Physics Letters B 681 (2009) 310–314

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Kaonic helium-4 X-ray measurement in SIDDHARTA

SIDDHARTA Collaboration

M. Bazzi [a], G. Beer [b], L. Bombelli [c], A.M. Bragadireanu [a,d], M. Cargnelli [e], G. Corradi [a], C. Curceanu (Petrascu) [a], A. d'Uffizi [a], C. Fiorini [c], T. Frizzi [c], F. Ghio [f], B. Girolami [f], C. Guaraldo [a], R.S. Hayano [g], M. Iliescu [a,d], T. Ishiwatari [e,*], M. Iwasaki [h], P. Kienle [e,i], P. Levi Sandri [a], A. Longoni [c], V. Lucherini [a], J. Marton [e], S. Okada [a], D. Pietreanu [a], T. Ponta [d], A. Rizzo [a], A. Romero Vidal [a], A. Scordo [a], H. Shi [g], D.L. Sirghi [a,d], F. Sirghi [a,d], H. Tatsuno [g], A. Tudorache [d], V. Tudorache [d], O. Vazquez Doce [a], E. Widmann [e], J. Zmeskal [e]

[a] INFN, Laboratori Nazionali di Frascati, Frascati (Roma), Italy
[b] Dep. of Phys. and Astro., Univ. of Victoria, Victoria B.C., Canada
[c] Politechno di Milano, Sez. di Elettronica, Milano, Italy
[d] IFIN-HH, Magurele, Bucharest, Romania
[e] Stefan-Meyer-Institut für subatomare Physik, Vienna, Austria
[f] INFN Sez. di Roma I and Inst. Superiore di Sanita, Roma, Italy
[g] Univ. of Tokyo, Tokyo, Japan
[h] RIKEN, The Inst. of Phys. and Chem. Research, Saitama, Japan
[i] Tech. Univ. München, Physik Dep., Garching, Germany

ARTICLE INFO

Article history:
Received 21 July 2009
Received in revised form 9 October 2009
Accepted 17 October 2009
Available online 22 October 2009
Editor: V. Metag

PACS:
13.75.Jz
29.30.Kv
36.10.Gv

Keywords:
Exotic atoms
Kaonic helium
Silicon drift detectors

ABSTRACT

The kaonic helium-4 $3d \to 2p$ X-ray transition was measured in a gaseous target, where Compton scattering in helium is negligible. The X-rays were detected with large-area Silicon Drift Detectors (SDDs) using the timing information of the K^+K^- pairs produced by ϕ decays at the DAΦNE e^+e^- collider. A new value of the strong interaction shift of the kaonic ^{4}He $2p$ state was determined to be 0 ± 6 (stat) ± 2 (syst) eV, which confirms the recently obtained result by the KEK-PS E570 group.

1. Introduction

Studies of kaonic atoms have provided important information on the K^--nucleus strong interaction in the low energy regime. Low-lying energy levels of kaonic atoms are shifted and broadened due to the strong interaction between the kaon and nucleus. The shifts and widths of kaonic atom X-rays have been measured using targets with atomic numbers from $Z = 1$ to $Z = 92$, and they are systematically well understood with optical models for $Z \geqslant 3$. These results have been used for calculations of the $\bar{K}N$ interaction [1–4].

However, until recently, there has been a discrepancy in the energy shift of kaonic helium. Three measurements of the energy shift of the kaonic ^{4}He $2p$ state made in the 70's and 80's [5–7] gave consistent results with an average value of the shift[1]

* Corresponding author.
E-mail address: tomoichi.ishiwatari@oeaw.ac.at (T. Ishiwatari).

[1] In this article, the shift ΔE is defined as $\Delta E = E_{\rm exp} - E_{\rm e.m.}$, where $E_{\rm exp}$ is an X-ray energy determined by experiment, and $E_{\rm e.m.}$ is a calculated energy with the QED effect only.

