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KAONIC HYDROGEN MEASUREMENT WITH DEAR AT DAΦNE

GEORGE BEER

Department of Physics and Astronomy, University of Victoria, BC V8W 3P6, Canada

A.M. BRAGADIREANU*, C. CURCEANU(PETRASCU), C. GUARALDO, M. ILIESCU*, V. LUCHERINI, D. L. SIRGHI* and F. SIRGHI

INFN - Laboratori Nazionali di Frascati, C.P. 13, Via E. Fermi 40, I-00044 Frascati , Italy

M. CARGNELLI, H. FUHRMANN, T. ISHIWATARI, P. KIENLE†, J. MARTON and J. ZMESKAL

Institute for Medium Energy Physics, Austrian Academy of Sciences, Boltzmanngasse 3, 1090 Vienna, Austria

J.-P. EGGER

Institut de Physique, Université de Neuchâtel, CH-2000 Neuchâtel, Switzerland

K. ITAHASHI, T. KOIKE and M. IWASAKI

Institute of Physical and Chemical Research (RIKEN), Wako-shi, Saitama, 351-0198, Japan

B. LAUSS

Department of Physics, University of California, Le Conte Hall 366, Berkeley, CA 94720, USA

L. LUDHOVA, F. MULHAUSER and L.A. SCHALLER

Institut de Physique, Université de Fribourg, Bd. de Pérolles, CH-1700 Fribourg, Switzerland

T. PONTA

Institute of Physics and Nuclear Engineering "Horia Hulubei", P.O.Box R-76900 Magurele, Bucharest, Romania

R. SEKI‡

Department of Physics and Astrophysics, California State University, Northridge, CA 91330, USA

Received (Day Month Year)

*also at: Institute of Physics and Nuclear Engineering "Horia Hulubei", P.O.Box R-76900 Magurele, Bucharest, Romania

†also at: Technical University Munich, 80290 Germany

‡also at: W.K. Kellog Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

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The DEAR (DAΦNE Exotic Atom Research) experiment[1] measured the energy of X-rays emitted in the transitions to the ground states of kaonic hydrogen. The shift ϵ and the width Γ of the 1s state are sensitive quantities for tests of the current understanding of the low energy antikaon-nucleon interaction. We obtain ϵ_{1s} = -193 ± 37 (stat.) ± 6 (syst.) and Γ_{1s} = 249 ± 112 (stat.) ± 30 (syst.)

Keywords: kaonic atoms; low-energy QCD.

1. Introduction

In the experiment X-rays emitted in the transitions to the ground states of kaonic atoms were measured.

A kaonic atom is formed when a negative kaon enters a medium, looses its kinetic energy through ionization and excitation of the atoms and molecules and eventually is captured, replacing the electron, in an excited orbit (n $\simeq$ 25). Via different cascade processes (Auger effect, Coulomb deexcitation, scattering) the kaonic atom deexcites to lower states.

When a kaon reaches a low-n state with small angular momentum, strong interaction with the nucleus causes its absorption. The strong interaction is the reason for a shift in the energies of the low-lying levels from the purely electromagnetic values and the finite lifetime of the state corresponds to an increase in the observed level width.

Measuring shift and width allows to study the K^-p interaction at threshold using some counterpart of Deser-type relations[2].

In a previous experiment[3] at KEK Iwasaki et al. have found that the strong interaction shift of the $1s$ state in kaonic hydrogen is repulsive in agreement with scattering data and in disagreement with earlier kaonic hydrogen experiments. The origin of this repulsive strong interaction at threshold can be traced back to the presence of the $\Lambda(1405)$ resonance which leads on one hand to a repulsive K^-p scattering length and on the other to the possible existence of strongly bound kaonic states in light nuclei[4].

For a quantitative test of recent theoretical work[5] on the topic, additional data with better precision and finally a kaonic deuterium measurement is required. With DEAR we succeeded to perform an improved measurement of kaonic hydrogen. An experiment on kaonic deuterium is currently under development – the SIDDHARTA project.

