

The measurement of the E2 nuclear resonance effects in kaonic atoms at DAΦNE: the KAMEO proposal

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Abstract. KAMEO (Kaonic Atoms Measuring Nuclear Resonance Effects Observables) is a proposal for an experiment aiming to perform the first consistent measurement of the E2 nuclear resonance effects in kaonic molybdenum $A=94,96,98,100$ isotopes. The E2 nuclear resonance mixes atomic states, due to the electrical quadrupole excitation of nuclear rotational states. It occurs in atoms having the energy of a nuclear excitation state closely matching an atomic de-excitation state energy, and affects the rates of X-ray atomic transitions matching the energy of the resonance. The measurement E2 nuclear resonance effect in KMO isotopes allows the study of the strong kaon-nucleus

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interaction in a rotational excited nuclear state. Moreover, the effect enables the K^- to access an inner atomic level not easily reachable by the kaon normal cascade, due to the nuclear absorption. The KAMEO proposed apparatus consists of 4 enriched Mo $A=94,96,98,100$ isotope strips, exposed to the kaons produced by the DAΦNE collider, for kaonic atoms formation, with a high-purity germanium detector, cooled with liquid nitrogen, used to measure the X-ray atomic transitions. The DAΦNE collider is located at the National Laboratories of Frascati (LNF-INFN), in Italy. It is already suited for kaonic atoms measurement by the SIDDHARTA-2 collaboration.

1 Introduction

Hadronic atoms are atomic systems with a negatively charged hadron, like π^- , K^- , Σ^- etc., replacing an electron in the atomic shell, captured via electromagnetic interaction. Kaonic atoms are formed through the atomic capture of a K^- , which usually occurs on a highly excited atomic level [1]. Then, the K^- starts an electromagnetic cascade through the atomic levels, going deeper into the atomic shell. Reaching the innermost levels of the atom, the kaon approaches the nucleus and the strong interaction comes into play, altering the atomic structure. The effect is a broadening of the atomic levels and a shift in the energy, with respect to the purely electromagnetic values calculated with QED [1]. In light kaonic atoms, like H or He, atomic transitions of the innermost levels, where the shifts and broadening due to the strong kaon-nucleus interaction become detectable, are measured with dedicated X-ray spectroscopy [1–4]. In heavier kaonic atoms, like kaonic Mo isotopes, the probability for a K^- of reaching the innermost atomic levels is extremely small, due to the nuclear absorption, but the effects of the strong kaon-nucleus interaction start to be detectable at higher levels. The E2 nuclear resonance impacts the atomic states, and is occurring in atoms where the energy of a nuclear excitation state closely matches an atomic de-excitation state energy. This resonance has been studied since the 1970s in hadronic atoms [5–8]. In recent studies on antiprotonic Tellurium isotopes, the E2 nuclear resonance effects were observed and used to determine widths and shifts of the LS-split deeply bound $(n,l)=(6,5)$ state in $^{130}_{52}\text{Te}$, otherwise not accessible [9]. Then, shifts and widths measured, corrected with the E2 nuclear resonance effect, allowed the investigation of nucleon density in the nuclear periphery. The E2 nuclear effect represents a fundamental instrument to investigate the kaon-nucleus strong interaction, enriching knowledge and comprehension of the mechanisms that rule this interaction at low energy, and providing parameters for theoretical models and important data on nucleon density in the nuclear periphery [7, 9, 10].

In four kaonic Mo isotopes, $K^-_{42}\text{Mo}^{-94}$, $K^-_{42}\text{Mo}^{-96}$, $K^-_{42}\text{Mo}^{-98}$ and $K^-_{42}\text{Mo}^{-100}$, the E2 nuclear resonance occurs [6, 7]. In past, only the $K^-_{42}\text{Mo}^{-98}$ was investigated, in 1975 at Lawrence and Berkeley Laboratory, in California [8]. However, the data collected were not enough to provide a conclusive result [7, 8]. With modern technologies, advanced compared to 1975, and a consolidated experience in the field of spectroscopic measurements of kaonic atoms [1–4, 11–13], the SIDDHARTA-2 collaboration aims to measure the E2 nuclear resonance effects in kaonic Mo isotopes within the KAMEO proposed experiment at the DAΦNE collider (National Laboratories of Frascati INFN-LNF) [14].

