Precision spectroscopy of kaonic helium-4 X-rays

The KEK E570 Collaboration

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Abstract. The Balmer-series X-rays of kaonic helium-4 have been re-measured with a projected goal of determining the $2p$-level strong-interaction shift to a precision better than a few electron volts. Preliminary results indicate that the shift must be much smaller than the current world average of -43 ± 8 eV.

PACS. 13.75.Jz Kaon-baryon interactions – 21.30.Fe Forces in hadronic systems and effective interactions – 25.80.Nv Kaon-induced reactions – 36.10.Gv Mesonic atoms and molecules, hyperonic atoms and molecules

1 Introduction

In this talk, I will present preliminary results of our recent efforts (E570 collaboration at KEK) to measure the K^{-4}He Balmer-series X-rays, so as to determine the $2p$-level strong-interaction shift to a precision better than a few electron volts.

As is well known to this audience, there have already been three measurements of kaonic-helium X-rays. Fig. 1 compares the X-ray spectra observed by the three past experiments; the Balmer-series X-rays were clearly observed in all three, and the reported $2p$-level strong-interaction shifts[1], $\Delta E_{2p} = E_X^{\text{exp}} - E_X^{\text{EM}}$,

-41 ± 33 eV (Wiegand *et al.*) [1],
-35 ± 12 eV (Batty *et al.*) [2],
-50 ± 12 eV (Baird *et al.*) [3],

agree with each other within errors, resulting in a world average of -43 ± 8 eV [4] (see Fig. 2(a)). It thus appears that the matter is already well settled as far as the experimental situation is concerned.

However, it has long been known that these experimental results disagree sharply with optical-model calculations obtained from a fit to available data for nuclei with $Z > 2$, which give $\Delta E_{2p} \approx 0$ eV [4], more than 5 standard deviations away from the world average value.

This "kaonic helium puzzle" has recently attracted a renewed interest in connection with the Akaishi-Yamazaki (AY) prediction of deeply-bound $\bar{K}$-nuclear states [5, 6]. Treating $\Lambda(1405)$ as a $\bar{K} - N$ bound state, the AY model predicts unconventionally deep $\bar{K}$-nucleus potentials, which accommodate the deeply-bound $\bar{K}$-nucleus states. Fig. 2(b) shows the kaonic-^{4}He $2p$ level shift calculated by Akaishi [7]; for the $\bar{K}$-nucleus potential depth compatible with the AY-prediction of the deeply-bound states, indicated by the gray band, the shift can be up to ± 10 eV. Although this is still smaller than the experimental value of -43 eV, such a non-zero shift, if established, provides a positive support for the 'deep' $\bar{K}$-nucleus potential. This situation motivated us to measure the energy of Balmer X-rays of the kaonic-^{4}He atom with much improved precision.

[1] E_X^{exp} and E_X^{EM} respectively are the measured X-ray energy and the energy calculated only with the Coulomb interaction. The negative ΔE_{2p} value of the world average correspond to a *repulsive* $2p$-level shift (less binding).

