LABORATORI NAZIONALI DI FRASCATI
SIS – Pubblicazioni

LNF-02/006 (P)
6 Maggio 2002

A NEW METHOD TO OBTAIN A PRECISE VALUE OF THE MASS OF THE CHARGED KAON

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Abstract

The results of a feasibility study performed by measuring, with a test setup at the collider DAΦNE of Frascati, two previously unobserved transitions of kaonic nitrogen, demonstrated the possibility to make a precision measurement of the mass of the charged kaon.

PACS : 36.10.Gv; 14.40.Aq; 11.10.Q

Key words: Charged kaon mass; Kaonic nitrogen; Klein-Gordon equation

To appear in Phys Lett. B 535 (2002) 52

1 Introduction: the case for a remeasurement of the charged kaon mass

The Particle Data Group [1] assigned a precision to the charged kaon mass which is one order of prmagnitude worse with respect to that on the charged pion mass:

$$M_{K^{\pm}} = 493.677 \pm 0.013 \; MeV, \tag{1}$$

the error representing an uncertainty of 26 p.p.m. This is to be compared to 2.5 p.p.m. for the charged pion mass. Further, the value in eq. (1) is obtained by making a weighted average of six charged kaon measurements characterized, respectively, by the following errors: 7 keV [2]; 11 keV [3]; 54 keV [4]; 29 keV [5]; 20 keV [6]; 40 keV [7]. Their weighted average is 5 keV (10 p.p.m.), but a huge scale factor (S = 2.4) was introduced on the error, to take into account a serious disagreement between the most recent and more precise results of Denisov [2] and Gall [3], which differ by 60 keV and whose average, weighted by their small variances, dominate the overall average. Both experiments were carried out by measuring x-ray energies from kaonic atoms using solid targets. Experiment [2] used a carbon target and a crystal spectrometer, whereas experiment [3] used germanium detector spectra from lead and tungsten targets. The use of a crystal spectrometer significantly improves the energy resolution and the light nucleus reduces the probability for overlap by contaminant γ rays. Thus experiment [2] uses a more favorable setup, but there is no obvious reason (see discussion in [1]) to discard the other data.

The Particle Data Group retained eventually the Gall data [3] in the overall average and accepted the resultant large scale factor on the error of the charged kaon mass, "until further information can be obtained from new measurements...".

This uncertainty on the kaon mass has severe implications on the determination of the K^- p (and K^- d) scattering lengths from the measurement at the few percent level of the K_α strong interaction line shift of kaonic hydrogen (and kaonic deuterium). The shift is, in fact, proportional to the scattering length through a simple relation (the Deser formula [8]), known to hold quite accurately since corrections are smaller than 1%. Therefore the uncertainty on the shift is directly reflected in that of the scattering length.

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One measures the energy shift of the K_α peak from the position calculated on the basis of a purely electromagnetic interaction, obtained by solving the corresponding Klein-Gordon equation and applying corrections for finite size and QED effects. The calculated transition energy so obtained has an error of $\simeq$ 1 eV, dominated by the uncertainty in the kaon mass. This 1 eV error contributes directly to the uncertainty in the shift. Since the strong interaction shift is of the order of few hundreds eV [9], a percent-level measurement requires a global error (statistic + systematic) of the order of a few eV. Therefore, the uncertainty in the kaon mass has a serious impact on the precision of the determination of the isospin dependent K^-N scattering lengths.

K^-N scattering lengths with a few-percent precision would indeed represent a breakthrough in the field of low-energy antikaon-nucleon phenomenology, where little significant progress has been made for nearly a quarter of century. Moreover, they will significantly improve the determination of a crucial quantity of non-perturbative QCD, the kaon - nucleon sigma terms, which describe the degree of chiral symmetry breaking [10].