Finally we want to point out that the scattering lengths are related to the so called meson-nucleon sigma terms[6] as shown by 'low energy theorems'. These terms are important quantities in non perturbative Quantum Chromo Dynamics (QCD) since they provide a measure of the chiral symmetry breaking.

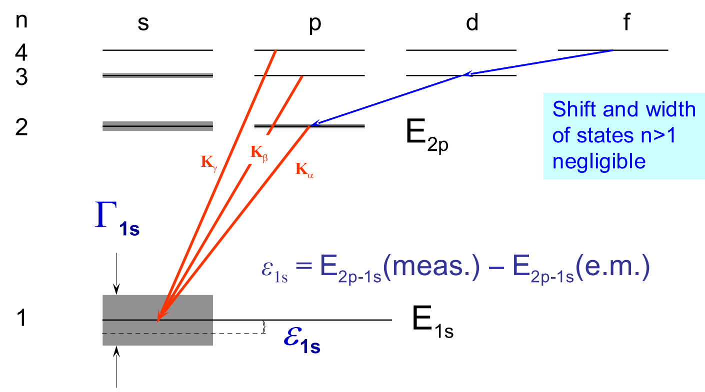

Fig. 1. Schematic view of the energy levels of kaonic hydrogen showing shift and width

2. Experiment

Our experiment was performed at the electron-positron collider DAΦNE at Frascati and used for the first time low energy, nearly monoenergetic kaons from the decay of Φs produced almost at rest for the formation of kaonic hydrogen. The small energy spread of the kaons introduced by a lateral boost of 15.2 MeV/c due the crossing angle of e^+ e^- was compensated by a special degrader. The use of a lepton machine results in a very low pion background as compared to proton machines. The low energy kaons were stopped in a special cryogenic light weight hydrogen gas target consisting of specially chosen structure materials to supress fluorescence X ray radiation as far as possible. CCDs (Marconi Applied Technologies, CCD55-30) were used as X-ray detectors. Their advantages are large area, pixel analysis capability for background reduction and excellent energy resolution.

The target was operated with hydrogen at 25 K and 2 bar resulting in a density of 2.1 g/l (0.03 of liquid hydrogen density). 16 CCD detectors with a total area of $116 cm^2$ and a resolution of 160eV FWHM at 7.6 keV were used. The 10^6 pixels of each chip were read out every 2 min. The intensity of the charged kaons was measured by two plastic scintillators which detected the back to back emitted kaons[7]. The kaons initial energy of ≈16 MeV was reduced by plastic degraders to ≈3 MeV which allows to stop them within a few cm in the hydrogen gas. For a measurement of kaonic nitrogen transitions[8] nitrogen gas at 120 K 1.5 bar was filled instead of hydrogen. This measurement was done immediately before the hydrogen run and was also used to optimize the kaon degrader and as background measurement for the kaonic hydrogen data. Data corresponding to an integrated luminosity of 32 pb^{-1} (45.6 10^6 K^-) were taken for nitrogen (272 GB files). In the final experiment we collected kaonic hydrogen data for 58.4 pb^{-1} (84.1 10^6 K^-, 288 GB files). Furthermore a background measurement with separated e^+ e^- beams and intentionally high X ray background was performed.