0370-2693/$ – see front matter
doi:10.1016/j.physletb.2009.10.052

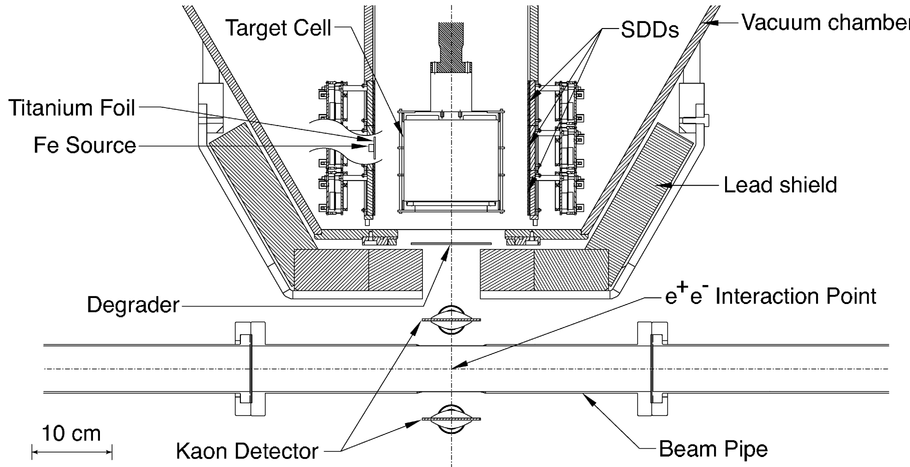

Fig. 1. An overview of the experimental setup. The whole system was installed at the interaction point of DAΦNE.

$\Delta E = -43 \pm 8$ eV [1,7]. On the other hand, the theoretical calculations based on the kaonic atom data with $Z \geqslant 3$ gave a shift of $\Delta E \sim 0$ eV (-0.13 ± 0.02 eV [1], -0.14 ± 0.02 eV [1], -0.4 eV [8], -1.5 eV [9]). Recent theoretical calculations predict a possible maximum shift of 10 eV [9]. No theoretical model could explain the large shift, and this difference between experiment and theory was known as the "kaonic helium puzzle".

A recent experiment performed by the KEK-PS E570 group gave a shift of $\Delta E = +2 \pm 2$ (stat) $\pm$ 2 (syst) eV [10], which is consistent with theory. This result has a much smaller error than the average value of the previous experimental results, but differs by more than three standard deviations, thus making an independent experimental verification necessary.

Here, we report a new measurement of the kaonic ^{4}He $3d \to 2p$ X-ray transition energy from which the strong interaction shift of the $2p$ level was determined. This measurement was made as part of the performance test of the SIDDHARTA setup at the DAΦNE ϕ factory of LNF in Frascati, Italy. The apparatus consists of an array of large-area Silicon Drift Detectors (SDDs) coupled to a gas target which is to be used for precision kaonic X-ray spectroscopy to determine the antikaon–nucleon isospin dependent scattering lengths.

An advantage of this new kaonic ^{4}He measurement comes from the use of a gas target resulting in negligible Compton scattering in helium — one of the sources of systematic errors in the previous experiments. The availability of kaons with low energy and low momentum spread produced by ϕ decays in the DAΦNE collider results in efficient kaon stopping in this gas target.

2. The SIDDHARTA experimental setup

The SIDDHARTA setup consists of three parts: a kaon detector, an X-ray detection system, and a cryogenic target system. Fig. 1 shows an overview of the setup. This whole system was installed at the e^+e^- interaction point of the DAΦNE collider.

The target cell is cylindrical with a radius of 6 cm and a height of 12 cm. It was filled with helium gas at a temperature of 27 K and a pressure of 0.95 bar, which corresponds to about 10.0 bar at normal temperature and pressure. The bottom of the vacuum chamber, shown in Fig. 1, has a circular window made of a Kapton foil with a radius of 6.5 cm, through which kaons enter the target cell. An energy degrader, installed on the bottom of the vacuum chamber, was adjusted in thickness to optimize the maximum number of kaonic helium X-rays. It had a step-like shape to compensate the ϕ boost effect caused by a finite crossing angle of the electron and positron beams.