In summary, a precise determination of the charged kaon mass is badly needed, but only a new measurement can settle the disagreement between the present input data. It is sufficient, in principle, that the new measurement has the same $\simeq$ 10 keV precision as the two which are responsible for the large scale factor caused by a 60 keV difference. If the new result turns out compatible with the data of ref. [2] - and, consequently, the data of ref. [3] are disregarded from the overall average - the precision on the mass, including the weighted new measurement, would turn out 5 keV (10 p.p.m.). If, instead, the data of ref. [3] are those reliable, the precision would be 7 keV (14 p.p.m.). In both cases, the net result would be a substantial improvement in the precision of the charged kaon mass.

The purpose of this letter is to indicate a new methodology to make a precision measurement of the charged kaon mass. It is shown that a measurement of the kaon mass to 10 keV precision can be performed on the Frascati collider DAΦNE by the DEAR (DAΦNE Exotic Atom Research) collaboration [11] with a layout based on the results of a feasibility study performed by DEAR with a test setup and on an experimental approach similar to that adopted at PSI for a precision measurement of the charged pion mass [12]. By using a gaseous light Z (nitrogen) target and CCDs as detectors, the DEAR experiment has measured two previously unobserved transitions of kaonic nitrogen [13], thus demonstrating the feasibility of creating and identifying kaonic atoms formed by the very low-energy "kaon beam" from decay of the ϕ 's produced by DAΦNE. The measurement allowed to make an exploratory test to evaluate the charged kaon mass. The results of this study, based on a small data sample, are reported in Section 2 of the paper. Sections 3 contains the description of the proposed new experimental layout and Section 4 shows the

substantial increase in the signal / background ratio, with respect to the test measurement, obtainable with the new configuration. An evaluation of the integrated luminosity necessary to get the required precision is as well given. The conclusions are that the new proposed method can reduce the charged kaon mass discrepancy by yielding a new, high precision mass value.

2 Kaonic nitrogen measurement with DEAR at DAΦNE as an exploratory test

The data were taken during five days in May - June 2001 on the DEAR interaction region at DAΦNE, with an integrated luminosity of 1 pb^{-1} [13]. A cooled gaseous nitrogen target, into which the negative kaons enter by passing through a thin beam pipe, was viewed by Charge-Coupled Device (CCD) x-ray detectors. CCDs with pixel size of 20 ÷ 40 μm x 20÷40 μm and a depletion depth of 30÷ 40 μm are excellent photon detectors in the energy region between 1 and 15 keV [14]. The essential features are that a photon of, for example, 3 keV deposits its energy in a single pixel in 90% of the cases. Since most background events, which outnumber the true x-ray events by 3 to 4 orders of magnitude, as measured by DEAR at DAΦNE [15], are multi-pixel (cluster) events, the single pixel condition reduces the background efficiently.

The cryogenic setup to measure kaonic nitrogen is described in [16]. Figure 1 shows a sketch of the setup installed at DAΦNE. Target pressure was 1.52 bar at 118 K, corresponding to about 4 bar at NTP. The 6 CCD-22 detectors (Marconi), each with 600 x 600 pixels, had a pixel size of 40 x 40 μm^2 and a depletion depth of 40 μm. The measurement was the first stage of the scientific programme of DEAR [17], the final goal being the measurement to the percent-level of the K_α line shifts in kaonic hydrogen and kaonic deuterium. This stage represented a feasibility study to show the capability of the DEAR setup and of the CCD detectors to create and detect exotic atoms on a high-current, low-energy collider. The negative kaons come from the interaction point as decay products from the ϕ-resonance excited by electron-positron collisions in one of the two interaction regions. The aim of the study was to demonstrate the production of kaonic atoms, by identifying kaonic x-ray transitions with high yields.

