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The yield of kaonic hydrogen X-rays in the SIDDHARTA experiment

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Abstract. We measured K-series kaonic hydrogen X-rays in the SIDDHARTA experiment performed at the DAΦNE electron-positron collider of Laboratori Nazionali di Frascati. With a gaseous hydrogen target of density 15 $\rho_{\mathbf{STP}}$, preliminary values of the absolute yields, defined as the number of atomic X-rays emitted per kaon stopped inside the target, were determined to be $0.012^{+0.003}_{-0.004}$ for K_α transition and $0.045^{+0.009}_{-0.012}$ for K_{tot}, the summation of all the emitted K-series transitions.

1 Introduction

There are two major interests in the recent kaonic hydrogen atomic X-ray measurements. One is the shift and width of the $1s$ level due to the strong interaction between the proton and kaon. Derived directly from the K_α transition energy, the precise values for the shift and width provide crucial constraints on the theoretical description of the low-energy $\bar{K}N$ interaction. The other interest is the intensities of the atomic X-rays for each kaon stopped in the target. Also known as the absolute yields of the X-rays, the experimental results for the intensities are the testing ground for the cascade model

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[1] which consists of a series of processes that describe the life-history of a kaonic atom starting from the capture of a kaon to its final absorption by the nucleus.

The best precision on the measured shift and width of the $1s$ level was achieved by the SIDDHARTA experiment reported previously by the group [2], with the impacts of the results on low-energy QCD theory discussed therein. On the other hand the results on the absolute yields of kaonic hydrogen X-rays are still extremely meager. The only unambiguous result was published by the E228 experiment, which determined the absolute yield of K_α to be 0.015 ± 0.005 per stopped kaon with a target density of 10 $\rho_{\mathbf{STP}}$ [3]. The K_α to K_{tot} intensity ratio was estimated to be 0.27 using constraints from the cascade calculations, yet no absolute yield of K_{tot} was deduced due to the ambiguities of relative intensities of the higher transitions from n-th states to the ground state where $n \geq 3$.

This paper presents the preliminary absolute yields for both K_α and K_{tot} determined from the measurement of kaonic hydrogen K-series X-rays with a target density of 15 $\rho_{\mathbf{STP}}$. With details given in reference [4], we show that the method enables us to determine the yield of K_{tot} independent on any cascade model.

2 The SIDDHARTA experiment

The experimental setup, the performance and the calibration method of the detectors have been systematically introduced in the previous publications of the SIDDHARTA collaboration [2, 5]. Here we give a concise review of the main features of the experiment which are needed for later discussion.

As the kaon source, we use the low momentum and almost monochromatic kaons from the $\phi(1020) \rightarrow K^+K^-$ decay at the interaction point (IP) of DAΦNE. The kaons that eventually enter the target are identified by the coincidence of two scintillators close to the IP. A cylindrical cell made of Kapton polymide foils was used to hold the target gas, and the cell was 15.5 cm high with a diameter of 13.7 cm. By tuning the thickness of a Mylar degrader, we succeeded to stop inside the gaseous volume about 61 ± 3 % of the kaons that hit the target cell. (This ratio is estimated from a Monte Carlo simulation which will be introduced in next chapter.) Subsequent X-rays from the kaonic atoms are then detected by 144 Silicon Drift Detectors (SDDs) surrounding the target. With the timing capability of the SDD, we succeeded in selecting the X-ray events correlated to the timing of kaon triggers. The hydrogen target was a Kapton container filled to 1.3 bar and kept at 23 Kelvin by a cryogenic system.

3 Yields of kaonic hydrogen X-rays

We determine the absolute yields of kaonic X-rays by:

$$\mathrm{Y(absolute\ yield)} = \frac{\mathrm{N_{X\text{-}ray}/N_{ktrg}}}{\mathrm{N^{MC}_{X\text{-}ray}/N^{MC}_{ktrg}}}, \tag{1}$$

where the ratio between the number of X-ray events ($\mathrm{N_{X\text{-}ray}}$) related to any kaonic atom signal and the number of kaon triggers ($\mathrm{N_{ktrg}}$) gives the detection efficiency of kaonic X-rays in the experiment. The denominator denotes the same efficiency estimated from the Monte Carlo simulation of the full set up using the Geant4.9.4 toolkit. The simulation starts from the incident K^-K^+ pairs, taken into account the realistic features of the DAΦNE beams. Energy deposit of the kaons at the kaon detectors is used to define the number of triggers $\mathrm{N^{MC}_{ktrg}}$. At the position where a K^- stops, one kaonic hydrogen K_α X-ray event is generated isotropically. Consequently we count the number of X-ray events for the same SDDs as used in the real data, to obtain $\mathrm{N^{MC}_{X\text{-}ray}}$.

As a reliability check for the simulation, we compared the simulation-estimated stopped kaon ratio dependence on the thickness of the Mylar degraders, to the measured dependence obtained from our helium target measurement [5], whose objective includes the tuning of the degrader. We found in the hydrogen target measurement, the optimized thickness in the simulation is 50 μm thicker than the actually used thickness which was determined based on the optimization done in the helium target measurement, and which was scaled accordingly considering the difference in the configurations of the setups. We therefore introduced the 50 μm Mylar uncertainty as one source for the systematic error in the simulation, and found it to be the most dominant one followed by the uncertainties in the gas density and the beam momenta, which are also the main systematic errors to the absolute yields. Further discussions about our Monte Carlo simulation can be found in reference [6].