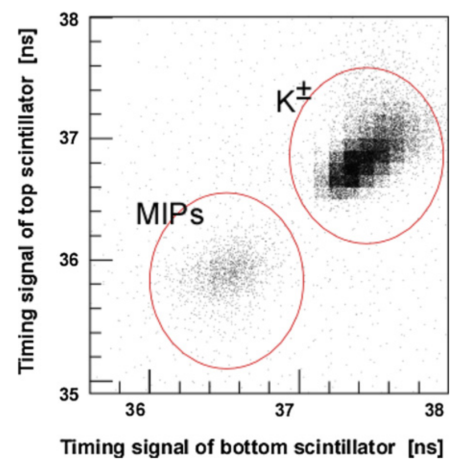

Fig. 2. Timing spectrum of the two scintillators in the kaon detector. The time difference between the clock signals delivered by DAΦNE and the coincidence of the two scintillators is shown. The K^+K^- and MIPs coincidence events are marked in the figure.

The K^+K^- pairs produced by ϕ decay were detected by a kaon detector, using a method similar to that used in a previous kaonic atom X-ray measurement at DAΦNE [11]. This detector consists of two scintillators installed above and below the beam pipe at the interaction point. Each scintillator has a size of 152×72 mm, and a thickness of 1.5 mm, through which almost all kaons pass. Two fast photomultipliers (Hamamatsu R4998) were optically coupled to the ends of each scintillator.

In this detector, charged kaon pairs were identified by a time-of-flight technique. The slow kaon pairs are clearly separated from fast minimum ionizing particles (MIPs), due to excellent time resolution (<100 ps FWHM) and the stability of the clock pulses (380 MHz RF) delivered by DAΦNE. A correlation of the time difference on the two scintillators is shown in Fig. 2. The K^+K^- pair production events are indicated. The ratio of kaon coincidences to MIPs during the kaonic helium measurements was about 20:1.

The kaonic helium X-rays were detected using recently-developed large area SDDs having an active area of 1 cm^2 and a thickness of 450 µm [12,13]. After detailed performance tests, 144 SDD chips were installed surrounding the target cell. The SDDs were cooled to a temperature of 170 K with a stability of ± 0.5 K.

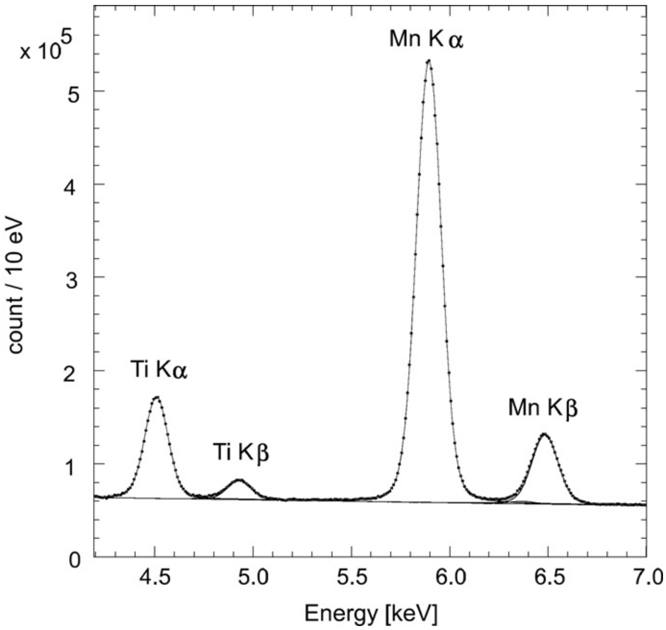

Fig. 3. SDD spectrum of X-rays uncorrelated with kaon production. Excellent statistics of the Ti and Mn X-rays are evident. The fit functions are shown as solid lines. These data were used for energy calibration and determination of the detector response.

