained. With a theoretical calculation using the measured yields, the electron screening effect on the kaonic nitrogen atoms during the kaon cascade was estimated. We found that a precise determination of the charged kaon mass can be performed without theoretical uncertainty due to the electron screening effect.

1 Introduction

Measurements of kaonic atom X-rays were performed using gas targets by the DEAR (DAΦNE Exotic Atom Research) collaboration. The kaonic nitrogen X-ray lines from high n states and the kaonic hydrogen K X-ray lines were successfully observed. The yields of kaonic nitrogen and the shift and width in the 1s state of kaonic hydrogen were deduced. The results of these measurements can be found in Refs. [1], [2]. Here, a short summary of the kaonic nitrogen X-ray measurement is given.

Determination of X-ray yields of kaonic atoms is important for understanding their characteristics. Roughly speaking, kaonic atoms in a low density target consist of only a kaon of charge $-e$ and a nucleus of charge $+Ze$ – a highly ionized system. On the other hand, kaonic atoms in a high density target consist of a kaon and a nucleus together with electrons, since the holes in electron orbits, created by kaon capture and Auger emission, can be refilled by electrons transfered from surrounding atoms.

Cascade processes such as Auger transitions, electron refilling, etc, have strong dependencies on target materials and densities, which are not yet well understood. In particular, there is no data for kaonic atom X-ray yields in gaseous targets except for hydrogen [1]. Thus, the determination of kaonic X-ray yields in a gaseous target is an important issue in kaonic atom physics.

The charged kaon mass was precisely determined from kaonic atom X-ray energies by two experimental groups. Their reported values are, however, inconsistent, and have a 60-keV difference, which is larger than the precision of the charged kaon mass assigned by PDG [3]. To solve this kaon mass problem, we proposed a new kaon mass measurement using a nitrogen gas target [4]. When the kaon mass is deduced from the X-ray energies of kaonic nitrogen, the knowledge of the energy shifts due to the residual electrons becomes important. Therefore, we obtained the probabilities for kaonic atoms to have orbital electrons using the experimentally determined X-ray yields and the cascade calculation [5].

2 Kaonic nitrogen X-ray measurement at the DEAR experiment

The setup of the DEAR experiment is described in Refs. [2], [6], [7]. The target cell is made of Kapton foils reinforced by thin epoxy-fiberglass. Small Zr and Ti foils are installed to obtain in-beam energy calibration lines. Nitrogen gas at 1.5 bar and 120 K ($\sim 3.4\ \rho_{NTP}$) was used as the target. The thickness of the kaon degrader was optimized from Monte Carlo simulations and test measurements changing the degrader thickness.

The kaonic nitrogen X-rays are detected by 16 CCDs, which are installed around the target cell. The total area of the detectors is 116 cm^2. The CCDs are cooled down to 150 K and the readout period is set to 2 minutes. Energy resolution at 7.6 keV is 160 eV (FWHM).

The CCDs consist of a large number (1.4 million) of small pixels (500 μm^2) with a thin depletion layer (30 μm). Due to different ionization processes between X-rays and charged particles, the total X-ray energy is stored in a few pixels (mainly 1 or 2 pixels), while the events due to charged particles and high energy gamma rays are distributed in many pixels. Because of this characteristic, X-ray events are detected by selecting events having 1 and 2 hit pixels. As seen in Fig. 1, the X-ray events are clearly separated from the events due to charged particles or gamma rays. The background rejection capability is about 10^4.

To obtain better X-ray energy resolution, charge loss during transfer is corrected. In addition, defect pixels, which may make an artificial signal, are properly rejected. The stable CCDs and the good data are selected by checking CCD gain stability and signal counting rates. The deviation from linearity is less than 1 eV. A detailed description of the CCD analysis can be found in Ref. [8].

The data taking on kaonic nitrogen X-rays was performed in 2002. Data taken with 10.8 pb^{-1} (which corresponds to about 10000 of kaonic nitrogen atoms) were selected for the analysis.

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[1] In the case of kaonic hydrogen, X-ray yields are mainly determined by the Stark effect, while in the case of kaonic atoms with $Z > 2$, the Auger effect and the electron refilling dominate.

