PROCEEDINGS OF SCIENCE

HAPG mosaic crystal Von Hamos spectrometer for high precision kaonic atoms spectroscopy

A. Scordo,[a,*] **C. Curceanu,**[a] **V. Di Leo,**[b] **M. Miliucci**[a] **and F. Sirghi**[a]

[a] *Laboratori Nazionali di Frascati INFN, Via E. Fermi 54, 00144 Frascati, Rome, Italy*

[b] *Università degli Studi di Roma "La Sapienza", Sezione INFN Roma 1, P.le Aldo Moro 2, 00185 Rome, Italy*

E-mail: alessandro.scordo@lnf.infn.it

Von Hamos (VH) spectrometers are widely used in several fields, ranging from pure physics applications to very different types of practical ones. However, these type of Bragg spectrometers are usally implied in high rate - high resolution experiments, where the typical source size can be as low as few tens of microns. These limitations prevented them to be used as X-ray detectors for high precision exotic atoms spectroscopy, except for cases where extremly high flux beams could be employed, like in the case of pionic atoms at PSI. Recently, we developed a VH spectrometer, within the VOXES collaboration at the INFN Laboratories of Frascati, making use of Highly Annealed Pyrolitic Graphite (HAPG) mosaic crystals and a X-ray beam optics optimization, which could be used for source sizes up to few mm, (in the Bragg plane), some tens of mm in the sagittal plane and, if gaseous sources are used, of several tens of cm in the X-ray propagation direction. Such kind of a spectrometer could be used, for example, to open a new era in the field of exotic (kaonic) atoms precision measurements, delivering data with unprecedented precision to the (strangeness) nuclear physics community. In this paper we present, together with an overall description of the VOXES spectrometer and of its main characteristics in terms of resolution and efficiencies, a comparison between a kaonic helium $3d \rightarrow 2p$ transition spectrum measured with Silicon Drift Detectors and ray tracing simulated spectra of how the same transition would appear if measured with our apparatus.

**** Particles and Nuclei International Conference - PANIC2021 ****
**** 5 - 10 September, 2021 ****
**** Online ****

*Speaker

PoS(PANIC2021)195

1. Introduction

Kaonic atoms represent a unique tool for a deeper understanding of the key mechanisms ruling the low energy strangeness QCD, allowing to investigate the antikaon-nucleon interaction at threshold [1]. In spite of a considerable amount of experimental data delivered since their discovery, a comprehensive understanding of these mechanisms could not have been yet achieved due to missing fundamental experimental measurements, requiring sub-eV precisions, of X-ray transitions emitted from macroscopic targets. A particularly significant test in this direction would be the measurement of the relative difference in the $3d \rightarrow 2p$ transition shifts between K^3He and K^4He (known as the isotopic shift problem); a determination of such a quantity with a sub-eV precision would be a crucial improvement towards the understanding of the theoretical models describing kaon-nucleon interactions below threshold [1].
From the experimental point of view, the most precise $K^{3,4}He$ $3d \rightarrow 2p$ transitions measurements up to now have been performed by the E570 experiment at KEK [2], in a liquid target, and by the SIDDHARTA experiment at LNF-INFN in gaseous one [3, 4]; however, the precision of the theoretical calculations is one tenth of an eV, while the experimental accuracies are an order of magnitude worse.
The most established technique to perform sub-eV precision X-ray measurement is represented by crystal spectroscopy, where the Bragg reflection rule is used to obtain energy spectra in which the resolution is limited, by the intrinsic parameters of the crystals and by the resolution of the position detector, to few eV. However, some critical aspects of this technique prevents it to be used for kaonic atoms measurements untill now: at first, Bragg spectroscopy requires photons sources with typical dimensions of few hundreds of microns (microscopic), in order to univocally determine the direction of the impinging angle; second, the typical lattice constants of standard crystals (Silica, Quartz, Mica) are in the order of 5, 5Å, leading to incidence angles below 10° for energies below 6 keV. The first issue is directly affecting the efficiency of this technique: in fact, only a very small portion of the photons emitted from macroscopic sources can be exploited in order to match the required microscopic dimensions, resulting in a very small geometrical acceptance. The second issue is, instead, related to the huge electromagnetic and hadronic background present in the accelerators where kaonic atoms experiments take place; since the reflection angle is the same as the incidence one, Bragg angles as small as 10° or less, which correspond to energies above 6 keV, would need experimental setups where the position detector almost directly faces the primary photon source, where usually they are produced together with a high flux of particles resulting in a huge background. For all these reasons, Bragg spectroscopy has been used, until now, for exotic atoms measurements, only in very few experiments [5], where very high rates and/or solid targets were used, like the one performed to measure the pion mass [6].