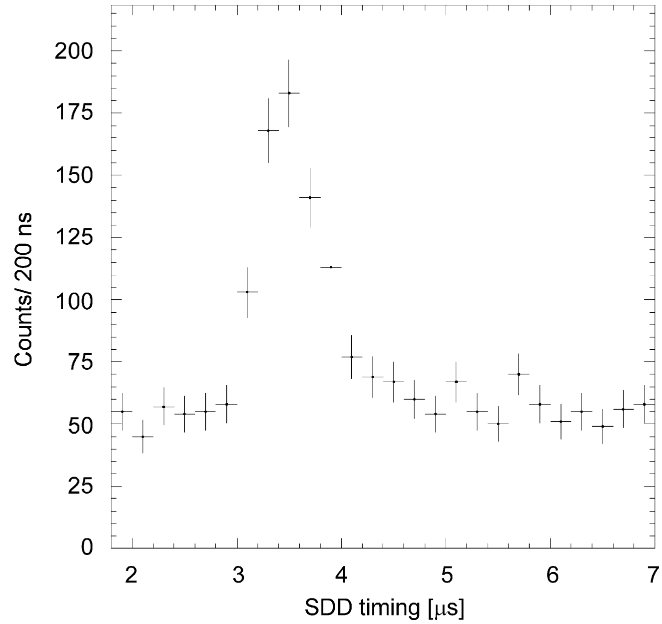

Fig. 4. Time spectrum of the SDDs. The time difference between the K^+K^- coincidence and SDD X-ray hits was measured. The peak region corresponds to the coincidence of the K^+K^- and X-ray events. The broadening reflects the drift time distribution of the SDDs, which determines the time resolution of the SDDs.

X-ray signals in the SDDs were read out using a specially designed data acquisition system. Energy data of all the X-ray signals detected by the SDDs were recorded. In addition, time differences between the coincidence signals in the kaon detector and X-ray signals in the SDDs were recorded using a clock with a frequency of 120 MHz, whenever the coincidence signals occurred within a time window of 6 μs. In the current system, MIP coincidence events cannot be rejected in the SDD data, but due to a good kaon/MIP ratio, X-ray background produced by the MIP coincidence events was small.

The SDD data are categorized as one of two types. One type contains X-ray events uncorrelated with the kaon coincidence ("non-coincidence data"), which provides large statistics of calibration X-rays, as well as information on peak shape. The other type contains X-ray events correlated with the kaon coincidence ("coincidence data"), which provides kaonic atom X-ray energy spectra with a high background suppression.

The energy shift of the kaonic helium X-ray line is expected to be much smaller than the detector resolution (typically 150 eV FWHM at 6 keV), so a precise energy calibration and knowledge of peak shape are crucial. Thus a ^{55}Fe source of about 0.4 MBq and a thin Ti foil in front of the source were installed in a place close to the target cell to monitor the stability of the SDD X-ray detection system. Using the Kα lines of Ti (4.5 keV) and Mn (5.9 keV), a dedicated stability check and energy calibration has been performed. The kaonic helium X-ray data were taken for about two weeks in January 2009. In this period, an integrated luminosity of 20 pb^{-1} was collected, which corresponds to about 4.7×10^6 kaons detected by the kaon detector.

3. Analysis of kaonic helium X-ray data

Fig. 3 shows the energy spectrum of the non-coincidence data. Ti and Mn X-ray peaks produced by the ^{55}Fe source are seen with high statistics. Here, data of 60 SDDs were selected out of the 144 SDDs installed, based on energy resolution, peak shape and stability of the Ti and Mn lines.

These known calibration peaks were fitted using the following method. For the fit, the reported values of X-ray energy and width were used, determined by high-resolution X-ray measurements [14,15], where asymmetric distribution of the peak shape is included. Because precise data on the Ti Kβ line are not available, a symmetric function was used. In addition to the asymmetry of the K line shape, there are weak satellite lines. In particular, the intensity of the KMM Radiative Auger Emission (RAE) peak, which is located just below the Kβ line, is not negligibly small [16–18], but a detailed structure is neither simple nor well known. Thus, in our analysis, a simple function assuming the KMM peak consists of one single line was used. Intensities of possible other satellite lines were found to be negligible within our collected statistics. A Voigt function was applied as a model of the detector response function instead of a Gaussian, to take care of low- and high-energy tails on an X-ray peak. Due to the complicated structure of the Kβ peaks as discussed above, only the Ti and Mn Kα lines were used for energy calibration, as suggested in [14]. The fit functions are shown in Fig. 3.

Fig. 4 shows the time difference spectrum of K^+K^- (and MIPs) events in coincidence with X-rays in the energy region from 6.2–7.0 keV, where the kaonic helium Lα line exists. The origin of the horizontal axis is arbitrary since it depends on a delay time of the electronics. The start and stop time signals were generated by coincidence timing on the kaon detector, and X-ray timing on the SDDs, respectively.

