DEAR Technical Note IR-47

DEAR kaonic hydrogen results of the data analysis performed in Frascati

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18 December 2003

1 Introduction

The goal of the present Note is to present to the DEAR Collaboration the method followed in the kaonic hydrogen data analysis performed in Frascati. The procedure followed, step by step, with details of the analysis, is presented, together with the obtained results, in terms of shift and width of the $1s$ kaonic hydrogen level. Results of various fit-tests, under different hypotheses, are included, in order to show that the "best possible solution" was found.

The principle of the method followed in Frascati is a simultaneous fit of signal (kaonic hydrogen) and background (no-collisions data of December 2002) data. The choice of the background data as being the December 2002 no-collisions data is motivated by the fact that this set of data is taken with the same setup and with same conditions of machine optics as the signal data, having the advantage of allowing the disentangling of continuous as well as structured (electronic transitions, mainly Iron) background in the signal spectrum.

Another problem which we had to deal with, is the fact that we don't know the relative yields of kaonic hydrogen K-complex transitions. This problem is important, since the fit, if done for all the K-complex, requires as input values the relative yields of high (higher than $5 \rightarrow 1$) transitions. In order to avoid systematic errors coming from hypotheses on the relative yields for high transitions, the following solution was adopted: it was fitted the energy region in which kaonic hydrogen transitions with free yields could be considered. This turned out in a cut in the energy region, from about 7.74

to 8.82 keV. In this way the results of the fit are independent on any cascade-model. A Monte Carlo study of an eventual systematic error introduced by this cut was performed and showed that this error is at the level of eV.

The present Note is structured as followed: in Section 2 a brief description of the data set used for analysis is performed; Section 3 deals with the method of the simultaneous fit, while in the Section 4 the results of the fit are presented. Further tests are discussed briefly in Section 5, while Conclusions are presented in Section 6.

2 Data considered for the analysis

For the simultaneous fit of kaonic hydrogen and background data the following data sets were considered:

- kaonic hydrogen data, collected in the period 30 October - 16 December 2002, for a total of about 58 pb^{-1} integrated luminosity;
- no-collisions background data, taken from 16 to 23 December 2002, for which the beams were slightly separated in the DEAR interaction point, with same machine optics as that used for colliding beams, and with a scrapers configuration such to obtain an overall statistics for background camparable (factor 1.4 less) with that for the signal spectrum.

In the first half of 2003 a procedure of Charge Transfer Correction was performed in Frascati, raw-by-raw, starting from the calibration data taken during the data acquisition. Both single and double pixel signals were considered for analysis. The data were then re-processed (in July 2003) with the new code, allowing to obtain, with respect to the non-corrected data:

- about 15% higher statistics;
- cleaner spectra with smoother shape - very important in the simultaneous fit which was performed - as will be shown in Section 3;
- better resolution - going from about 140 eV at Ca position to 155 eV at Fe position

The kaonic hydrogen and background spectra obtained for all 16 CCDs after applying the Charge Transfer Corrections and further on considered in the simultaneous fit are shown in Figures 1 and 2.

In the next Sections the procedure, results and further tests of data analysis are presented.

3 Data analysis - description of the method

In order to establish a strategy for data analysis, a closer look to the signal anc background spectra is mandatory. The two zoomed spectra, in the region of interest, defined as from about 3 to 10 keV, are shown in Figures 3 and 4.

By a quick analysis of the 2 spectra, the following considerations can be done:

- in the signal spectrum there is a clear bump - absent in the background spectrum - in correspondence with the K-complex transitions (7-8 keV region);
- the Iron transition is present in the spectra and contaminates the K_α transition; one should find a clever way to disentangle it by the use, possibly, of the background spectrum;
- the shape of the two spectra looks the same - key point in the strategy which was followed, as seen below.

Starting from the last consideration in the previous list, the problem of how to make the better use of the background data in order to extract the kaonic hydrogen signal, was put forward. A study of the spectrum obtained by dividing the signal spectrum by the background one was performed as a starting point. The spectrum obtained by the division of the signal and background spectra is shown in Figure 5.

A fit of the divided spectrum from 2.9 to 10.4 keV, excluding the region interested for kaonic hydrogen transitions ($5.5 \rightarrow 8.8$ keV), gave as result a constant (i.e. if a linear fit is tried, the term multiplying the energy is less than one sigma-error, i.e. compatible with zero). This is very important, since it means that the shape of the overall background (i.e., continuous plus electronic transitions) is the same for signal and no-collisions (background),