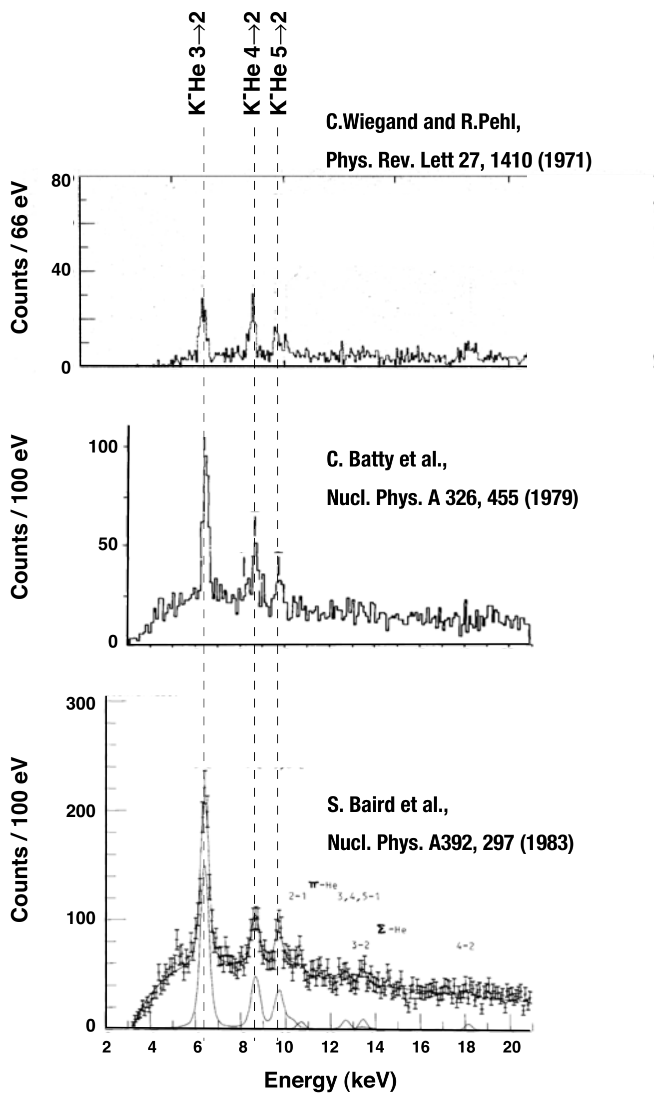

Fig. 1. Kaonic-helium X-ray spectra obtained by the three past experiments are compared.

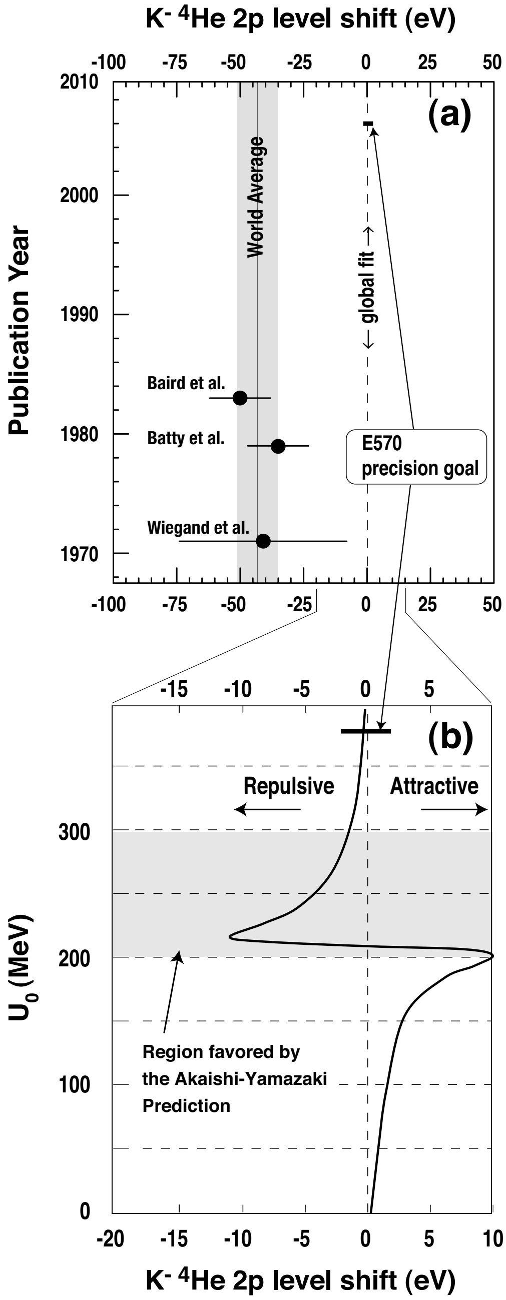

Fig. 2. (a) The kaonic-helium $2p$ level shift deduced from past experiments, indicated by the vertical gray band, is -43 ± 8 eV (repulsive), which is more than 5 standard deviations away from predictions using global fits to existing kaonic-atom X-ray data on various nuclei. The precision goal of E570 is a few eV. (b) The kaonic-helium $2p$ level shift calculated by Akaishi [7]. The region favored by the Akaishi-Yamazaki prediction of deeply-bound $\bar{K}$-nucleus bound states is indicated by the horizontal gray band, where the $2p$ shift can be up to ±10 eV.

2 Experiment

The E570 experiment was carried out at the K5 beamline of the KEK 12-GeV proton synchrotron, in conjunction with the search for deeply-bound $\bar{K}$-nuclear states in ^{4}He$\,$(*stopped* K^-, N) reactions (E549) [8,9]. The data were taken in two parts, the first in October 2005 and the second in December 2005.