Figure 2 presents the kaonic nitrogen x-ray energy spectrum after the continuous background has been subtracted. For calibration of the spectrum, the electronic aluminum K_α line at 1.49 keV and the corresponding zirconium line at 15.7 keV were taken. Energy resolution in the region between 4 and 8 keV was about 340 eV FWHM. In addition to all electronic lines, two kaonic nitrogen transitions are visible, at 4.6 keV (7→6) and 7.6 keV (6→5). Each peak contains approximately 800 events, corresponding to transition yields of

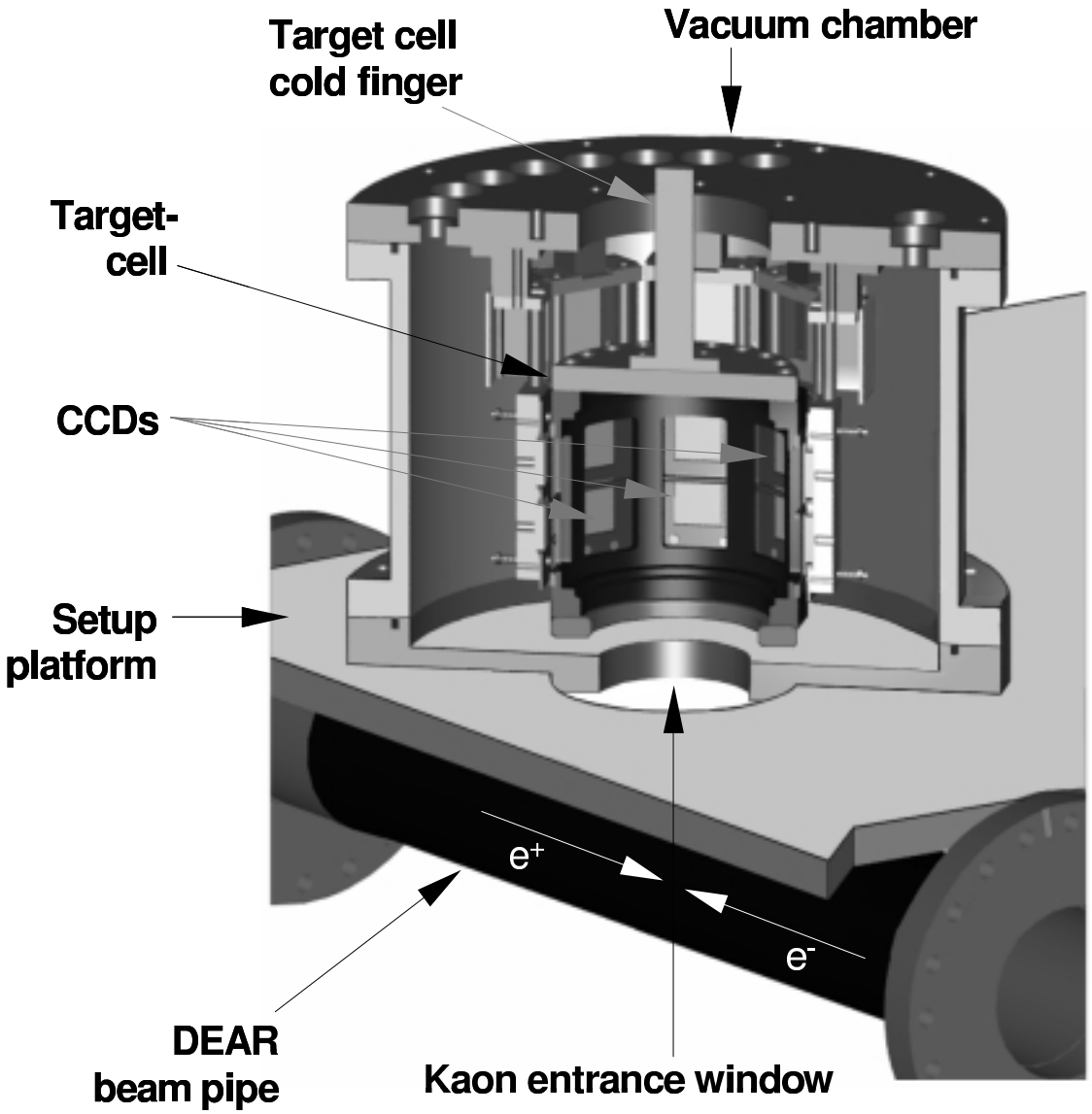

Fig. 1. Sketch of the experimental setup used for the test measurement of kaonic nitrogen.

the order of 90%. Kaonic transitions at lower energies could not be seen due to absorption in the window material between the nitrogen target and the CCDs. The kaonic nitrogen (5→4) peak near 14 keV is at the position of the zirconium escape peak.