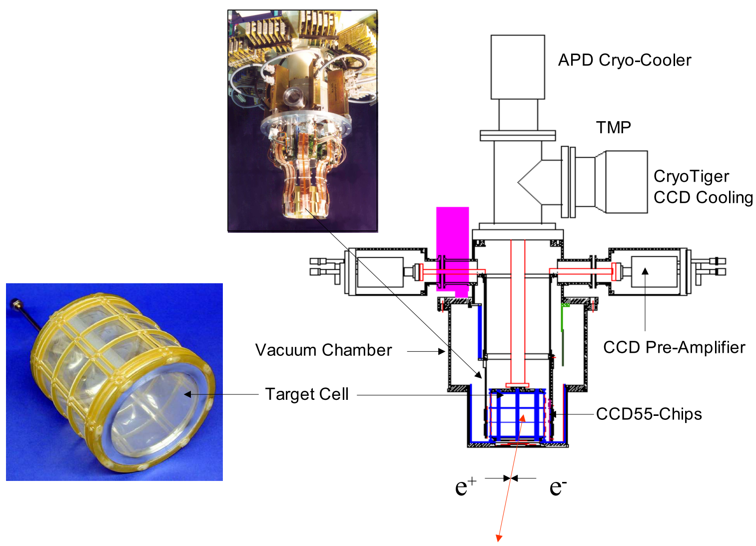

Fig. 2. Scheme of the experimental setup

The experimental challenge is the large low-energy X ray background (mainly from electron gamma showers resulting from lost e^+ or e^- due to either Touschek scattering (interaction within the particle bunch) or interaction with residual gas. It was minimized by shielding of our experimental setup and by improvements in the beam optics achieved by the machine crew.

3. Data Analysis

The clean extraction of the kaonic X-ray spectrum requires careful treatment of the raw data. The procedure applied consists of the following steps:

The 'cluster analysis' selects single and double pixel events - the charge produced by minimal ionizing radiation is spread over a larger pixel area, producing a 'cluster' event which can be rejected. Even without irradiation CCDs have a charge pedestal due to noise. This 'noise peak' is analyzed in position and width and data with broadened width are rejected. From position and width the noise threshold is derived: a pixel with charge above that threshold is regarded as a hit pixel. The CCD charge transfer efficiency depends on the position within the chip and is corrected. The individual exposures ('pictures') are added. For each detector the data are histogrammed and the individual energy calibrations using fluorescence background lines are calculated. The data of all individual detectors are added. A correction for the sightly different energy gains is applied. The overall resolution for the sum of detectors is determined.

The same procedure was applied to the data taken with the target filled with nitrogen (N-data), with hydrogen (H-data) and with hydrogen but separated beams which means without kaons ('No-collision' data). The data analysis for the nitrogen measurement is described in detail in [8].

The spectra consist of a *continuous component* (low energy Bremsstrahlung and remaining events from minimal ionizing radiation) and *fluorescence lines* from excitation of structure- and detector materials and the *kaonic lines*.

The analysis of the kaonic hydrogen K lines meets 3 crucial challenges:

- The determination of the continuous background, since the width of the kaonic hydrogen lines is very sensitive to this.
- The iron K_α X ray fluorescence line overlaps the kaonic K_α signal. These lines must be disentangled.
- The yields of the higher kaonic hydrogen K transitions (5-1 and higher) can not be obtained directly from the data, the sensitivity of the result to theoretic input concerning the yield ratios has to be examined.

Two completely independent analysis starting from raw (pixel) data were done. In both procedures a H spectrum (see Fig.3) and a background spectrum with no kaonic hydrogen signal (denoted as B) were fitted.

Approach 1 was to use for the background spectrum all 'No-collision' data and fit H and B data simultaneously by constructing a χ^2 function as the sum of 2 individual distributions ${\chi^2}_H$ and ${\chi^2}_B$ and use the same quadratic polynomial for the continuous background in H and B.

Four fit parameters for the continuous background were used: 1 for the normalisation of B vs. H plus 3 for the coefficients of a quadratic polynomial. The validity of using identical polynomial coefficients for H and B was checked by fitting the quotient spectrum H / B (exluding the KH signal regions) with a constant. For the selected fitrange of 2.9-10.4 keV no significant deviations were found. The electronic fluorescence lines from structure materials and the calibration foil (Ti) present in H and B were included in the fit model with the ratio given by the fitted normalization factor.