2 The KAMEO experimental proposal

The E2 nuclear resonance effect is a mixing of the atomic states due to the electrical quadrupole excitation of the nucleus. In the specific, the mixing occurs among $(n, l, 0^+)$ and

$(n', l - 2, 2^+)$ states. The wave function of the mixed state is expressed as [7]:

$$\psi = \sqrt{1 - |\alpha|^2} \cdot \phi(n, l, 0^+) + \alpha \cdot \phi(n, l - 2, 2^+) \quad (1)$$

where $\alpha = \pm \frac{\langle n', l - 2, 2^+ | H_q | n, l, 0^+ \rangle}{E_{(n', l - 2, 2^+)} - E_{(n, l, 0^+)}}$ is the admixture coefficient and H_q is the electric kaon-nucleus quadrupole interaction. In kaonic atoms, the nuclear absorption rate experiences a several-hundred-fold increase with each reduction in the orbital angular momentum unit [6, 7]. In the case of the E2 nuclear resonance effect, for mixing levels with $\Delta l = 2$, the nuclear absorption rate increases by $\sim 10^5$ [7]. This produces a small admixture coefficient ($\alpha \sim 1\%$), but a significant reduction of the induced width:

$$\Gamma_{n,l}^{ind} = |\alpha|^2 \Gamma_{n',l-2}^0 \quad (2)$$

The final result is a significant weakening/attenuation of the involved kaonic X-ray line and of any lower lines, that can be experimentally observed.

In kaonic Mo A=94,96,98,100 isotopes, the E2 nuclear resonance mixes the $(6h, 0^+)$ and $(4f, 2^+)$ states (see Fig. 1 as example for molybdenum 98) [6, 7]. The wave function of the mixed state is expressed as:

$$\psi = \sqrt{1 - |\alpha|^2} \phi(6h, 0^+) + \alpha \phi(4f, 2^+) \quad (3)$$

where $\alpha = \pm \frac{\langle 4f, 2^+ | H_q | 6h, 0^+ \rangle}{E_{(4f, 2^+)} - E_{(6h, 0^+)}}$. The KAMEO experiment aims to perform conclusive and precise

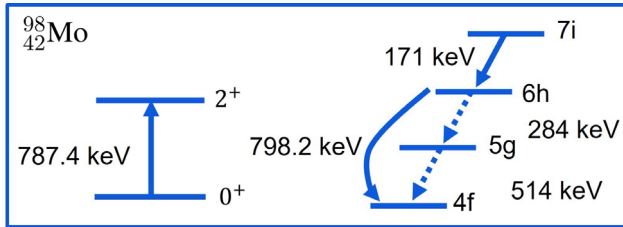


Figure 1. Schematic diagram of energies, atomic and nuclear transitions involved in the E2 nuclear resonance effect of K^- - $^{98}_{42}\text{Mo}$. In the figure are shown the matching energies of $0^+ \rightarrow 2^+$ nuclear excitation and $6h \rightarrow 4f$ atomic transition. The resonance mixes $(6h, 0^+)$ and $(4f, 2^+)$ states, reducing the rates of $6h \rightarrow 4f$, $6h \rightarrow 5g$ and $5g \rightarrow 4f$ transition lines compared to the non-resonant K^- - $^{92}_{42}\text{Mo}$.