If, in the fit of the spectrum, the position of the two kaonic nitrogen lines is left free, the results for the transition energies are:

(6→5) kaonic nitrogen transition: 7560 ± 32 eV
(7→6) kaonic nitrogen transition: 4589 ± 37 eV.

An exploratory evaluation of the charged kaon mass can be obtained from

a calculation using the first term in the Klein-Gordon equation, where the reduced mass is obtained using M(^{14}N) = 13040.34 MeV. The results are:

(6→5) transition: $M_{K^-} = 492.086 \pm 2.409$ MeV
(7→6) transition:$M_{K^-} = 495.418 \pm 3.455$ MeV.

These two results are statistically compatible and can be averaged. The weighted average is: $M_{K^-} = 493.176 \pm 1.976$ MeV.

3 Proposed experimental setup for a precision measurement of the charged kaon mass

On the basis of the results of the test measurement performed with DEAR at DAΦNE, a new setup is proposed, to make a precision measurement of the charged kaon mass. The basic experimental layout is shown in figure 3. A gaseous low Z target, that can be cooled, such as nitrogen, as in the test setup, should be used. In fact, the determination of meson masses from the x-ray energies of mesonic atoms requires the measurement of transitions which must not be affected by the strong interaction. The levels involved are therefore of lower binding energies and are influenced by the interaction with the electrons. The status of the electron shells is difficult to assess: the first steps of the atomic cascade proceed via Auger emission which, together with the electron recombination, results in an unknown degree of ionization. A complete ionization has been demonstrated only in a low Z gaseous target, such as nitrogen or oxygen [18], being not straightforward the evaluation of the electron screening in solid state targets.

A reasonably sized target cell of about 2 dm^3 volume (cylinder 14 cm height, 7 cm radius) could be assumed. In the cryogenic target of the test setup used to measure kaonic nitrogen, in a volume of 1.3 dm^3 (octagonal cell, 14 cm height, 5.5 cm side length), 122 mm far from the interaction point (IP) - due to necessity of shielding -, the fraction of stopped kaons turned out about 2%, at the optimized pressure equivalent to about 4 bar at NTP [13]. In order to increase this fraction in the new setup, the more direct way is to increase the solid angle seen by the IP, by reducing the distance from the IP, and by enlarging the volume. The stopping efficiency can also be improved by the eventual use of a magnetic trap [19], with a specific design for DAΦNE, which takes advantage of the small momentum band (δp/p $\simeq 10^{-3}$) of the emitted kaons. By combining all the above improvements, it should be possible to achieve a stopping efficiency above 30%.

A crystal spectrometer, consisting of a two-arm fixed, curved, graphite crystals assembly, coupled with CCD detectors arrays used as position sensitive x-

