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Kaonic Helium 3 and 4 measurements by the SIDDHARTA experiment at DAΦNE

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The SIDDHARTA experiment (SIlicon Drift Detector for Hadronic Atom Research by Timing Application) had the aim to perform kaonic atoms X-ray transitions measurements, with the goal to better understand aspects of the low-energy QCD in the strangeness sector. The experiment combined the excellent low-energy kaon beam generated at DAΦNE, allowing to use gaseous targets, with excellent fast X-rays detectors: Silicon Drift Detectors. SIDDHARTA was installed on DAΦNE in autumn 2008 and took data till late 2009. During this period, we have performed the kaonic helium transitions to the 2*p* level (L-lines) measurements: for the first time in a gaseous target for helium4 and for the first time ever for kaonic helium3. The interest for such type of meeasurements was triggered by two reasons: the so-called "kaonic helium puzzle" (even if this was solved by KEK-PS E570 experiment, but a cross-check was useful) and some theoretical predictions of possible high energy shift. In this paper the results for the measurements to the 2*p* level (L-series) for kaonic helium4 and kaonic helium3 are presented.

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1. Introduction

The SIDDHARTA experimental setup [1] was installed on the DAΦNE accelerator in the middle of 2008 and took data until end of 2009. The big part of the data taking was dedicated to the hydrogen and deuterium data, but we have, as well, performed measurements of kaonic helium4 and, for the first time ever, of kaonic helium3 atoms.

Although kaonic atom X-ray data have been taken using many target materials, little was known about kaonic atoms with Z =1 and 2.

Concerning kaonic helium, no data was available for kaonic helium3, while, until recently, there were discrepancies in the energy shift for 2*p* level of the kaonic helium4.

In the 70's-80's, the kaonic helium4 X-rays were measured by three experiments [2], which gave consistent results and the average value for the shift was: ΔE=-43± 8 eV. On the other hand, the theoretical calculations [3], gave a shift comparable with 0 eV. Recent theoretical calculations [4] predict a possible maximum shift of 10 eV. No theoretical calculation could explain the large experimental shift, and this difference between the experiment and theory was known as the "kaonic helium puzzle". A recent experiment performed at KEK-PS of the E570 [5] group gave a shift of ΔE=-2± 2(stat)± 2(syst) eV, which is consitent with theory. This results has a much smaller error than the average value of the previous experiments, but differ by more than three standard deviations, thus making an independent experimental verifcation necessary.

As soon as the low-enery kaon beam from DAΦNE, allowing the use of gaseous target, and fast-timig X-ray detectors became available, for the first time, kaonic helium3 X-rays was measured [6] and also a new kaonic helium4 measurement was done by the SIDDHARTA experiment [6],[7].

2. The SIDDHARTA experimental setup

The SIDDHARTA setup was installed at the e^+e^- interaction point of the DAΦNE collider. It consists of an X-ray detection system, a cryogenic target system, and a kaon detector, as shown in Fig. 1.

The gas (helium3 or helium4) was contained in a cylindrical target cell (with a radius of 72 mm, and a height of 155 mm), made of 75 μm thick Kapton foils. Large area silicon-drift detectors (SDDs) having an active area of 1 cm^2each and a thickness of 450 μm [8], [9], [10] were used for X-ray detection.

A total active area of 144 cm^2 was installed with a distance of 78 mm between the SDDs and the target central axis. The SDDs were cooled to a temperature of 170 K with a stability of ± 0.5 K. The K^+K^- pairs produced by Φ decay were detected by two scintillators installed above and below the beam pipe at the interaction point (called "the kaon detector"). The scintillator installed below the beam pipe has a size of 72 × 72 mm^2 and a thickness of 1.5 mm, while the one installed above the pipe has a smaller size of 49 × 45 mm^2 and a thickness of 1.5 mm. Above the upper scintillator a degrader was installed to degrade the kaon energy so that the K^- mesons are stopped in the helium target volume. High intensity X-ray lines for energy calibration were periodically provided by irradiating thin foils of titanium and copper with an X-ray tube to excite them. They were installed at the interaction point, replacing the kaon detector.

Two types of data were taken with the e^+e^- beams.

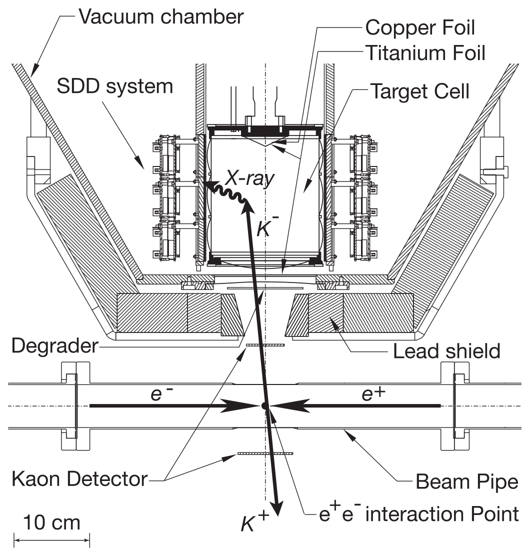

Figure 1: An overview of the SIDDHARTA setup installed at the interaction point of DAΦNE

The first type ("production" data) are data taken with the kaon detector and degrader, to be used for collection of kaonic atom X-ray events.