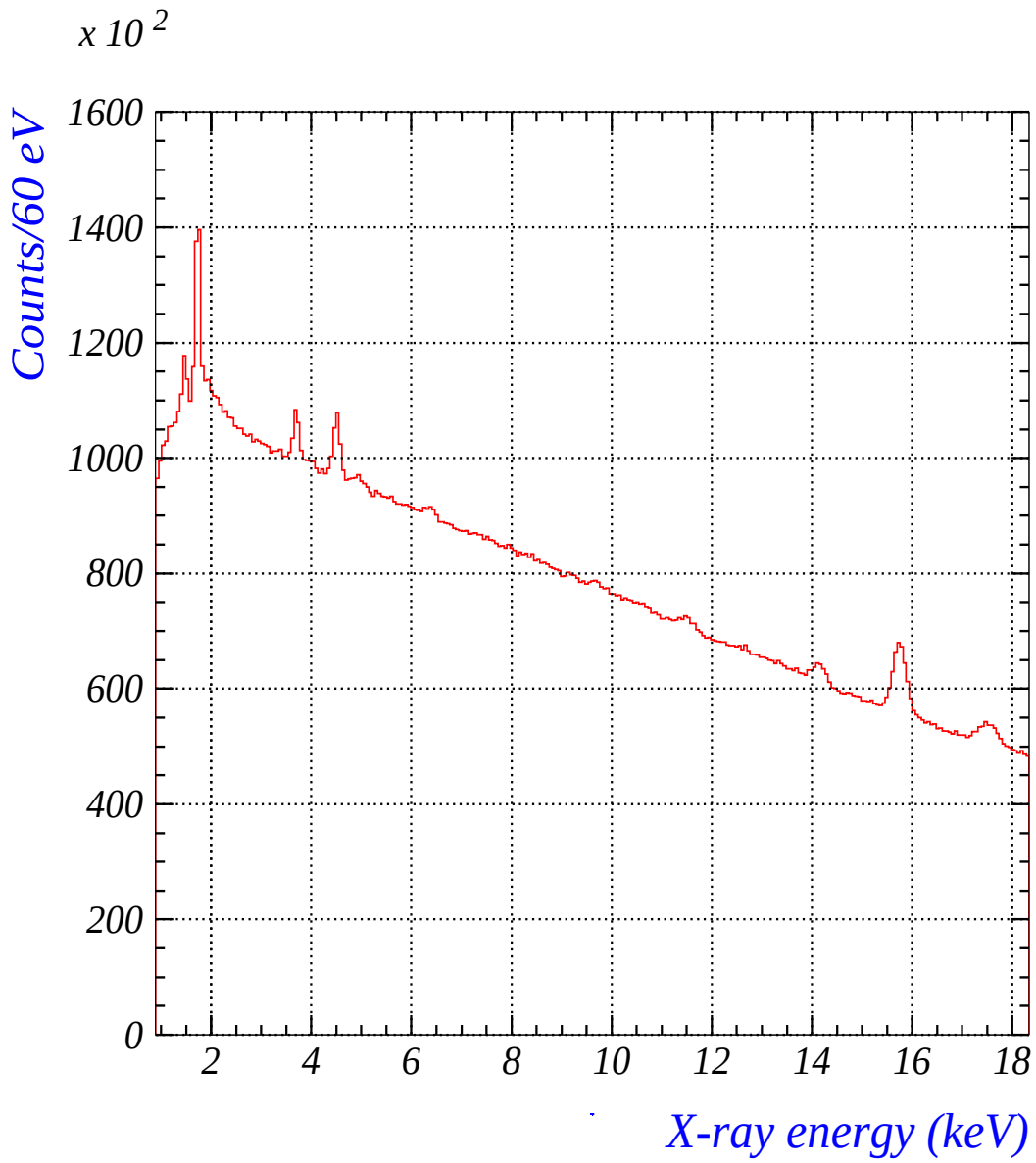

Figure 1: The overall kaonic hydrogen spectrum; the relevant electronic transitions, from left to the right are: Silicon (1.7 keV), Calcium (3.6 keV), Titanium (4.5 keV), Iron (6.4 keV), Lead (11.5 keV), Strontium (14.1 keV), Zirconium K_α and K_β (15.7 keV and 17.7 keV)

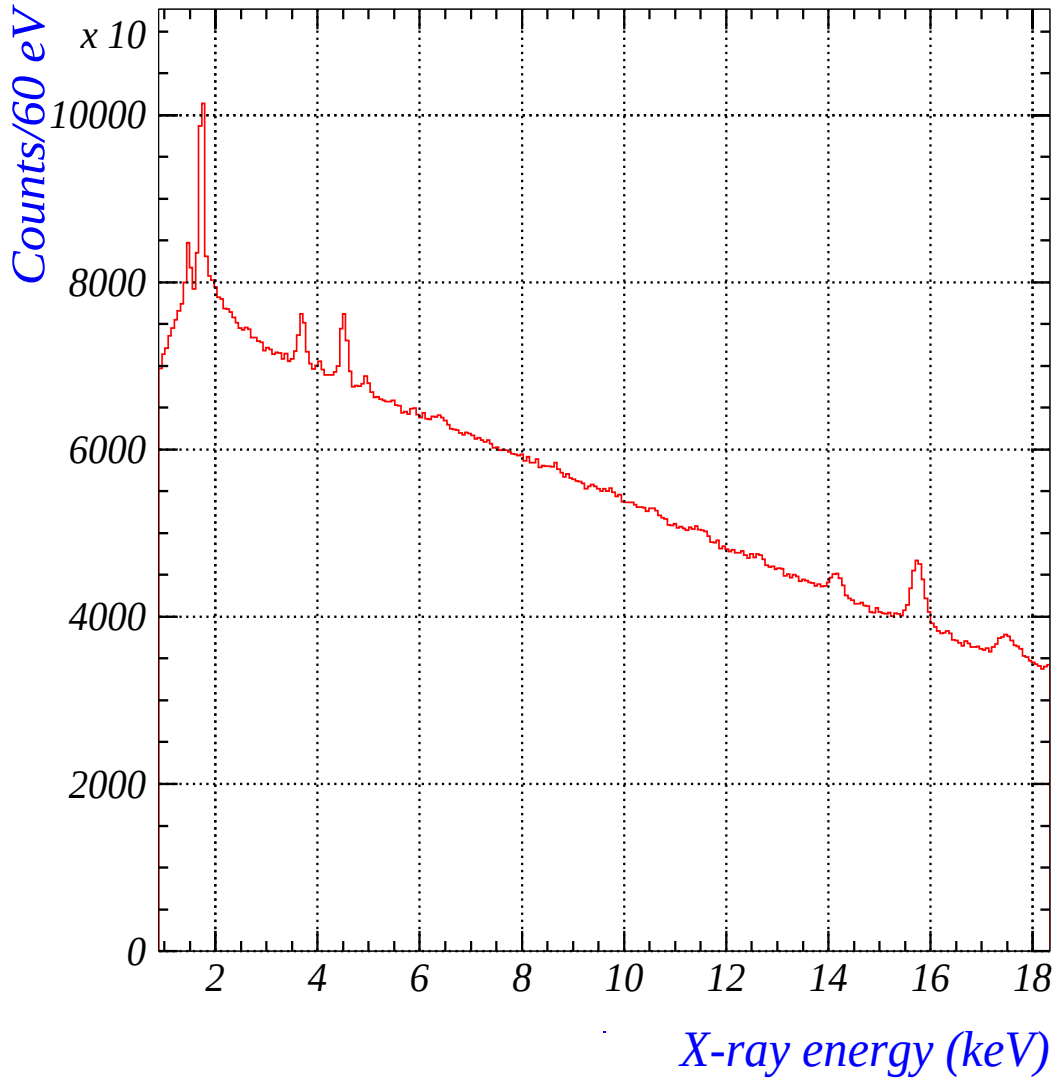

Figure 2: The overall background spectrum; the relevant electronic transitions, from left to the right are: Silicon (1.7 keV), Calcium (3.6 keV), Titanium (4.5 keV), Iron (6.4 keV), Lead (11.5 keV), Strontium (14.1 keV), Zirconium K_α and K_β (15.7 keV and 17.7 keV)