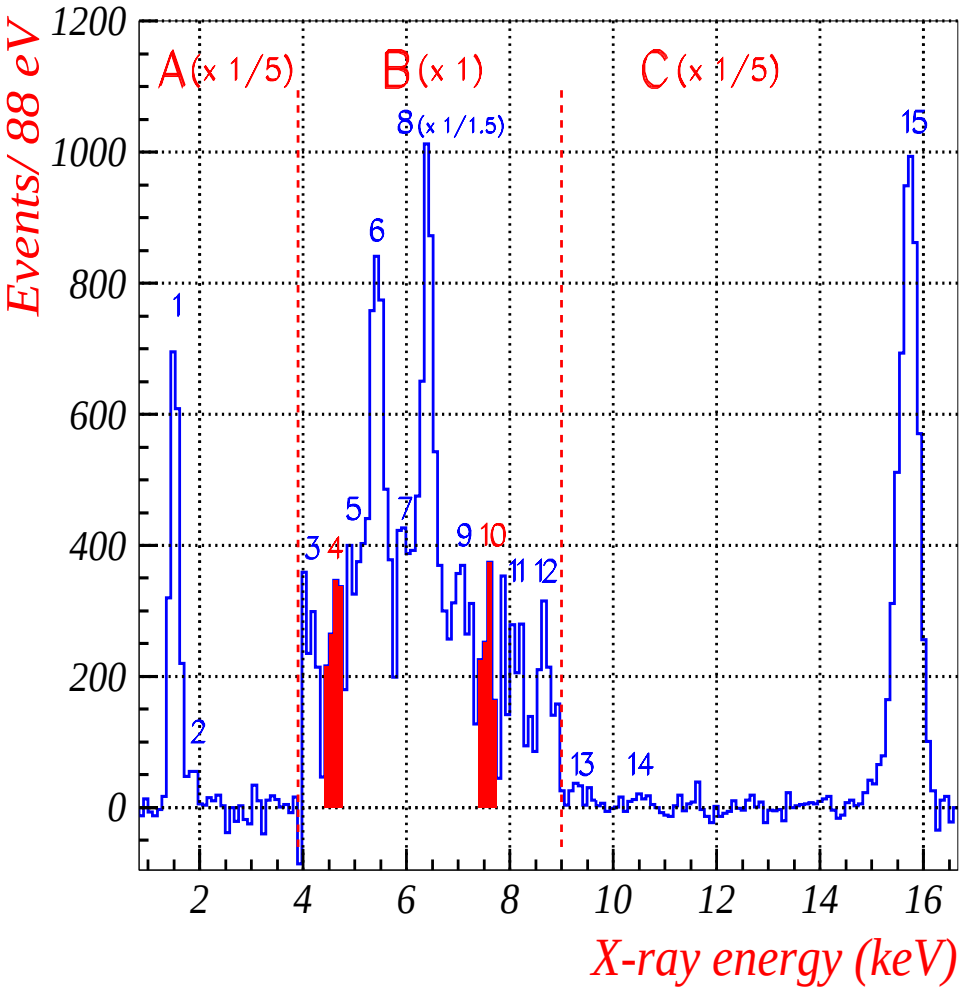

Fig. 2. Kaonic Nitrogen x-ray energy spectrum after continuous background subtraction. The peaks are: 1. Al K_α X rays at 1.49 keV, from the target frame. This peak is used for CCD energy calibration; 2. Si K_α X rays at 1.74 keV, from the CCDs; 3. Sc K_α X rays at 4.09 keV, from the CCD ceramics; 4. Kaonic nitrogen ($7 \rightarrow 6$) transition at 4.6 keV; 5. V K_α X rays at 4.95 keV (stainless steel); 6. Cr K_α X rays at 5.41 keV (stainless steel); 7. Mn K_α and Cr K_β X rays at 5.89 and 5.95 keV (aluminum and stainless steel); 8. Fe K_α and Mn K_β X rays at 6.40 and 6.49 keV (stainless steel and aluminum); 9. Fe K_β X rays at 7.06 keV (stainless steel); 10. Kaonic nitrogen ($6 \rightarrow 5$) transition at 7.6 keV; 11. Cu K_α X rays at 8.04 keV (target cooling system); 12. Zn K_α X rays at 8.63 keV (stainless steel); 13. Pb L-complex and Zn K_β X rays around 9.4 and 9.57 keV (shielding and stainless steel); 14. Pb L-complex X rays at 10.5 keV (shielding); 15. Zr K_α X rays at 15.7 keV (degrader). This line is also used for CCD energy calibration.