In Eq. (1), the yield is well-defined only when the numerator and the denominator are obtained under the same configuration of apparatus and the same target density. For this reason, we made a selection of kaonic hydrogen data which fulfills the criteria that, the temperature and the pressure of the target are stable so that the calculated density is within $\pm 0.5\ \rho_{\mathrm{STP}}$ from 15 ρ_{STP}. Compared to the analysis dedicated to determining the $1s$ shift and width [2], the data satisfying the criteria are roughly one third in size and correspond to an integrated luminosity of 106 pb^{-1}. The subsequent timing and the X-ray spectra are shown in Fig. 1. The timing spectrum of the selected data set has better signal to background ratio than that of the full data set [2], since the selection criteria coincide with the best working conditions during the complete hydrogen target measurement.

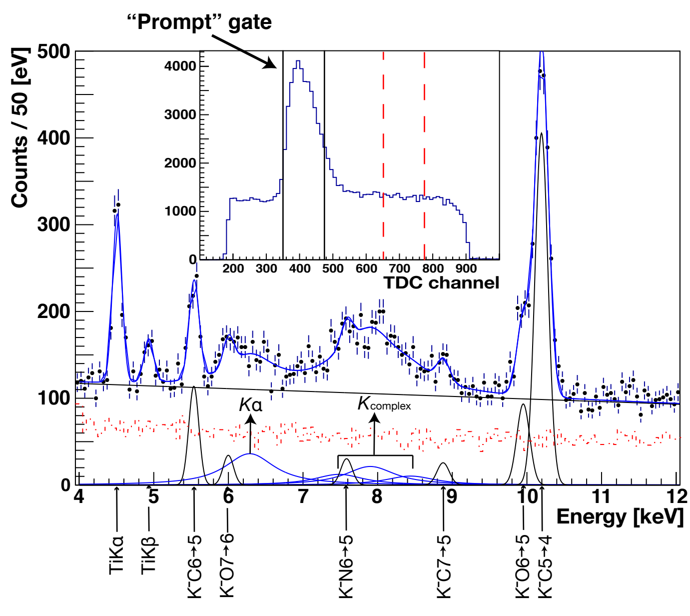

Figure 1. The X-ray spectra are represented by dots with error bars for the signals which are in coincidence with the kaons and by red dashed lines for the uncorrelated signals. The shapes of the polynomial function background and the background from other kaonic atoms are determined from a simultaneous fit with spectrum from the deuterium target measurement [4] not shown in this graph. In the inset we show the kaon timing spectrum of the selected data set; the solid lines define the "prompt gate" correlated to kaon coincidences and the dashed lines define the uncorrelated timing gate with the same width.

The kaonic hydrogen spectrum was fitted, together with the spectrum obtained from the deuterium target measurement performed with the same set up as hydrogen measurement. In the simultaneous fit, the following parameters that determine the background are common: the slope and the curvature of the polynomial background, the florescence X-rays from the titanum foil excited by the charged particles, and other kaonic X-rays originating from the kaons stopped in the Kapton.

For the fit function of the kaonic hydrogen, the relative intensities of the kaonic hydrogen higher transitions are set to be free, and we used no reference to the cascade model for input parameter. The fit result for the hydrogen spectrum is shown in Fig. 1 and indicates that the higher transitions for the kaonic hydrogen X-rays are highly correlated. To evaluate the correlations in the calculations of the total number of X-ray events, we use the covariance matrix that the Minuit processor (MINOS) [7] calculates when a fit process is successful. The information provided by the off-diagonal components in the covariance matrix was applied to determine the contribution to the statistic error for the number of K_{tot} events [4], which originates from the uncertainty of the relative statistical intensities of the higher transitions. As a test of the consistency with the previous results, the intensity of the kaonic deuerium K_α X-rays was introduced as a free parameter of the simultaneous fit and the result is fully consistent with the previous result published by the SIDDHARTA experiment [8].

Starting from $N_{ktrg} = (1.09\pm0.10)\times10^7$ kaon triggers, we observed 835±170 (stat.)±10 (sys.) events for K_α and 3137±500 (stat.)±40 (sys.) events for K_{tot}. The X-ray detection efficiency ($N^{MC}_{X\text{-ray}}/N^{MC}_{ktrg}$) for K_α determined by means of the Monte Carlo is evaluated to be $N^{MC}_{X\text{-ray}}/N^{MC}_{ktrg} = 0.0063^{+0.0007}_{-0.0012}$. Based on Eq. (1), the preliminary absolute yields obtained by the present analysis for K_α and K_{tot} are $Y(K_\alpha) = 0.012^{+0.003}_{-0.004}$ and $Y(K_{tot}) = 0.045^{+0.009}_{-0.012}$.

The dominant error in the number of X-ray events comes from the statistic uncertainty of the relative intensities of K-series higher transitions; while the origins of the dominant systematic errors in the simulation as discussed before, are the degrader thickness, the target density, and the beam momenta. Details about the error assignment and discussions on the kaonic hydrogen cascade together with the final results on the yields will be presented in a subsequent paper under preparation.

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