The second type ("X-ray tube" data) are data taken with the X-ray tube and the Ti and Cu foils. These X-ray tube data were taken periodically (typically every several hours), to be used for the determination of the energy scale of each SDD, and for monitoring temporal changes in the positions of the Ti and Cu X-ray peaks.

Energy data of all the X-ray signals detected by the SDDs were recorded using a specially designed data acquisition system.

Time differences between the X-ray signals in the SDDs and the coincidence signals in the kaon detector were recorded using clock signals with a frequency of 120 MHz, whenever the X-ray signals occurred within a time window of 6 μs. In addition, time differences between the coincidence signals in the kaon detector and the clock pulses delivered by DAΦNE were recorded. We explain in the next Section the use of this information.

3. Analysis of kaonic helium X-ray data

In tha analysis of the kaonic helium X-ray data, first, the X-ray tube data were analyzed. Energy spectra of each SDD contain Ti and Cu Ka peaks with high statistics, mainly induced by radiation from the X-ray tube. Since each SDD has a different gain, the energy scale was determined using the known X-ray energies of the Ti and Cu lines. In addition, SDDs having good performance were selected, based on energy resolution, peak shape, and stability during the measurements. The energy spectrum of the X-ray tube data is shown in Fig. 2(a), where data of all the selected SDDs were summed.

The production data were then analyzed using the energy scale determined from the X-ray tube data after corrections for temporal fluctuations of the peak positions.

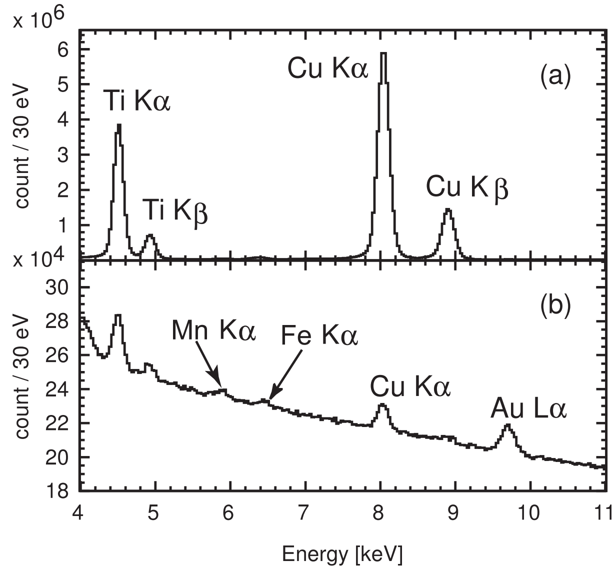

Figure 2: X-ray energy spectra of the SDDs, where data of all the selected SDDs were summed: (a) data taken with the X-ray tube, and (b) data uncorrelated to the kaon production timing in the production data.

The production data are categorized as two types, based on whether or not the coincidence signals between the SDD and kaon detector occurred within a coincidence window of 6 μs. One type contains X-ray events correlated with the kaon coincidence (triple coincidence data), providing kaonic atom X-ray energy spectra with a high background suppression. The other type contains X-ray events uncorrelated with the kaon coincidence (non-coincidence data), providing large statistics of background events, as well as X-ray lines from the target materials induced by the beam background.

Fig. 2(b) shows the energy spectrum of the non-coincidence data. The Ti and Cu peaks are seen at an energy of 4.5 keV and 8.0 keV, respectively. These peaks were produced by the Ti and Cu foils installed on the top of the target, as well as by the Ti foil, which is a part of the degrader. In addition, the Au $L_\alpha$line is seen at 9.7 keV, which was produced by the material of the SDD support structure. The Mn K_α and Fe K_α peaks were seen at 5.9 keV and 6.4 keV, being produced by a ^{55}Fe source and the Fe foil installed during part of the measurement.

The timing information of the coincidence data was analyzed to reject X-ray events uncorrelated to the K^+K^- production timing. The charged kaons were identified by means of the time-of-flight technique in the kaon detector [7], [11].

The time-difference spectrum of the K^+K^- pair events in the kaon detector and the X-ray events in the SDDs is shown in Fig. 3.

The origin of the horizontal axis is arbitrary because of a delay time of the electronics. The peak in the figure corresponds to the coincidence events of the K^+K^- pairs and X-rays (triple coincidences). A region from 2.9 μs to 4.6 μs was selected as the timing window of the coincidences. X-ray events uncorrelated with the K^+K^- production are seen as background events. Selecting X-ray events within a peak region suppresses background events associated with accidental coincidences.