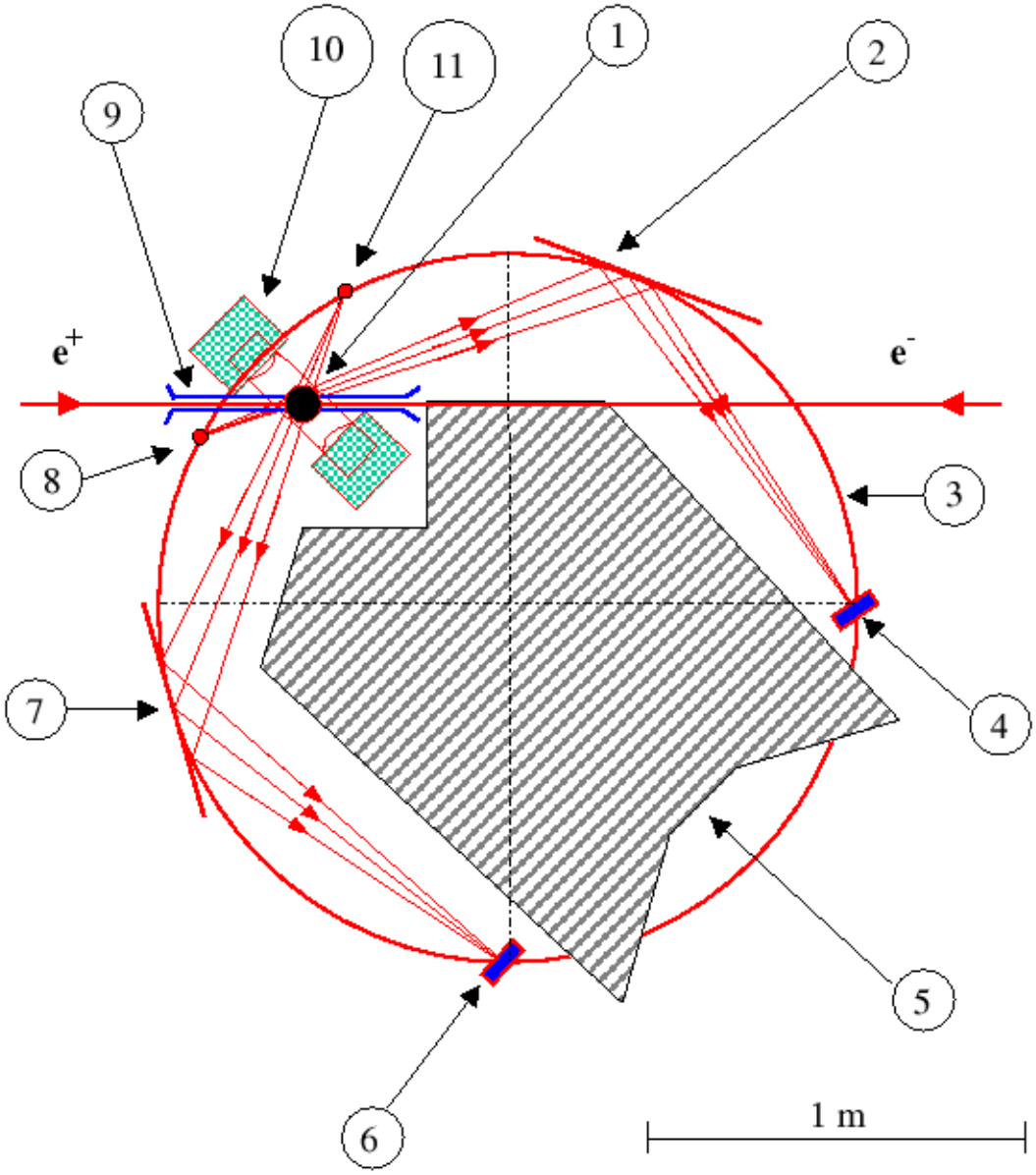

Fig. 3. Proposed experimental setup. 1: Interaction point, nitrogen target; 2,7: Crystals; 3: Focal circle; 4,6: CCD detectors; 5: Shielding; 8,11: X-ray calibration sources; 9: Beam pipe; 10: Magnetic Trap.