The E570 setup was essentially the same as that for E549, except for the inclusion of X-ray detectors in the helium-target cryostat. A schematic drawing of the central part of the E570 setup is shown in Fig. 3.

Negatively-charged kaons were identified by a Lucite Čerenkov counter, degraded in a carbon degrader, counted with beam-line counters, tracked by high-rate drift chambers (these elements are not shown in the figure), and were brought to rest in a superfluid helium target. At the position of the beam-line counters, the K^--to-π^- ratio was about 1/200. Eight X-ray detectors (SDDs, to be described below) viewed the target from downstream through a 75-μm-thick Mylar window of the target vessel. Charged particles produced in kaon absorption events were detected by a pair of charged-particle trigger/tracking systems (not shown in the figure) placed above and below the target cryostat.

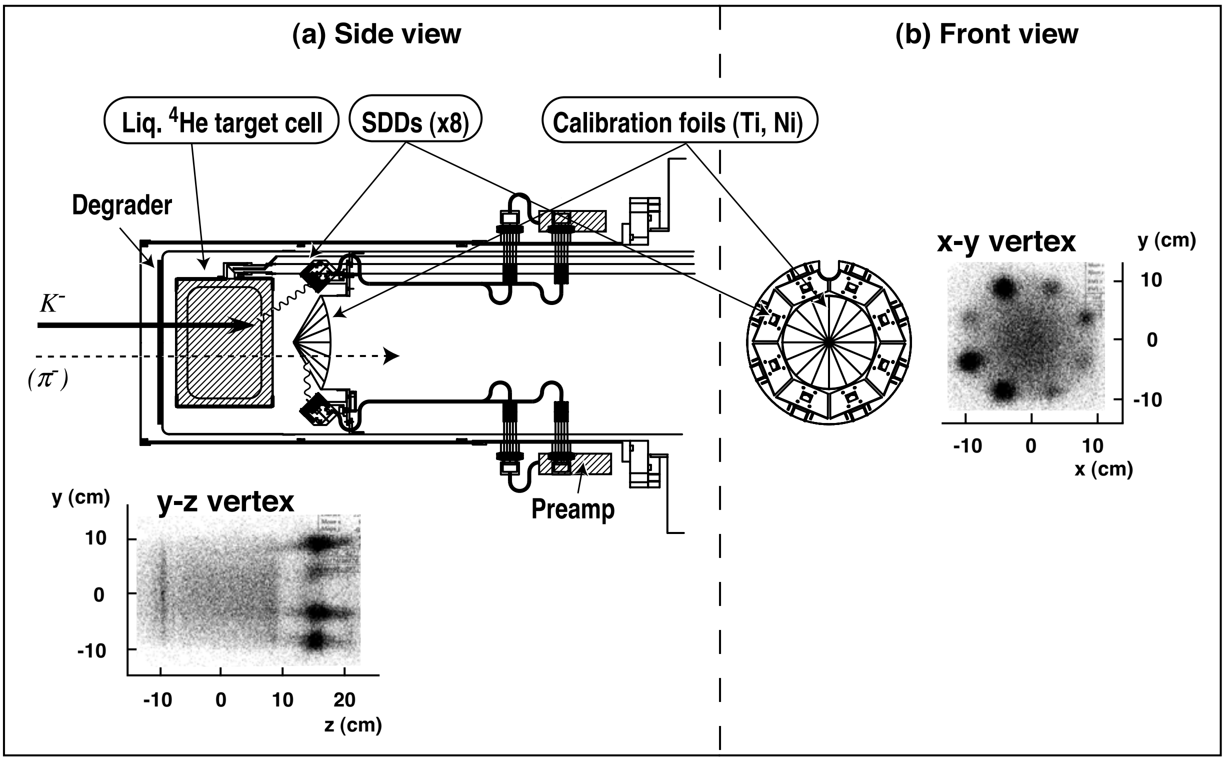

Fig. 3. (a) A schematic side view of the central part of the E570 setup. (b) A front view of the silicon drift detector (SDD) assembly. Eight detectors are mounted on an annular holder, and high-purity titanium and nickel foils are conically mounted on the beam axis. The $y-z$ and $x-y$ projections of the vertex points reconstructed from the incoming kaon track and an outgoing charged-particle track, are also shown.