2. The VOXES spectrometer

In the last years, in the framework of the VOXES project at INFN-LNF, we developed a Highly Annealed Pyrolitic Graphite (HAPG) mosaic crystal based Von Hamos spectrometer, which proved to be capable to measure transitions, in the range 5-20 keV thanks to a lattice space constant $d = 3,356$Å, with resolutions typical of Bragg spectrometer but using effective sources of millimetric

PoS(PANIC2021)195

dimensions. These results have been obtained thanks to a particular geometrical shaping of the X-ray beam, obtained with a pair of adjustable motorized micrometric slits used to define its effective source size (S'_0), an angular divergence ($\Delta\theta'$) and to create a virtual point-like source between the two. A sketch of the VOXES setup and its main components, as well as a sketch of the geometry above described, are represented in the sketch and the schematics of Fig. 1 left and right, respectively. A full and comprehensive description of all the components of the VOXES spectrometer, the definition of the geometrical parameters both in the Bragg and the vertical plane, together with deep investigations of the dependance of the VOXES spectrometer capabilities with respect to the crystal mosaicity, thickness and curvature radius can be found in our previous works [7–9].

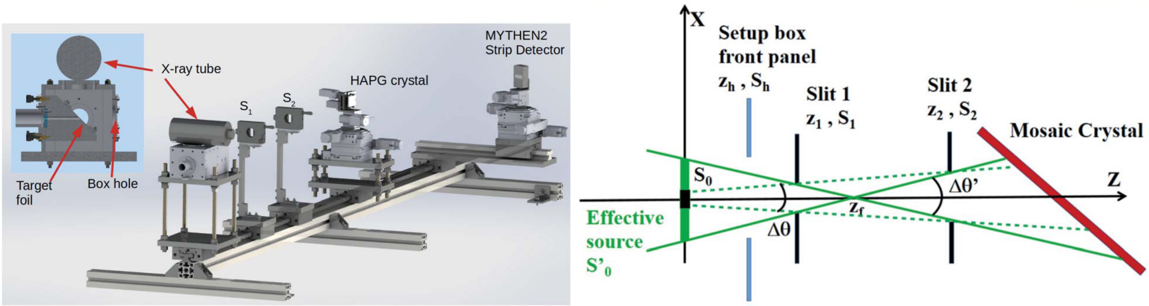

Figure 1: Sketch of the VOXES spectrometer (left) and a schematics of the beam geometry and its main parameters (right) [9].

In particular, in [8] the geometrical configurations in terms of $S'_0, \Delta\theta'$ pairs leading to the best achievable precisions and resolutions for measurements of Fe, Cu, Zn, Mo, Nb transitions can be found; as an example, being the $K^{3,4}$ $3d \rightarrow 2p$ transition energies at $6,2\,keV(K^3He)$ and $6,4\,keV(K^4He)$, we report in Fig. 2 the fitted spectra corresponding to the best resolution (left) and best precision (right) for $Fe(K\alpha_{1,2})$ transitions at $6,4\,keV$ using a $\rho = 206,7\,mm$ curvature radius crystal. The values of the effective source size and of the angular acceptance used in these two measurements are also reported.