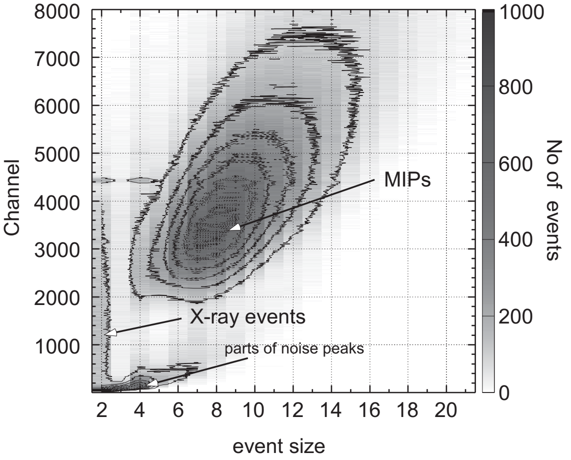

Figure 1: Relationship between the event size and energy. The gray scale corresponds to the number of events. Charged particles or gamma rays create events with a large size. Selecting events with a small size, X-ray events are obtained with a good signal-to-background ratio.

3 Experimental results

In Fig. 2, the X-ray energy spectrum of kaonic nitrogen is shown. Three kaonic nitrogen X-ray lines are observed. The kaonic nitrogen 6 → 5 transition (7.6 keV) is clearly seen. The energy is found to be 7.588±0.005 (stat) keV, where the systematic error is negligible. This energy is consistent with the theoretical value within the error.

The kaonic nitrogen $n = 7 \rightarrow 6$ (4.6 keV) and $n = 6 \rightarrow 5$ (14.0 keV) transitions are partially overlapped with Ti Kα and Sr Kα lines, respectively. These kaonic nitrogen peaks are fitted with multi-Gaussian functions. The measured number of events for the three kaonic X-ray lines is tabulated in Table 1.

To estimate the efficiencies for kaon stopping and X-ray detection, a Monte Carlo simulation was performed. Table 1 shows the simulated number of kaonic nitrogen X-rays assuming 100% yields. The errors in the simulation are 10%, which determine the systematic error on the results of the X-ray yields.

The yields of the kaonic nitrogen X-ray lines are obtained from the ratios of the measured number to the simulated number. The results of the X-ray yields are tabulated in Table 1.

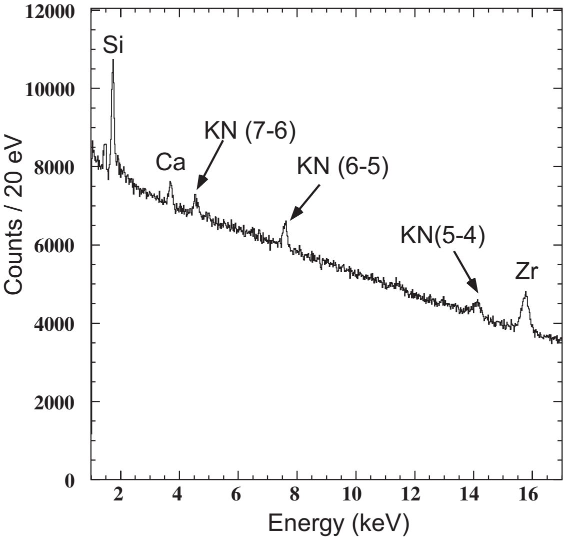

Figure 2: X-ray energy spectrum of kaonic nitrogen. The arrows show positions of the kaonic nitrogen X-ray lines: the 7 → 6 transition at 4.6 keV, the 6 → 5 transition at 7.6 keV, and the 5 → 4 transition at 14.0 keV. The peaks at 1.4, 1.7, 3.6, 4.5, 4.9, 14.2, and 15.7 keV are Al Kα, Si Kα, Ca Kα, Ti Kα, Ti Kβ, Sr Kα, and Zr Kα lines, respectively.

Table 1: Experimental yields of kaonic nitrogen X-rays. Measured numbers and predicted numbers (if the yields are 100%) in the Monte Carlo simulation are also tabulated.

Transition	7 → 6	6 → 5	5 → 4
Calculated energy (keV)	4.5773	7.5957	13.996
Measured number of events ($\times 10^3$)	3.31±0.69	5.28±0.38	1.21±0.32
Predicted number of events ($\times 10^3$)	7.97±0.79	9.59±0.96	2.10±0.21
Yield (%)	41.5±8.7±4.1	55.0±3.9±5.5	57.4±15.2±5.7

4 Conclusion

We measured kaonic nitrogen X-rays formed in the gaseous target. This measurement successfully set the stage for the kaonic hydrogen experiment [1]. With the cascade calculation [5], we found that kaonic nitrogen atoms are a highly ionized system. A precise determination of the charged kaon mass can be possible without theoretical uncertainty of the energy shift due to electrons in kaonic nitrogen atoms.

Acknowledgments

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