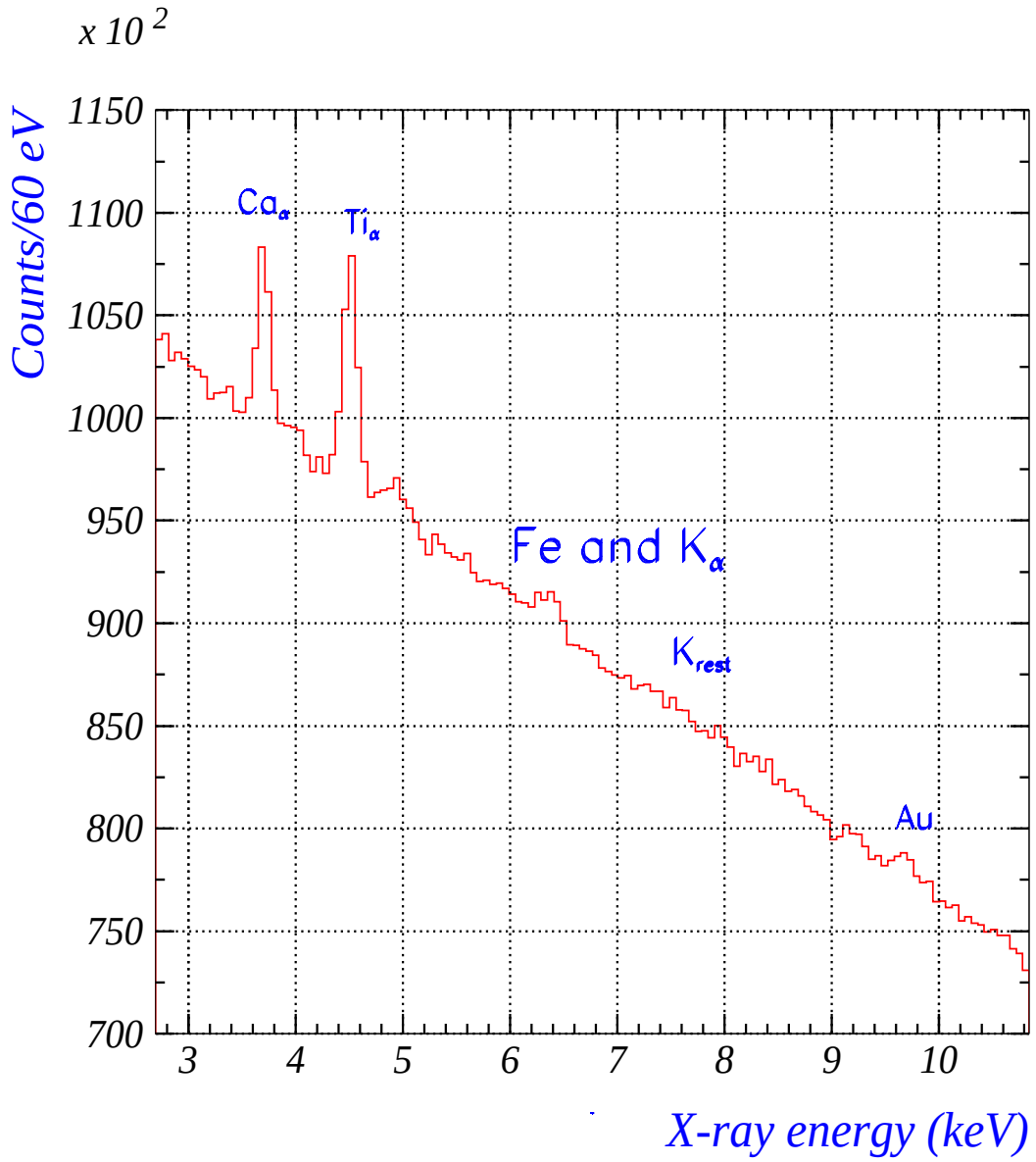

Figure 3: The zoomed signal spectrum; the Calcium (3.6 keV), Titanium (4.5 keV) and Gold (9.7 keV) electronic transitions are shown. The K_α plus Iron peak and the K-complex position are indicated