Approach 2 used the sum of N and a subset of the 'No-collision' data as background spectrum. This analysis proceeded in the following way: (1) Normalize the B spectrum to the same intensity in the Si fluorescence peak as the H spectrum. (2) Fit the normalized B spectrum using a cubic polynomial for the continuous

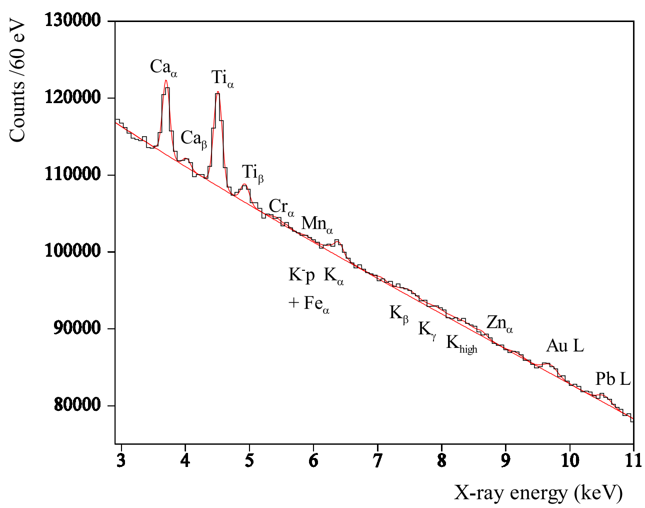

Fig. 3. X ray spectrum and fit curves. Nothing subtracted.

component and Gausspeaks for Cr, Mn, Ti, Fe, Zn, Au and Pb fluorescence lines and for the kaonic nitrogen lines at 4.58 keV and 7.59 keV. (3) Fit the H spectrum using a cubic polynomial for the continuous component and Gausspeaks for the fluorescence lines and the kaonic Carbon transition (6-5) and Voigt peaks for the kaonic hydrogen lines. The intensity of the Fe K_α peak is constrained by the result of the fit of the normalized B spectrum from step 2.

The fit model for the kaonic hydrogen lines used Voigt functions with fixed Gaussian width for the detector resolution known from fluorescence lines and kaonic nitrogen transitions. Fit parameters are the intensities of K_α, K_β and K_γ, the energy of K_α and the hadronic width of the kaonic hydrogen lines. One Lorentzian width was fitted and used for all K lines, since the hadronic broadening comes from the ground state width only. The energy *differences* of the kaonic hydrogen lines as compared to K_α were fixed to the electromagnetic values.

Concerning the influence of the K_{high} transitions, we restricted the fitrange to a region where these contribute only by the effect of their low energy tails. For the individual K_{high} yields and K_{high}/K_γ yields we used values from theory[9] (${K_{high}}^{(1)}$, ${K_{high}}^{(1)}/K_\gamma$). Furthermore we tested the effect of a different set of yields by assuming that the higher yields decrease exponentially and leaving this parameter float in a fit using the whole energy region. This procedure gave us an alternative set of yields, ${K_{high}}^{(2)}$ and a value ${K_{high}}^{(2)}/K_\gamma$. Applying a restricted fitrange, as described above, we find that the results using the theoretical yield values and the

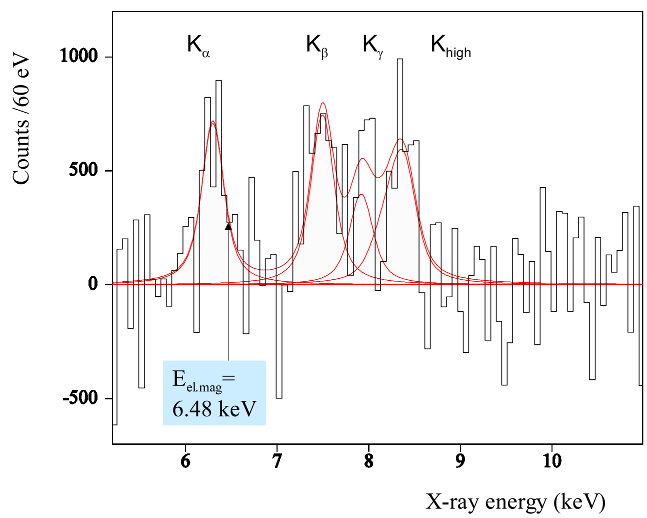

Fig. 4. Kaonic hydrogen X ray spectrum. All fit components except the kaonic lines are subtracted.

results using the alternative yields is consistent within ±3 eV.