This setup, significantly more complex than those used in the past experiments (which typically comprised a liquid helium target, counters in front and behind the target, and a single Si(Li) detector which viewed the helium target through a beryllium window), was constructed so as to achieve i) higher resolution, ii) better energy calibration and iii) better signal-to-noise ratio, compared with past experiments, and these goals were fulfilled by employing the following methods.

2.1 Silicon drift detectors (SDDs)

Kaonic X-rays have so far been measured using a single Si(Li) detector of some 300 mm^2 with a FWHM resolution at 6.4 keV (the energy of kaonic $3d \to 2p$) of 250–360 eV. In E570, we instead employed eight silicon drift detectors (SDDs) [10] produced by KETEK GmbH [11], each having an area of 100 mm^2. In the SDD, the electrons produced by an X-ray hit drift radially toward a small anode at the center where they are collected. The small anode size (and hence small capacitance) is essential to realize a good energy resolution of $\sim$ 185 eV FWHM at 6.4 keV, about a factor 2 better than in previous experiments.

2.2 In-beam energy calibration

Behind the helium target, on the beam axis, we placed high-purity titanium and nickel foils as shown in Fig. 3. Negative pions which abundantly existed in the beam penetrated the target, hit the foils, and produced characteristic X-rays at 4.5 keV (Ti) and at 7.5 keV (Ni) (on both sides of the kaonic helium $3d \to 2p$ X-rays at 6.4 keV). The SDD self-trigger events, recorded together with the kaon-trigger events, thus provided highly-accurate in-situ calibration spectra.

2.3 Fiducial volume cut, timing cut and in-flight reaction rejection

The kaonic-hydrogen X-ray spectroscopy (KpX) at KEK [12] successfully demonstrated that the kaonic X-ray spectra can be dramatically cleaned up by measuring charged particles emitted from the K^--stop vertices, in coincidence with the X-rays. In E570, we employed this technique to reduce background, as described below.

2.3.1 Fiducial volume

The kaon-reaction vertex were reconstructed from an incident kaon track and an outgoing charged-particle track. The $z-y$ projection of the vertices reveals (Fig. 3), from left to right, the images of the final carbon degrader, the helium target and the SDDs. The $x-y$ projection reveals the eight SDDs. We required that the vertex position should be within the fiducial volume of the target.

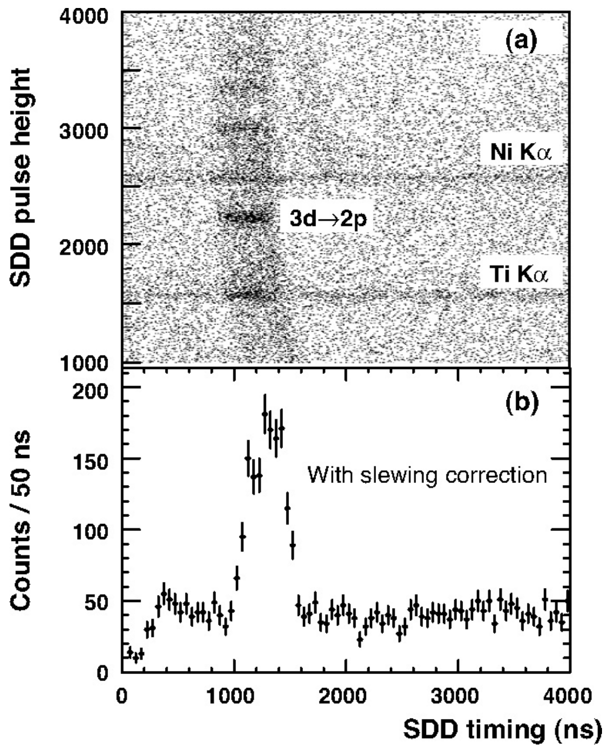

Fig. 4. (a) A typical scatter plot of the kaon-SDD time difference vs SDD pulse height. (b) A typical slewing-corrected kaon-SDD time spectrum.

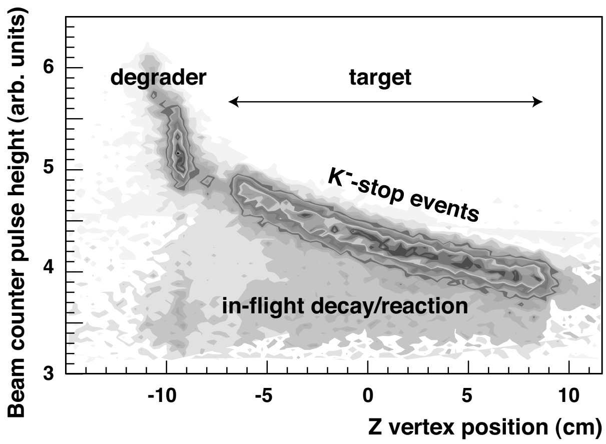

Fig. 5. A typical density plot between the vertex z coordinate and the beam-counter pulse height, used to reject in-flight kaon decays/reactions.