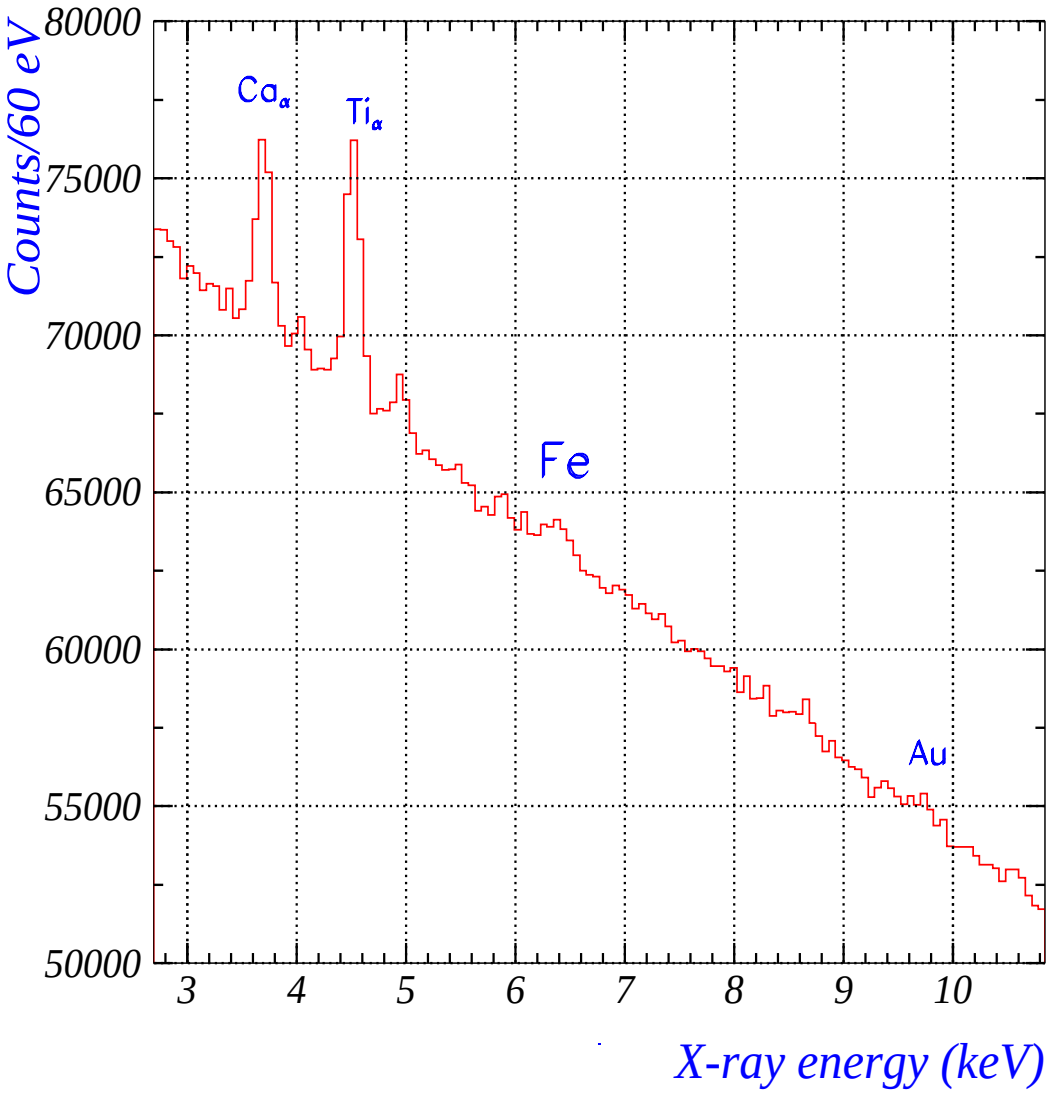

Figure 4: The zoomed background spectrum; the Calcium (3.6 keV), Titanium (4.5 keV), Iron (6.4 keV) and Gold (9.7 keV) electronic transitions are shown.

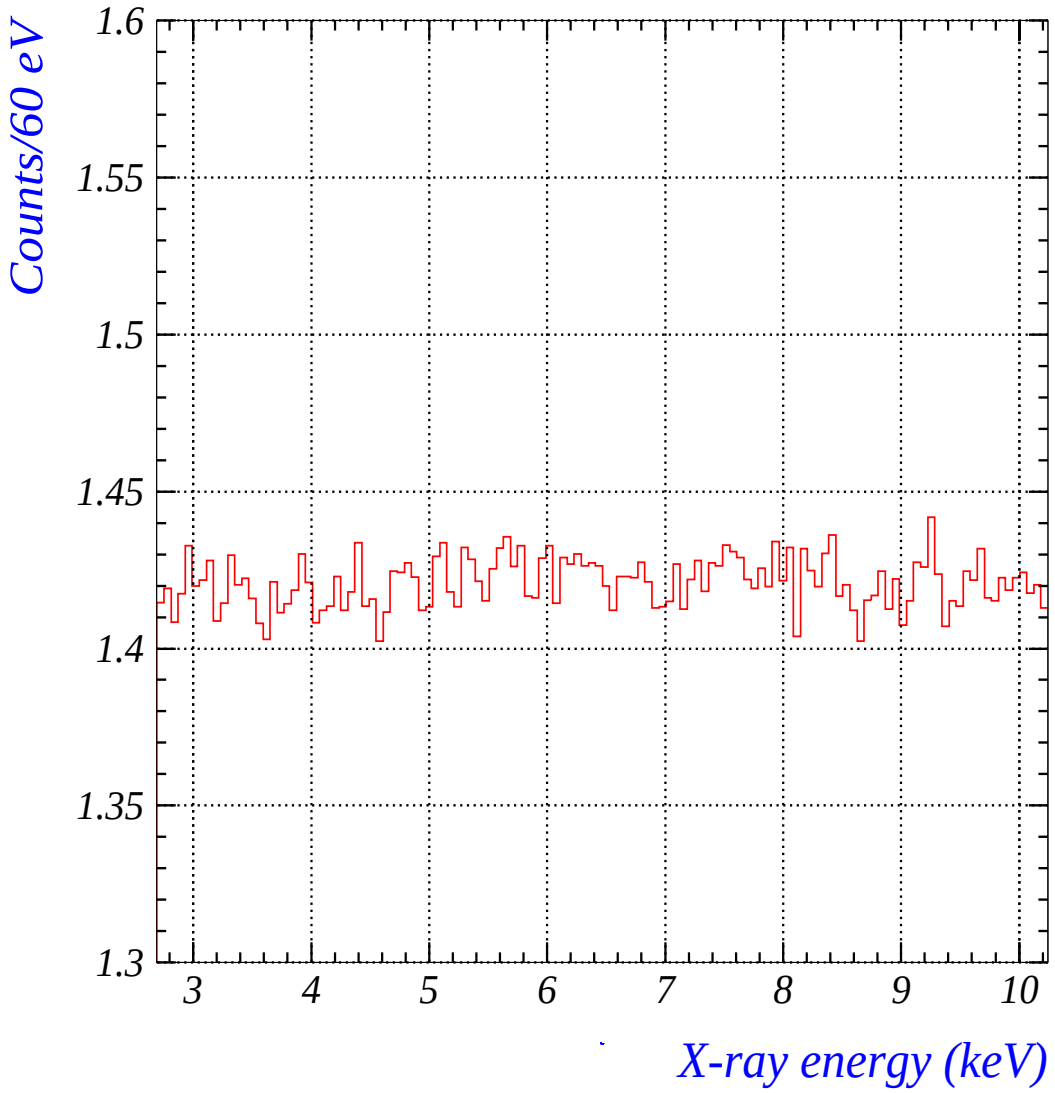

Figure 5: The signal/background spectrum.