ray detectors, is proposed. This reflection-type crystal spectrometer is chosen because the higher transitions in a low Z target give low-energy x-rays in the region between 1 keV and 15 keV. To make up for the important loss of count rate, the solid angle must be optimized and a highly reflecting crystal used, if

possible of large size. In general the target, crystal and detector are located on a circle, called Rowland circle. An improved design of a graphite spectrometer [20], which reduces the possible systematic errors coming from the calibration procedure, is proposed. A two-arm symmetric curved crystals assembly of 20 x 10 cm^2 with a Rowland circle radius of 95 cm on the CCD detectors side will be used. However, the extended target can be moved 20 cm towards the center along a radius of the focal circle, placing it closer to the crystal. Different target slices of monoenergetic x-rays are focused into the same CCD position. The lattice spacing associated with the (002) reflecting plane is 3.355 Å. If, for example, the kaonic nitrogen (8→7) transition at 2.96 keV, with a Bragg angle of 38.2^0, was chosen to be measured, the manganese K_α calibration line at 5.9 keV could, in second order, be projected into the same CCD assembly. Therefore data taking and calibration can be carried out without moving the crystal or the CCD detectors, thus reducing systematic errors. The choice of graphite is dictated by its very high reflectivity in the low-energy x-ray range, compared to other crystals with similar lattice spacings [21]. The reflectivity amounts to 4% at 3 keV and the overall efficiency of each arm of the graphite spectrometer (including CCD efficiency) at this energy is about 5.4 x 10^{-5}, which is about 400 times lower than the efficiency of the test setup [13].

With a layout similar to that here proposed, the PSI experiment to measuring the mass of the charged pion [12] yielded a precision of 3.8 p.p.m., which should turn out to 1 p.p.m. with more statistics and further improvement of the setup.

4 Feasibility of a precision measurement of the charged kaon mass with the proposed layout

As shown in the previous section, the overall efficiency of the new setup, based on a crystal spectrometer, is about 400 times less in count rate when compared with the exploratory measurement performed with the test setup. However, a dramatic reduction of background can be obtained in the new configuration. This, together with the increase of the fraction of kaons that stops in the target allows a substantial increase in the signal/background ratio. The required precision may be reached by collecting reasonable statistics and taking advantage of the better spectrometer resolution (one order of magnitude better than the test setup).

Background is decreased by more than two orders of magnitude due to the reduction of the solid angle at which CCDs are seen from the interaction point (the distance in the new setup is more than 10 times that in the test setup). Moreover, a further background reduction (factor 2÷4) can be obtained with the improved shielding configuration which can be realized in front of the

CCDs, covering a relevant fraction of the focal plane, as shown in fig. 3. Finally, background can be decreased of another order of magnitude through cuts in the CCDs energy spectrum applied to the CCDs position spectrum. In fact, the improved energy resolution due to the use of a crystal spectrometer in front of the CCDs, allows an additional cut in the CCDs energy spectrum around the line to be measured.

As far as signal is concerned, since the shielding below the target can be reduced with respect to the test setup because the CCDs are farther from the interaction point, the target itself can be moved closer to the IP, few mm from the beam pipe: together with the enlarged volume, this gives an increase of solid angle by a factor more than 12. A specially designed magnetic trap around the target should allow another gain of a factor of about 1.5. In summary, one should gain a factor of about 20 in signal for each spectrometer arm, taking advantage of the increased fraction of stopped negative kaons.

In conclusion, it is possible to achieve an increase of a factor of about 100 in the signal/background ratio over that measured in the test setup (1:30). By assuming a signal/background ratio 3:1 and an energy resolution of the graphite crystal spectrometer of 25 eV [20], a precision at the level of 10 keV on the kaon mass can be achieved by collecting 20000 events. Since the lines in the test measurement contain approximately 800 events each, collected with 1 pb^{-1} of integrated luminosity, the new counting rate of about 40/400 with respect to the test measurement requires 250 pb^{-1} of integrated luminosity to determine the charged kaon mass to 10 keV precision using the proposed two-arm setup.

Acknowledgement

The DEAR collaboration wishes to thank Gianni Corradi for his major contribution to the CCD electronics and Sergio Bertolucci and the DAΦNE machine crew for their friendly cooperation. This research was partially supported by the Swiss National Science Foundation and partially supported by European Community - Access to Research Infrastructure, contract number HPRI - CT 1999 - 00088.

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