2.3.2 Timing

The top panel of Fig. 4 shows a typical scatter plot of the SDD timing (time difference between kaon arrival and X-ray detection) vs SDD pulse height, which exhibits a vertical band due to kaon-induced X-rays. A dark spot at the center of this band is due to the $3d \rightarrow 2p$ kaonic X-rays. The titanium and nickel characteristic X-rays appear as thin horizontal bands, due to accidental pion hits on the metallic foils.

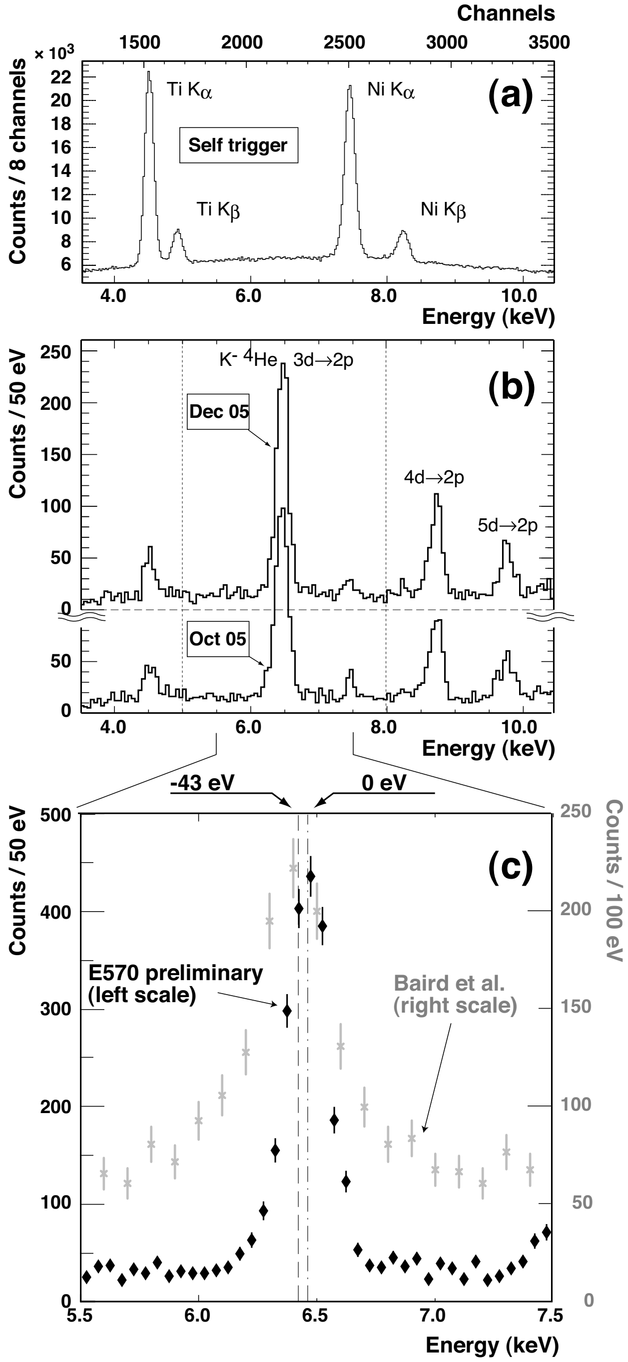

Fig. 6. (a) A typical SDD self-trigger spectrum, which provides high-statistics energy-calibration information. (b) Preliminary X-ray spectra obtained by the present work. The lower histogram is from the run in October '05, and the upper one is from the run in December '05. (c) The kaonic-helium $3d \rightarrow 2p$ peak observed in the present work (full statistics, use the left scale) is compared with the spectrum obtained by Baird *et al.* [3] (shown in gray, use the right scale).

The bottom panel of Fig. 4 shows a slewing-corrected time spectrum corresponding to Fig. 4(a), which clearly shows the kaon-induced X-ray events. The width of the peak, about 430 ns FWHM, reflects the drift-time distribution of the electrons in the SDD.