apart from a normalization constant. Is this the key-feature of the simultaneous fit performed of the 2 spectra.

The background function which is the same within a normalization constant for signal and no-collisions spectra contains:

- for the continuous component a second degree polinomial function;
- for electronic transitions: Ca K_α, Ca K_β, Ti K_α, Ti K_β, Cr K_α, Mn K_α, Fe K_α, Fe K_β, Zn_α and Au-L. Ni and Cu transitions were checked to be compatible with zero. The energy resolution for each line was deduced from the values for Ca, Ti and Zr transitions.

For the kaonic hydrogen spectrum, contributions from kaonic hydrogen and kaonic carbon were considered. The function describing the kaonic hydrogen signal was the Voigt-function (convolution between Lorentz and Gauss functions).

A χ^2 function was built as the sum of the 2 individual χ^2 distributions for each signal and background spectra and then minimized.

As anticipated in the Introduction, in order to avoid additional systematic errors, coming from hypotheses on kaonic hydrogen yields for high (higher than $5 \rightarrow 1$) transitions, which are necessary in order to make the fit convergent, the fit was performed on an energy region between 2.9 and 10.4 keV, excluding the 7.74 - 8.82 keV region, interested by K_{high} transitions, moreover biased by additional contribution of Zn transition. Monte Carlo simulations showed that this cut, properly taken into account, introduces systematic errors at the level of eV - so negligible.

The results of the simultaneous "best fit" of signal and background spectra are presented in Section 4, while further tests results are reported in Section 5.

4 Data analysis - results

The result of the "best fit" applying the procedure described in the previous Section are reported below.

The simultaneous fit of kaonic hydrogen and background spectra gave an overall $\chi^2/NDOF = 1.02$ for the best fit solution.

Apart from the background - described in the previous Section - in the signal spectrum, the kaonic hydrogen K_α, K_β and K_γ lines and the kaonic

carbon and lines were included. The fit was done from 2.9 to 10.4 keV, excluding the 7.76 - 8.82 keV region, for the reasons stated above. The total number of free parameters in the fit was 22: height of Ca K_α, resolution of Ca K_α, height of Ca K_β, height of Ti K_α, height of Ti K_β, height of Cr K_α, height of Mn K_α, height of Fe K_α, height of Fe K_β,resolution of Fe K_α, height of Au-L line, height of KC (3.36 keV), height of KC (5.58 keV), amplitude of kaonic hydrogen K_α, amplitude of kaonic hydrogen K_β, amplitude of kaonic hydrogen K_γ, position of K_α (the position of K_β and K_γ were fixed as a function of K_α), width of K_α, normalization factor between the background function of the background spectrum with respect to the signal one, three parameters for continuous background.

The signal and background spectra together with the best fit solution are shown in Figures 6 and 7.

The continuous background subtracted spectra are shown in Figures 8 and 9.

The **numbers of events** found in the kaonic hydrogen spectrum for each **electronic transition** are given below, growing in energy:

1. Ca K_α: 22570 ± 470 events;
2. Ca K_β: 2937 ± 495 events;
3. Ti K_α: 31862 ± 593 events;
4. Ti K_β: 5973 ± 507 events;
5. Cr K_α: 448 ± 498 events;
6. Mn K_α: 871 ± 478 events;
7. Fe K_α: 3962 ± 608 events;
8. Fe K_β: 403 ± 472 events;
9. Au-L: 4084 ± 667 events.

The **number of events** corresponding to **kaonic atoms** (**carbon** and **hydrogen**) transitions are