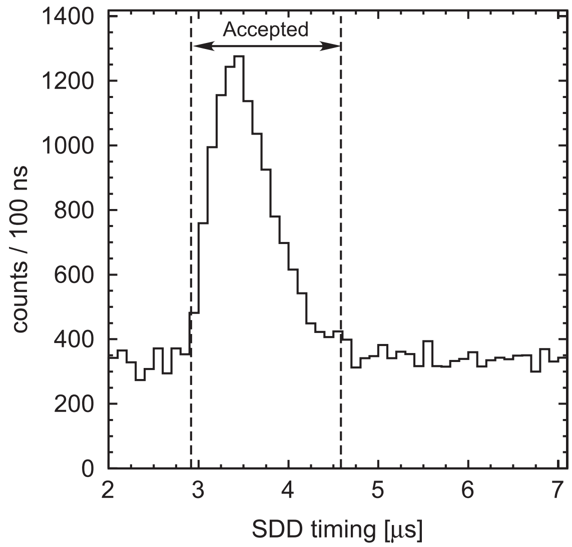

Figure 3: Time spectrum of the SDDs. The time difference between the K^+K^- coincidence and SDD X-ray hits was plotted. The peak region corresponds to the coincidence of the K^+K^- and X-ray events.

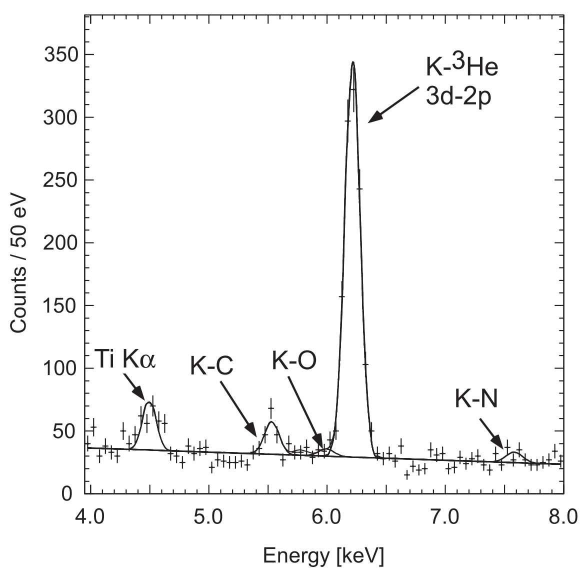

Figure 4: Energy spectrum of the kaonic helium3 X-rays in coincidence with the K^+K^- events. 3d $\rightarrow$ 2p transition is seen at 6.2 keV.

4. Kaonic Helium3 measurements

The kaonic helium3 X-ray data were taken for about 4 days in November of 2009. In this period, an integrated luminosity of 17 pb^{-1} was collected, which corresponds to about 2×10^6 kaons detected by the kaon detector.

Fig. 4 shows the X-ray energy spectrum of the SDDs in the triple coincidence timing, where the energy scale determined from the X-ray tube data was used for the horizontal axis.

A peak seen at 6.2 keV is identifed as the kaonic helium3 L_α line. Along with this peak, other small peaks are seen. They are identified as the Ti L_α line at 4.5 keV, the kaonic carbon 6h $\rightarrow$ 5g transition at 5.5 keV, the kaonic oxygen 7i$\rightarrow$ 6h at 6.0 keV, and the kaonic nitrogen 6h$\rightarrow$ 5g at 7.6 keV. The kaonic atoms X-rays others than kaonic helium, were produced by kaons stopping in the target window made of Kapton (polyimide) ($C_{22}H_{10}O_5N_2$).

The result obtained from these data for the 2p level strong interaction shift of the kaonic helium3 is [6] :

$$\Delta E_{2p} = E_{exp} - E_{e.m.} = -2 \pm 2(stat) \pm 2(syst)eV \tag{4.1}$$

5. Kaonic Helium4 measurements

Using the same setup, as well as the same measurement and analysis procedures, the kaonic helium4 3d $\rightarrow$ 2p X-rays were re-measured over short periods from September to November 2009. The strong-interaction shift of the kaonic helium 2p state was determined to be [6]:

$$\Delta E_{2p} = E_{exp} - E_{e.m.} = +5 \pm 3(stat) \pm 4(syst)eV \tag{5.1}$$

This result is in agreement, within the errors, with the results reported by the E570 [5] and SIDDHARTA collaborations [7].

6. Conclusions

The SIDDHARTA experiment measured the kaonic helium 3$d$$\rightarrow$ 2p transitions, L_α transitions: for the first time in a gaseous target for helium4 and for the first time ever for helium3.

DAΦNE proves to be an “ideal” kaonic atom “factory”.

For the future, the SIDDHARTA collaboration plans to upgrade the experimental setup, in order to do a precise measurement for the kaonic deuterium, and also to try to measure, the X-ray transitions for kaonic helium3 and kaonic helium4 to the *1s* level.

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