4. Result and Conclusions

We obtained a transition energy of kaonic hydrogen K_α of 6287±37 (stat.)±6(syst.) eV. Using 6480 eV as transition energy without strong interaction, the 1s strong interaction shift can be deduced:

$$\epsilon_{1s} = -193 \pm 37 \text{ (stat.)} \pm 6 \text{ (syst.) eV.} \tag{1}$$

We use here the so-called "Warsaw Convention" (measured X-ray minus calculated energy) for the sign of the shift. The negative sign of the shift means a repulsive strong interaction. The 1s absorption (strong interaction) width (FWHM) result is

$$\Gamma_{1s} = 249 \pm 111 \text{ (stat.)} \pm 30 \text{ (syst.) eV.} \tag{2}$$

The systematic error covers detector energy calibration and energy resolution. In addition, systematic effects like fit range and method were also included.

The results are nearly compatible for the shift and compatible for the width of an earlier experiment[3] but our errors are significantly smaller (see Fig. 5). The values for the hadronic ground state shift and width are smaller than those from[3]. Our experimental results can test new theoretical studies[10].

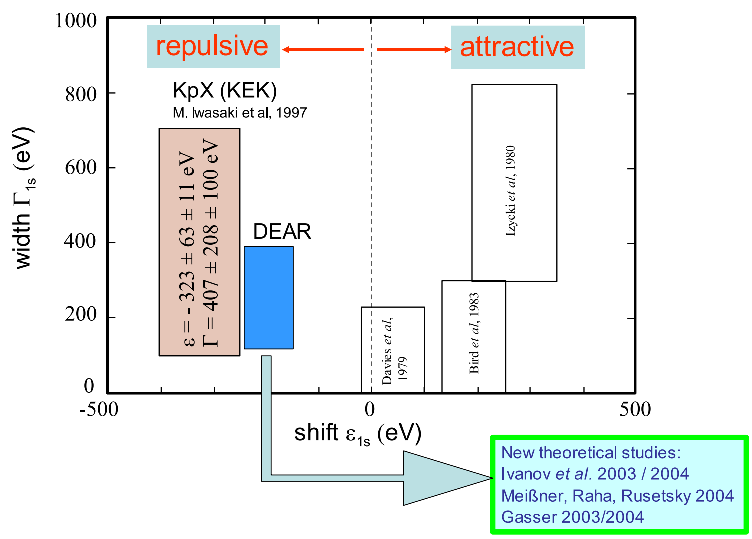

Fig. 5. The measured hadronic shift and width in kaonic hydrogen. Statistical and systematic errors have been added linearly.

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References

1. S. Bianco et al., Rivista del Nuovo Cimento 22, No.11, (1999) 1.
2. S. Deser et al., Phys. Rev. 96, 774 (1954) 774; T.L. Trueman, Nucl.Phys. 26, 57 (1961) 57; A. Deloff, Phys. Rev. C13, 730 (1976) 730.
3. M. Iwasaki et al., Phys. Rev. Lett. 78 (1997) 3067; T.M. Ito et al., Phys. Rev. C58 (1998) 2366.
4. Y. Akaishi and T. Yamazaki, Phys. Rev. C 65, 44005 (2002).
5. J. Gasser in Mini Proc. CD 2003, hep-ph/0311212; N. Kaiser, P.B. Siegel, and W. Weise, Nucl. Phys. A 594 (1995) 325; A. Ivanov et al., submitted to Eur. Phys. J. A, nucl-th/0310081.
6. E. Reya, Rev. Mod. Phys. 46, 545 (1974); H. Pagels, Phys. Rep. 16, 219 (1975).
7. V. Lucherini et al., Nucl. Inst. and Meth. A496 (2003) 315.
8. T. Ishiwatari et al., accepted Phys. Lett. B.
9. T. Jensen, DEAR Technical Note IR-45 (2003); T. Koike, private communication.
10. J. Gasser, in Frascati Physics Series, proceedings of the DAΦNE 2004: Physics at Meson Factories, Frascati 2004, to appear.