1. **Kaonic Carbon, 3.36 keV transition:** 537 ± 660 **events;**

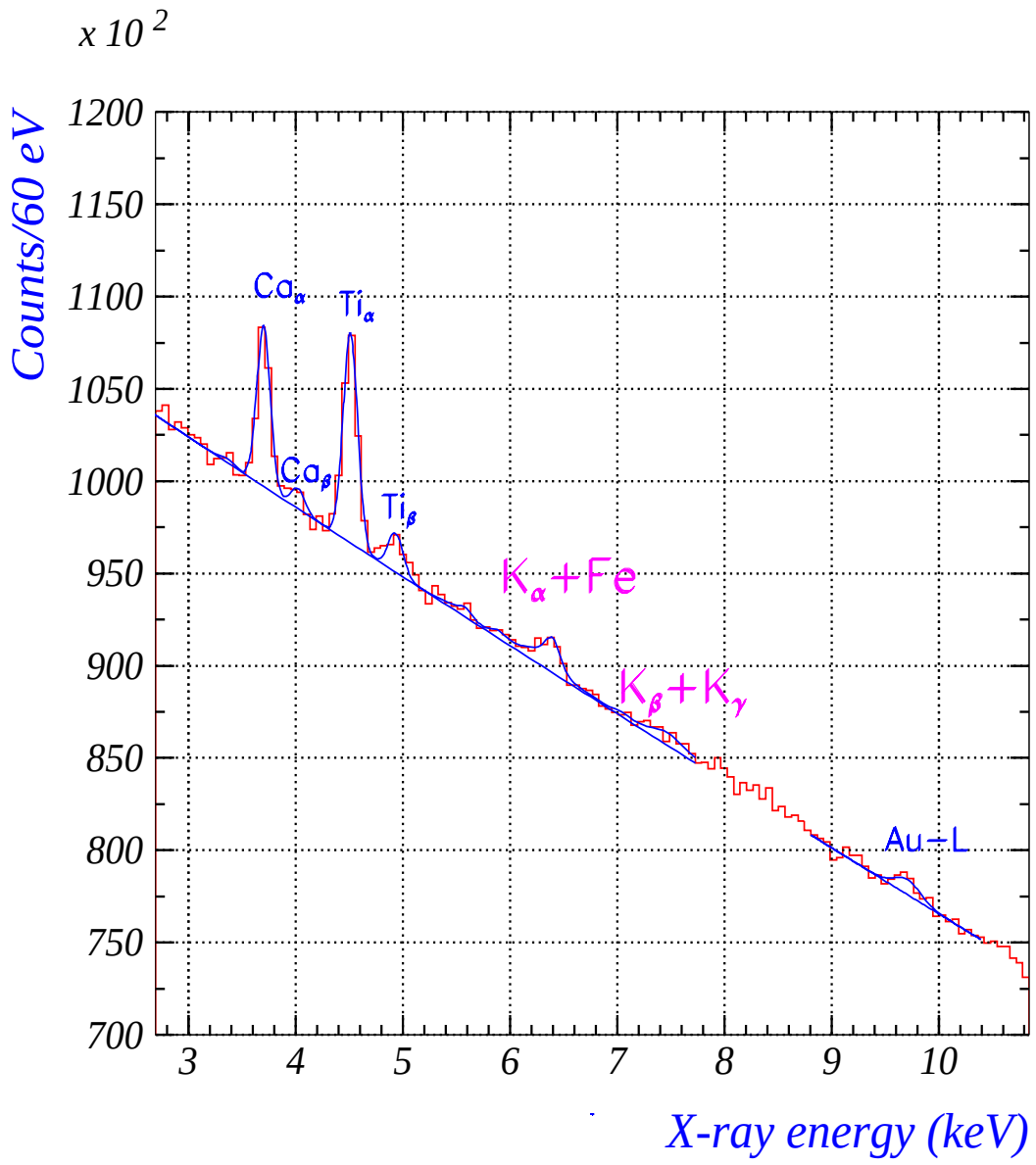

Figure 6: The signal spectrum with the best fit solution; the relevant transitions (electronic and kaonic hydrogen) are shown together with the continuous background.

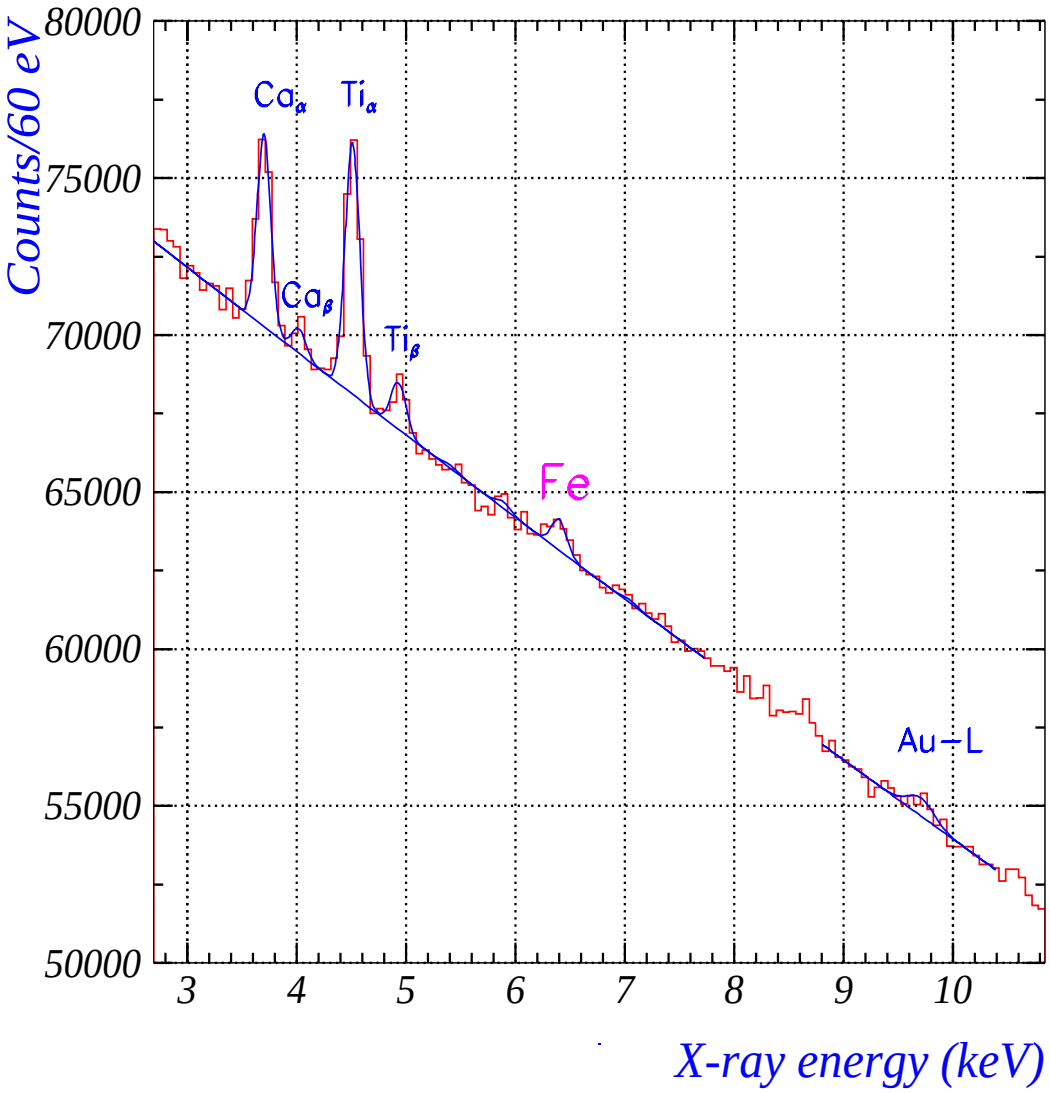

Figure 7: The background spectrum with the best fit solution; the relevant electronic transitions are shown together with the continuous background.