A peak in the figure corresponds to the coincidence events of K^+K^- pairs and X-rays (triple coincidence). X-ray events uncorrelated with K^+K^- production are seen as background events. The broadening of this peak, which is determined by the time resolution of the SDDs, reflects the drift time distribution of photoelectrons produced by X-rays to the central anode of the SDDs. The timing resolution was found to be 690 ns (FWHM). Selecting X-ray events within a peak region suppresses background events associated with accidental coincidences. The peak region from 2.8 μs to 4.0 μs was selected to obtain a minimum in the statistical error in the fit of the kaonic helium X-ray line.

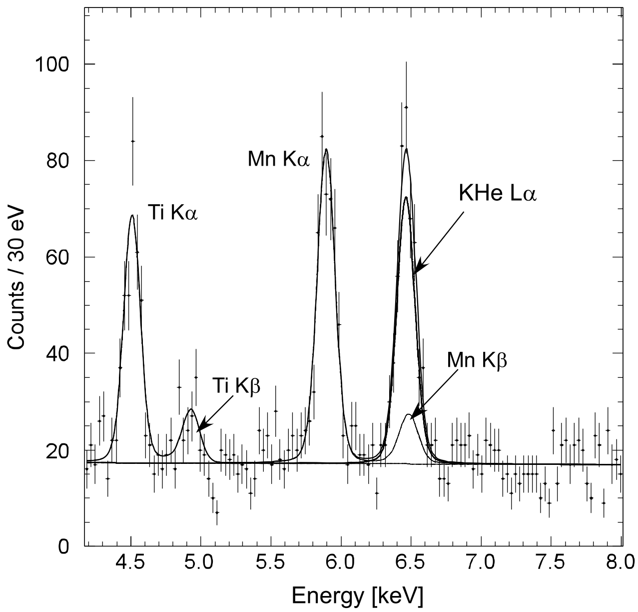

Fig. 5. Energy spectrum of the kaonic ^{4}He X-rays in coincidence with the K^+K^- events. Together with the accidental coincidence events of the Ti and Mn X-rays, the kaonic ^{4}He Lα line is seen at 6.4 keV.

Fig. 5 shows the X-ray energy spectrum selected by the triple coincidence timing events. The Ti and Mn X-ray peaks are still seen, due to accidental coincidences. A large enhancement at energies above the Mn Kβ peak (about 6.4 keV) is due to the existence of the kaonic helium Lα line. The ratio of the Mn and Ti X-ray lines is different from that in the non-coincidence data due to additional Ti X-ray production by particles hitting the Ti foils within the triple coincidence timing.

The X-ray peaks in the energy spectrum were fitted with the functions determined from the non-coincidence data. The relative ratio of the Mn Kα and Mn Kβ lines was fixed, as obtained from the calibration spectrum. The kaonic helium line was fitted with an additional Voigt function, where energy resolution evaluated from the calibration data was 151 ± 2 eV (FWHM). The X-ray energy of the kaonic helium Lα line was determined to be

$$E_{\text{exp}} = 6463.6 \pm 5.8 \text{ eV}, \tag{1}$$

where the second term is the statistical error. The natural width was found to be below the measurement limit within our statistics.

The contribution of systematic errors to the kaonic helium X-ray energy was studied. Energy linearity, gain drifts and rate dependence were found to be ± 0.5 eV each. A peak shift caused by contamination of the Mn Kβ line was found to be negligible. The total systematic error is estimated to be ± 2 eV, which includes other effects (e.g. uncertainty of the parameter determination in the fit functions, and possible satellite lines).

4. Discussion and conclusions

Because the strong interaction shift of the $3d$ state in kaonic helium is negligibly small, we use the value of $3d \to 2p$ energy calculated by QED only ($E_{\text{e.m.}} = 6463.5 \pm 0.2$ eV) [10] to obtain the strong interaction shift of the kaonic helium $2p$ state as:

$$\begin{aligned} \Delta E &= E_{\text{exp}} - E_{\text{e.m.}} \\ &= 0 \pm 6\,(\text{stat}) \pm 2\,(\text{syst})\,\text{eV}, \end{aligned} \tag{2}$$

where the second term denoted as (stat) is the statistical error and the third term denoted as (syst) is the systematic error.

Table 1
Energy shift of the kaonic helium $2p$ state.