2.3.3 Rejecting in-flight reactions

Even with the fiducial-volume cut and timing cut, there are still some background events due to in-flight kaon reactions. Fig. 5 shows a correlation between the $z-$coordinate of the vertex and the beam-counter pulse height. Slower incident kaons (hence larger pulse height) stop in the upstream of the target while faster kaons (smaller pulse height) stop further down stream. While a majority of events follow this trend, there are kaons which prematurely reacted in the target. We rejected those events, which further enhanced the signal-to-noise ratio.

3 Results

Fig. 6(a) shows a typical SDD self-trigger spectrum. Characteristic X-ray peaks of titanium and nickel were observed with high statistics. Such data were recorded simultaneously with the kaon-induced data, and were used to monitor and correct for the time-dependent gain drift, and also to obtain the energy calibration curve for each SDD.

Fig. 6(b) shows preliminary energy-calibrated K^{-4}He X-ray spectra, obtained by applying the event selection criteria described in the previous section. Here, the Ti and Ni X-ray peaks are much suppressed, and kaonic-helium $3d \rightarrow 2p$, $4d \rightarrow 2p$ and $5d \rightarrow 2p$ transitions are clearly observed. The lower histogram is from the run in October 2005 and the upper one is from the run in December 2005. In the October run, only 3 out of 8 SDDs yielded useful data. The faulty detectors were replaced, and 7 SDDs were functional in the December run. Therefore, these two histograms can be regarded as resulting from two independent measurements. As shown, the two spectra agree quite well.

The two spectra were then added and the region around the $3d \rightarrow 2p$ peak is expanded in Fig. 6(c) (use the left scale). The spectrum taken by Baird *et al.* [3] is overlaid in gray (use the right scale). Comparison of the two spectra demonstrates that E570 has indeed achieved better resolution, better signal-to-noise ratio, and higher statistics as compared with the past experiments.

The "Coulomb" value for the $3d \rightarrow 2p$ X-ray energy (6463 eV [13]) is indicated by the dash-dot vertical line in Fig. 6(c), and the -43 eV-shift by the dashed vertical line. The kaonic-helium peak observed by Baird *et al.* is indeed centered around the -43-eV line, while the E570 peak center is close to the "Coulomb" line.

The statistical accuracy of E570 is estimated to be $\sim$ 2eV, and a preliminary estimate of the energy-calibration systematic error is also of the same order.

A larger source of systematic error may be the low-energy tail visible in all the kaonic-helium X-ray peaks. These tails are not due to the SDD resolution function, since the calibration lines are free from such tails. GEANT simulations have established that the tails are due to the Compton scattering of X-rays in helium. The effect of this Compton process on the $2p$-shift value and on its systematic error is currently being studied using Monte Carlo simulations.

Although we are still working to obtain the final value for the $2p$-level strong-interaction shift, preliminary fits to the spectrum shown in Fig. 6(c) indicate that the shift is definitely much smaller than 40 eV, and is very likely to be less than ± 10 eV.

References

1. C.E. Wiegand and R.H. Pehl, Phys. Rev. Lett **27**, 1410 (1971)
2. C.J. Batty *et al.*, Nucl. Phys. A **326**, 455 (1979).
3. S. Baird *et al.*, Nucl. Phys. A **392**, 297 (1983).
4. C.J. Batty, Nucl. Phys. A **508**, 89c (1990).
5. Y. Akaishi and T. Yamazaki, Phys. Rev. C **65**, 044005 (2002).
6. Y. Akaishi, in these proceedings.
7. Y. Akaishi, Proceedings of EXA05, A. Hirtl, J. Marton, E. Widmann and J. Zmeskal eds., Austrian Academy of Sciences Press, Vienna 2005.
8. M. Iwasaki *et al.*, in these proceedings.
9. H. Yim *et al.*, in these proceedings.
10. E.Gatti and P.Rehak, Nucl.Instr. and Meth. A **225**, 608 (1984).
11. `http://www.ketek.net/`
12. M. Iwasaki *et al.*, Phys. Rev. Lett. **78**, 3067 (1997); T. M. Ito *et al.*, Phys. Rev. C **58**, 2366 (1998).
13. J. P. Santos, F. Parente, S. Boucard, P. Indelicato, J. P. Desclaux, Phys. Rev. A **71** 032501 (2005).