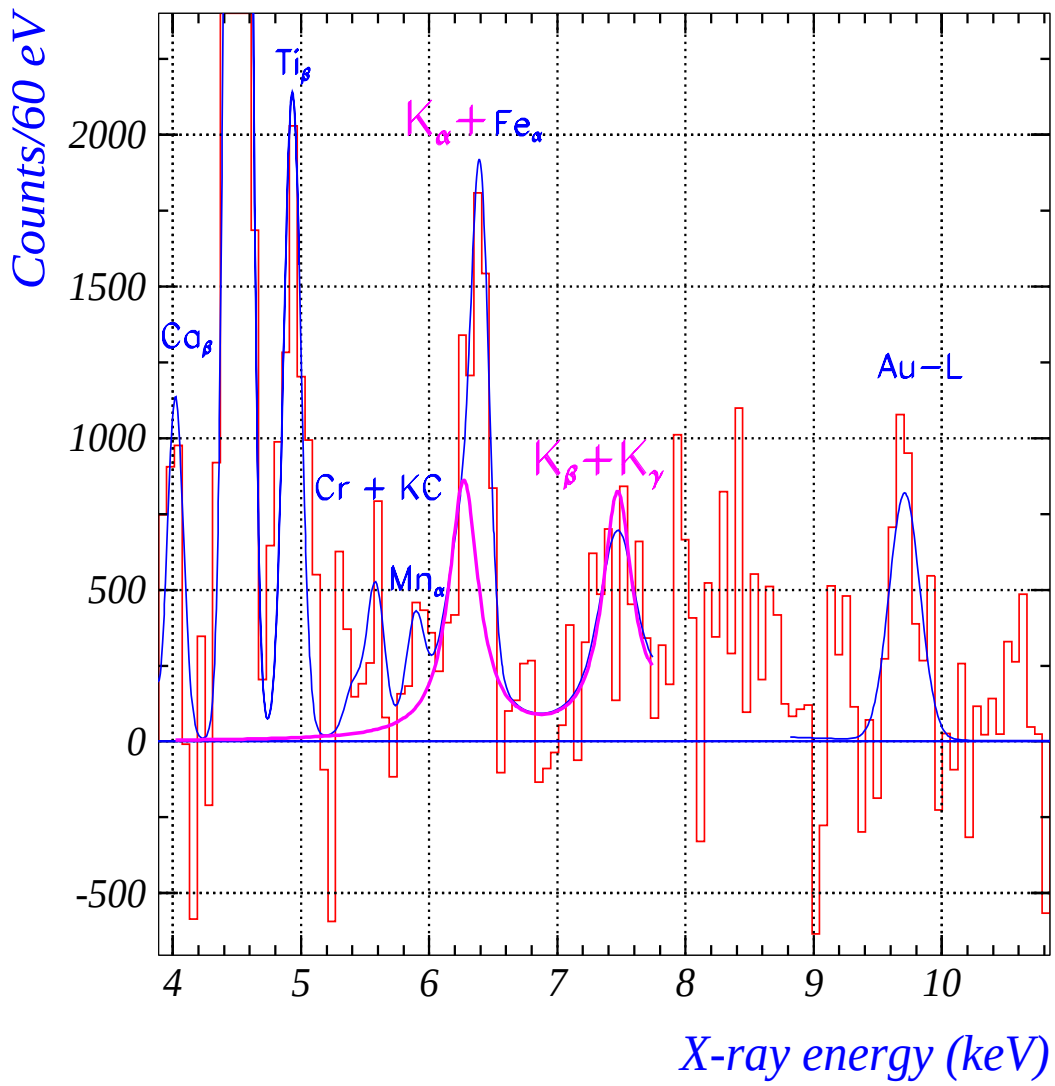

Figure 8: The continuous background subtracted kaonic hydrogen spectrum, with the electronic and kaonic (hydrogen and carbon) transitions indicated.