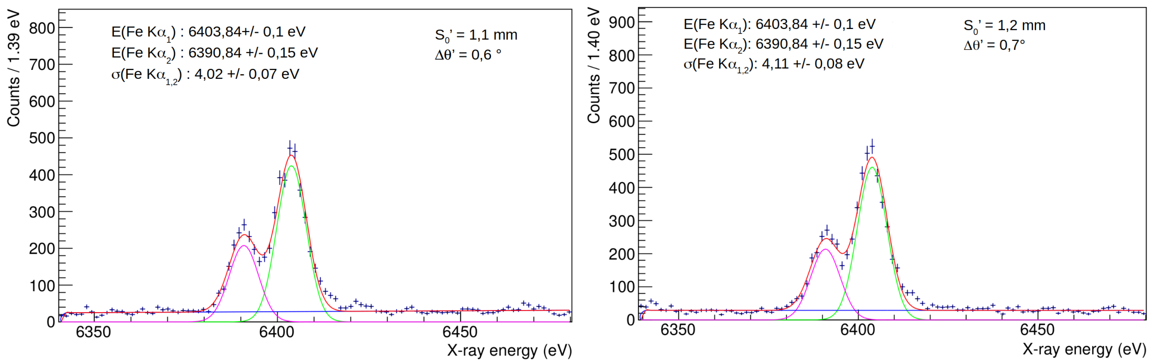

Figure 2: Fitted spectrum of Fe($K\alpha_{a1,2}$) lines for the $\rho = 206,7\,mm$, $S'_0 = 1,1\,mm$, $\Delta\theta' = 0,6°$ (left) and $S'_0 = 1,2\,mm$, $\Delta\theta' = 0,7°$ (right): $K\alpha_1$, $K\alpha_2$, polynomial background and total fitting function correspond to the green, violet, blue and red curves, respectively [8, 9].

3. $K^4He\,3d \rightarrow 2p$ transition: ray tracing simulations and comparison with Silicon Drift Detector measurements

In order to evaluate the possibility to measure kaonic transitions with our spectrometer, we performed X-ray tracing simulations using the XOPPY-SHADOW ray tracing simulation softwares embedded in the OASYS framework and checked the consitency of their outcomes with our measurements both in terms of spectral resolutions and of reflections efficiencies of the apparatus, which have been already published in [9, 10]. In Fig. 3 we report a fit on the simulated $K^4\,3d \rightarrow 2p$ transiton spectra obtained with the same geometrical parameters as in those of Fig. 2; to produce these spectra, since very small strong interaction effect is expected on the 2p level, we used a Lorentzian distribution, centered at $6463,6\,keV$ with $\Gamma = 2\,eV$, as input energy distribution for the X-ray source.

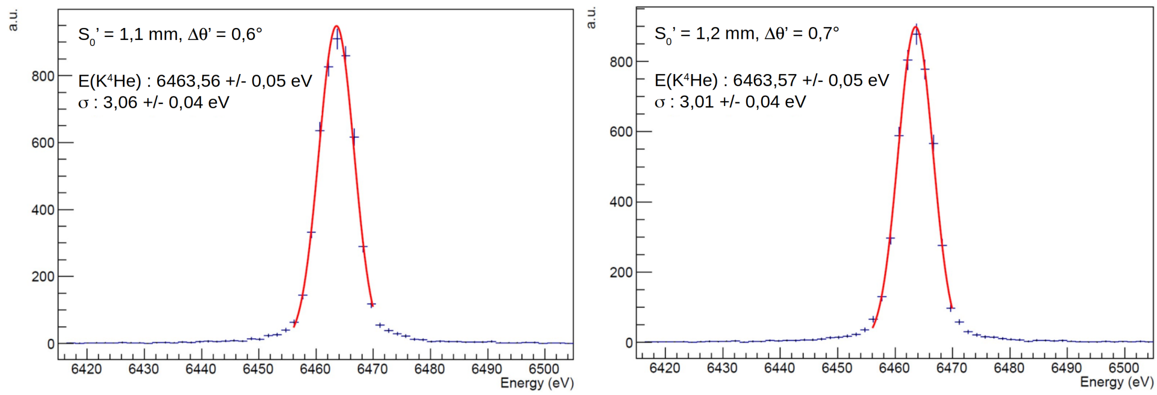

Figure 3: Fitted ray traced simulated spectra of $K^4He\ 3d \rightarrow 2p$ transitions for the $\rho = 206,7\,mm$, $S'_0 = 1,1\,mm$, $\Delta\theta' = 0.6°$ (left) and $S'_0 = 1,2\,mm$, $\Delta\theta' = 0.7°$ (right).

From these two figures, one can immediately appreciate how a peak resolution of $\sigma \simeq 3\,eV$ could be achieved in both cases, leading to precisions in the peak position determinations well below $0,1\,eV$. These would be a dramatic improvement with respect to what has been obtained so far; as an example, we show in Fig. 4 a fit of the same transition in a subsample of the K^4He data acquired by the SIDDHARTA experiment with Silicon Drift Detectors in 2009 [3, 4]. From these latter two figures, the huge difference in the peak resolution is immediately emerging; in particular, from the fit of the K^4He peak measured with SDDs (left) one can immediately see how a future measurement using the VOXES spectrometer would lead to an improvement in the energy resolution of a factor $\simeq$ 25.