ΔE (eV)	Ref.
-41 ± 33	Wiegand et al. [5]
-35 ± 12	Batty et al. [6]
-50 ± 12	Baird et al. [7]
-43 ± 8	Average of above [1,7]
$+2 \pm 2$ (stat) ± 2 (syst)	Okada et al. [10]
0 ± 6 (stat) ± 2 (syst)	This work

When compared to previous values [5–7,10] summarized in Table 1, our result is consistent with the results obtained by the E570 group [10], while it is inconsistent with the average of the other results [1,7].

In previous experiments, liquid helium was used as a target, where Compton scattering in helium is significant. About 10% of the 6-keV X-rays (corresponding to about the energy of the kaonic He line) can undergo Compton scattering. The experiment by the E570 group determined the contribution of a Compton tail with Monte Carlo simulations using the measured kaon stopping distribution in the target cell.

In the present experiment, the kaonic helium X-rays were measured in a gas target for the first time, where the Compton scattering was negligible, providing the kaonic atom X-ray peak without a Compton tail.

Both in our experiment and E570, the energy resolution was improved by a factor 2 compared to the previous three experiments. A precise determination of energy calibration and detector response was performed using high statistics X-ray data. These were essential to obtain the kaonic atom X-ray energy precisely.

In conclusion, the energy shift of the kaonic helium $3d \to 2p$ line was measured using the gaseous target in the SIDDHARTA experiment. The resultant shift of 0 eV confirms the result by the E570 group. Prior to the experiment by the E570 group, the average of the three previous results was $\Delta E = -43 \pm 8$ eV (Table 1), while most of the theoretical calculations give $\Delta E \sim 0$ eV [1,4,8]. This five-sigma discrepancy between theory and experiment was known as the "kaonic helium puzzle". A resolution of this longstanding puzzle provided by the E570 group is now firmly established by the present work.

Acknowledgements

We thank C. Capoccia, B. Dulach, and D. Tagnani from LNF-INFN; and H. Schneider, L. Stohwasser, and D. Stückler from Stefan-Meyer-Institut, for their fundamental contribution in designing and building the SIDDHARTA setup. We thank as well the DAΦNE staff for the excellent working conditions and permanent support. Part of this work was supported by HadronPhysics I3 FP6 European Community program, Contract No. RII3-CT-2004-506078; Austrian Federal Ministry of Science and Research BMBWK 650962/0001 VI/2/2009; Romanian National Authority for Scientific Research, Contract No. 2-CeX 06-11-11/2006; and Grant-in-Aid for Specially Promoted Research (20002003), MEXT, Japan.

References

[1] C.J. Batty, Nucl. Phys. A 508 (1990) 89c.
[2] E. Friedman, A. Gal, C.J. Batty, Nucl. Phys. A 579 (1994) 518.
[3] C.J. Batty, E. Friedman, A. Gal, Phys. Rep. 287 (1997) 385.
[4] S. Hirenzaki, et al., Phys. Rev. C 61 (2000) 055205.
[5] C.E. Wiegand, R. Pehl, Phys. Rev. Lett. 27 (1971) 1410.
[6] C.J. Batty, et al., Nucl. Phys. A 326 (1979) 455.

[7] S. Baird, et al., Nucl. Phys. A 392 (1983) 297.
[8] S. Bianco, et al., The DEAR Collaboration, La Rivista del Nuovo Cimento 22 (1999) 1.
[9] Y. Akaishi, in: Proc. Inter. Conf. on Exotic Atoms (EXA05), Austrian Academy of Sciences Press, Vienna, 2005, p. 45, http://dx.doi.org/10.1553/exa05s45.
[10] S. Okada, et al., Phys. Lett. B 653 (2007) 387.
[11] V. Lucherini, et al., Nucl. Instrum. Methods A 496 (2003) 315.
[12] P. Lechner, et al., Nucl. Instrum. Methods A 458 (2001) 281.
[13] C. Fiorini, et al., Nucl. Instrum. Methods A 568 (2006) 322.
[14] C.T. Chantler, et al., Phys. Rev. A 73 (2006) 012508.
[15] G. Hölzer, et al., Phys. Rev. A 56 (1997) 4554.
[16] A. Servomaa, O. Keski-Rahkonen, J. Phys. C 8 (1975) 4124.
[17] J.L. Campbell, et al., Phys. Rev. A 33 (1986) 2410.
[18] M. Budnar, et al., Nucl. Instrum. Methods B 63 (1992) 377.