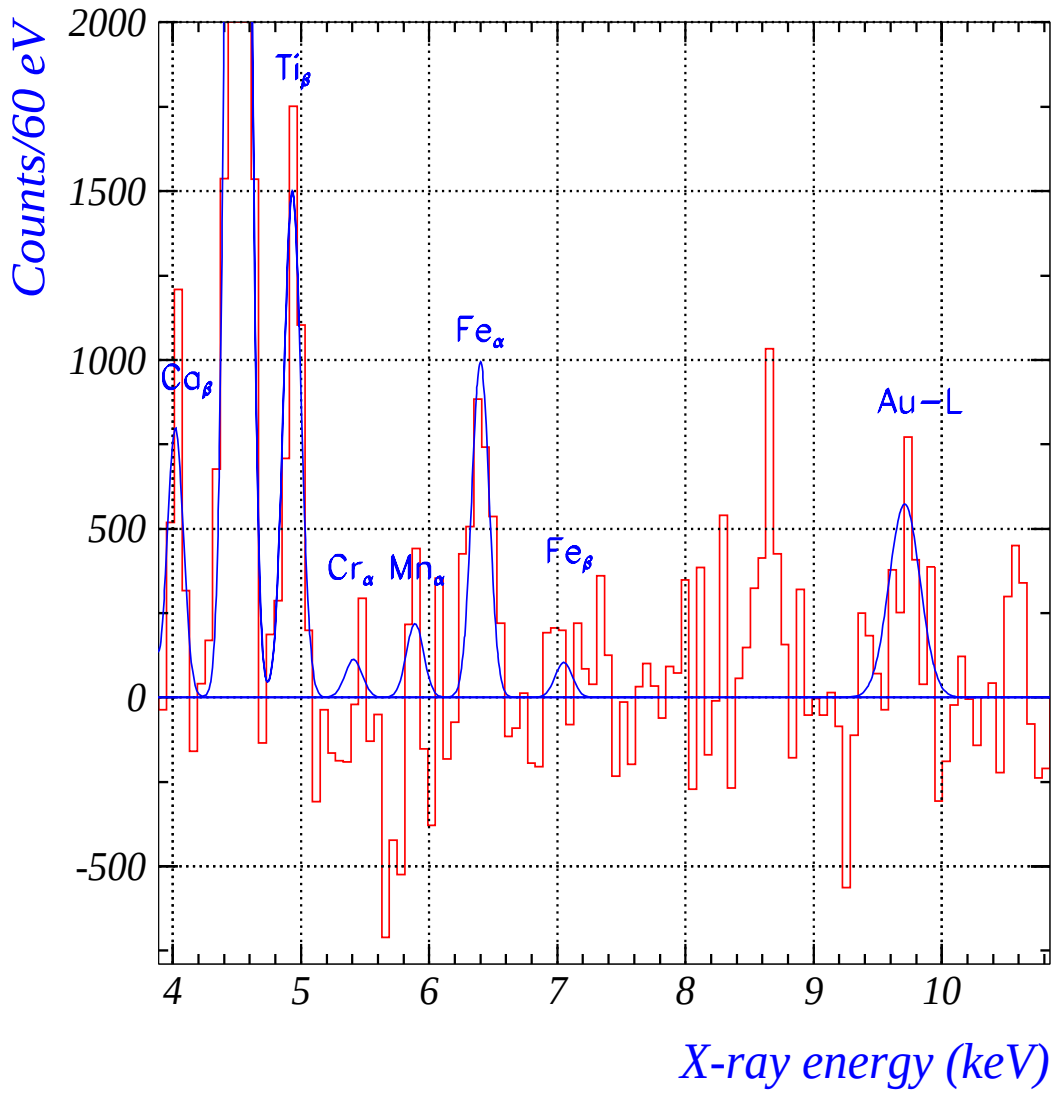

Figure 9: The continuous background subtracted no-collisions spectrum, with the electronic transitions indicated.

2. **Kaonic Carbon, 5.58 keV transition:** 1347 ± 638 **events;**

3. **Kaonic hydrogen K_α:** 5850 ± 1830 **events;**

4. **Kaonic hydrogen K_β:** 5485 ± 2076 **events;**

5. **Kaonic hydrogen K_γ:** 950 ± 3073 **events.**

The position and the pure Lorentzian width found for kaonic hydrogen K_α transition are:

$$Pos = 6.276 \pm 0.043 \ keV \tag{1}$$

$$\Gamma = 282 \pm 115 \ eV \tag{2}$$

out of which one deduces the shift:

$$\epsilon = -(204 \pm 43) \ eV \tag{3}$$

Finally, a Monte Carlo simulation was performed, in which a known kaonic hydrogen pattern was generated (according, for example, to Jensen's yields [1]) and then fitted by excluding the 7.74 - 8.82 keV region,taking into consideration only the first three kaonic hydrogen transitions. This simulation has shown that the systematic errors produced by the method are at the level of the eV for both position and width, the only parameter affected by about by about a 10% systematic error being the number of events of the K_γ transition (which, anyway, remains largely undetermined in the "best fit" solution).

5 Further tests

On the way of arriving to the "best fit" solution, different fit hypotheses were checked. In what follows, the results of these tests are reported.

a) No kaonic hydrogen and kaonic carbon in the kaonic hydrogen spectrum. In this situation the $\chi^2/NDOF = 1.25$, a dramatic worsening which is not acceptable;

b) no kaonic carbon in the kaonic hydrogen spectrum. In this situation the $\chi^2/NDOF$ goes from 1.02 for the "best fit" solution to 1.05, remaining position, width and number of events for kaonic hydrogen compatible (within 1σ) with the "best fit" solution;

c) fit on all energy region, 2.9 - 10.4 keV, under various kaonic hydrogen yields hypothesis (based on Thomas Jensen's and Koike's calculations). The results, with $\chi^2/NDOF$ about the same as for the "best fit" solution, are fluctuating by about 15 eV in position and 40 eV in width with respect to the "best fit" solution (with about the same statistical errors).

d) inclusion of Ni and Cu (when working on all energy region) signals in the fit did not change the $\chi^2/NDOF$, which means that these transitions are not necessary in the fit;

e) slightly changes of the excluded energy region, around the selected value (7.74 - 8.82 keV) give solutions compatible with the "best fit solution".

6 Conclusions

In the present Note the method,the results and the tests for the analysis of kaonic hydrogen data performedat Frascati are presented in detail.

The method relies on a simultaneous fit, from 2.9 to 10.4 keV, of the kaonic hydrogen and no-collisions data, with the same function describing the continuous as well as the structured (electronic transitions) background - apart of a normalization factor. In order to get free of systematic errors due to the uncknowledge of the yields of high kaonic hydrogen transitions, a cut of the energy region from 7.74 to 8.82 keV, was done.

The "best fit", performed with a function with 22 free parameters, gave a $\chi^2/NDOF = 1.02$, and required the presence of three kaonic hydrogen transitions and two kaonic carbon ones.

A 3.2σ evidence for K_α and 2.6σ for K_β transitions were found, while K_γ is marginal. This means a statistical evidence for the kaonic hydrogen measurement of 5.8σ. Concerning the kaonic carbon transitions, a 1σ evidence and a 2.1σ evidence for the 3.36 and 5.58 keV transitions were found.

The shift and width for the K_α line are: $\epsilon = -(204 \pm 43)\ eV$, $\Gamma = 282 \pm 115\ eV$. A study of the systematic error induced by the cut in the energy region showed that this error is negligible.

References

[1] T.S. Jensen, DEAR Technical Note IR-46, 6 March 2003.