4. Conclusions

In this paper we reported the ray tracing simulation spectra of a possible measurement of K^4He $3d \rightarrow 2p$ transition performed with the HAPG mosaic crystal based VOXES specrometer; a comparison with the fit on a subsample of the same transition spectrum measured in 2009 by the SIDDHARTA experiment has been also presented. From these results, the extremely good capabilities of the VOXES spectrometer show to be very promising in view of future possible sub-eV measurements. Solving the kaonic helium isotopic shift puzzle, as well as a new set of

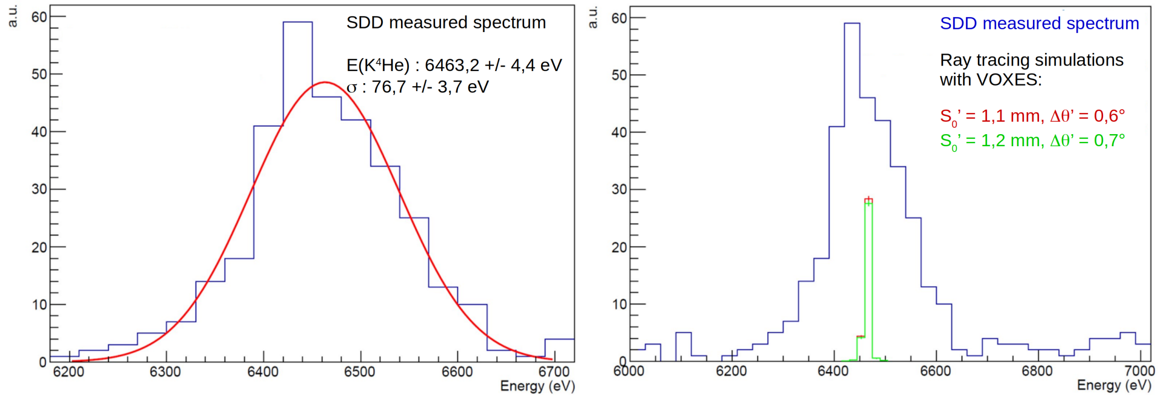

Figure 4: Fit of a subsample of the K^4He $3d \rightarrow 2p$ transition spectrum measured by the SIDDHARTA experiment using Silicon Drift Detectors [3, 4] (left); comparison with the same transition spectra (with arbitrary normalization) as resulting from the ray tracing simulations shown in Fig. 3.

kaonic atom transitions measurements of solid and gaseous targets, leading for example to a new high precision determination of the charged kaon mass or providing new inputs for cascade models calculations, would indeed represent a crucial breakthrough in the field of kaon-nucleon interactions at low energies [1]. In order to foreseen and propose future measurements of kaonic atoms with our spectrometer at the DAΦNE accelerator complex of INFN Laboratories of Frascati, detailed Monte Carlo simulations (GEANT4) are presently undergoing with the aim to fully describe the machine background and to optimize the kaon stopping in the targets; also, we are as well performing more detailed ray tracing simulations to estimate the overall (geometrical+reflection) efficiency of the spectrometer. First results in this direction, with the picture of a possible experimental setup, can be found in [11].

References

[1] C. Curceanu et al., Rev. Mod. Phys., 2019, 91, 025006.

[2] S. Okada et al., 2007, Phys. Lett. B , Vol. 653, p. 387.

[3] M. Bazzi et al. (SIDDHARTA collaboration), 2009, Phys.Lett. B, Vol. 681, p. 310-314.

[4] M. Bazzi et al. (SIDDHARTA collaboration), 2011, Phys.Lett. B, Vol. 697, p. 199-202.

[5] D. Gotta 2004, Prog. Part. Nucl. Phys, Vol. 52, p. 133.

[6] M. Trassinelli et al., 2016, Phys. Lett. B, Vol. 759, p. 583-588.

[7] A. Scordo et al., 2019, Condensed Matter, Vol. 4, p. 59.

[8] A. Scordo, et al., 2020, J. Anal. At. Spectrom, Vol. 35, p. 155-168.

[9] A. Scordo, et al., 2021, J. Anal. At. Spectrom., 2021, 36, p. 2485.

[10] V. Di Leo et al., arXiv:2111.01448v1 [physics.ins-det].

[11] C. Curceanu et al., arXiv:2104.06076v2 [nucl-ex].