measurements of the E2 nuclear resonance effects in kaonic Mo A=94,96,98,100 isotopes. The plan is to expose five solid target strips of enriched Mo isotopes (>99%): $^{94}_{42}\text{Mo}$, $^{96}_{42}\text{Mo}$, $^{98}_{42}\text{Mo}$, $^{100}_{42}\text{Mo}$ and $^{92}_{42}\text{Mo}$ to the kaons produced by the DAΦNE collider [14]. A High Purity p-type Germanium (HPGe) detector will be used for the X-ray spectroscopy. The HPGe detector is designed by Baltic Scientific Instruments to work under high-rate conditions (up to 150 kHz), as needed in the DAΦNE environment [15]. The cylindrical active volume of the detector is 59.3 mm in height and 59.8 mm in base diameter and it is cooled with liquid nitrogen to provide the best performances in efficiency and energy resolution. A test performed with ^{133}Ba and ^{60}Co sources (activity < 1 μCi) and analog electronics allowed to estimate the energy resolutions Full Width Half Maximum (FWHM) of the HPGe detector: 0.87 keV at 81 keV and 1.06 keV at 302.9 keV [15]. A schematic view of the KAMEO proposed setup is shown in Fig. 2.

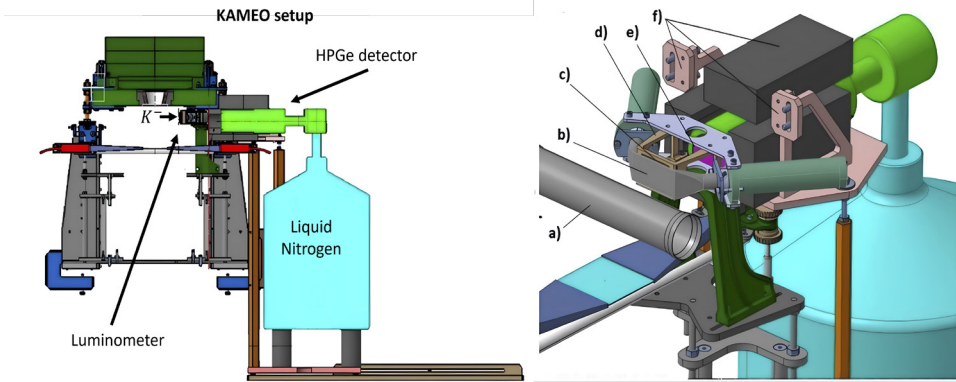


Figure 2. Schematic view of the lateral side and to view of the KAMEO proposed setup for the measurement of the E2 nuclear resonance effects in kaonic molybdenum isotopes at the DAΦNE collider [[14]], in Italy. On the left, the layout of the KAMEO setup: (a) beam pipe, (b) luminometer, (c) Mo target, (d) target holder, (e) active part of the HPGe detector, (f) lead shielding with the holder (figure done by C. Capoccia INFN).

3 Conclusions and future prospects

The E2 nuclear resonance allows to investigate the strong kaon-nucleus interaction and nucleon density in the nuclear periphery in hadronic atoms [6, 7, 9]. In pionic and anti-protonic atoms, the effect was successfully measured [5], but in kaonic atoms a conclusive result was not yet achieved [7, 8]. Four kaonic molybdenum isotopes ($A=94,96,98,100$) present the E2 resonance effect and their investigation could provide fundamental information for a better understanding of the strong interaction in the strangeness sector, and of the nuclear properties [6, 7]. The SIDDHARTA-2 collaboration is proposing the KAMEO experiment to measure the E2 nuclear resonance in kaonic Mo isotopes, with a dedicated X-ray spectroscopy, at the DAΦNE collider. The HPGe detectors are presently tested at the DAΦNE collider [14] to extract important information about the background [15]. Moreover, a Monte Carlo simulation is being performed to estimate and optimize the experimental parameters for the kaon capture and X-ray transitions energy measurement. Kaonic Molybdenum isotopes X-ray spectroscopy represent an important source of information for theoretical models which describe the strong kaon-nucleus interaction.

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