EPJ Web of Conferences **290**, 06003 (2023)
EuNPC 2022
https://doi.org/10.1051/epjconf/202329006003

Investigating the E2 Nuclear Resonance Effects in Kaonic Atoms: The KAMEO Proposal

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Abstract. The E2 nuclear resonance effect in kaonic atoms occurs when the energy of atomic de-excitation closely matches the energy of nuclear excitation, leading to the attenuation of some X-ray lines in the resonant isotope target. This phenomenon provides crucial information on the strong interaction between kaons and nuclei. The only nuclear E2 resonance effect observed so far was in the $K^-{-}^{98}_{42}$Mo isotope, measured by G. L. Goldfrey, G- K. Lum, and C. E. Wiegand at Lawrence Berkeley Laboratory in 1975. However, the 25 hours of data taking were not sufficient to yield conclusive results. In four kaonic Molybdenum isotopes ($^{94}_{42}$Mo, $^{96}_{42}$Mo, $^{98}_{42}$Mo, and $^{100}_{42}$Mo), the nuclear E2 resonance effect is expected to occur at the same transition with similar energy values. To investigate this, the KAMEO (Kaonic Atoms Measuring Nuclear Resonance Effects Observables) experiment plans to conduct research on kaonic Molybdenum isotopes at the DAΦNE e^+e^- collider during the SIDDHARTA-2 experiment. The experimental strategy involves exposing four solid strip targets, each enriched with one Molybdenum isotope, to negatively charged kaons and using a germanium detector to measure X-ray transitions. In addition, a non-resonant $^{92}_{42}$Mo isotope solid strip target will be used as a reference for standard non-resonant transitions.

1 Introduction

Kaonic atoms are formed when a negatively charged kaon (K^-) is captured by an atomic system due to the electromagnetic interaction with the nucleus, replacing an electron in an atomic shell. After capture, the K^- starts an electromagnetic cascade process, which ends with its nuclear absorption. As the kaon approaches the nucleus and fills the innermost levels of the kaonic atom, the strong kaon-nucleus interaction alters the atomic structure by shifting and broadening the levels which can be detected through dedicated X-ray spectroscopy techniques [1–3].The investigation of kaonic atoms began in the 1970s [4–6] and continues to this day [7–13], providing a crucial tool for understanding the strong kaon-nucleon interaction in the low-energy regime. In 2023, the SIDDHARTA-2 experiment will perform the first measurement of kaonic deuterium at the DAΦNE e^+e^- collider at the National Laboratories of Frascati (LNF) in Italy [14]. Combined with the kaonic hydrogen measurement performed by the SIDDHARTA experiment in 2011 [10], this measurement will enable the extraction of antikaon-nucleon scattering lengths with isospin dependence. Whenever a nuclear excitation energy is very close to an atomic de-excitation energy, a resonance occurs in the atomic system, known as E2 nuclear resonance [15]. Several kaonic atoms are predicted to be resonant, including four isotopes of kaonic

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Molybdenum ($^{94}_{42}$Mo, $^{96}_{42}$Mo, $^{98}_{42}$Mo, and $^{100}_{42}$Mo) [16, 17]. These isotopes may provide insight into the properties of deeply bound kaonic atomic levels, which are otherwise difficult to access through K$^-$ cascades due to nuclear absorption. By comparing the measurements of these isotopes, information about the strong nuclear potential can be obtained by investigating variations in the resonance's parameters with increasing neutron number along the Molybdenum isotopes. The first measurement of the E2 nuclear resonance effect in kaonic atoms was performed by G. L. Goldfrey, G. K. Lum, and C. E. Wiegand in $^{98}_{42}$Mo at the Lawrence and Berkeley Laboratory (LBL) in California, in 1975 [18, 19]. Unfortunately, only 25 hours of data were collected which was not sufficient for a definitive result. The E2 nuclear resonance effect has been measured in other exotic atoms such as pionic atoms and anti-protonic atoms. In particular, the measurement of the E2 nuclear resonance effect in even-A anti-protonic Tellurium isotopes has been used to determine the properties of the neutron density in the nuclear periphery of Te isotopes [20]. The same investigation can be performed on kaonic molybdenum isotopes, revealing the properties and parameters of the neutron density in the nuclear periphery. This may have an important role for the observation of the neutrinoless double beta decay of $^{98}_{42}$Mo which could demonstrate that neutrinos are Majorana particles [21]. The nuclear matrix elements for this decay are calculated using models that depend on the relative distance between the two neutrons involved in the decay. A more precise estimation of the root mean square (rms) of the neutron radius, obtainable through the study of the E2 resonance in $K^-{-}^{98}_{42}$Mo, could provide further constraints to define the relative distance among neutrons in the isotope. Finally, this paper briefly presents the possibility and advantages of investigating kaonic Molybdenum isotopes at the DAΦNE collider with the KAMEO setup, running in parallel with the SIDDHARTA-2 experiment.

2 The KAMEO proposal: the measurement of the E2 nuclear resonance effects in kaonic molybdenum isotopes

The E2 nuclear resonance effect occurs when the energy required for a nuclear excitation closely matches the de-excitation energy of an atomic transition, resulting in a mixing of atomic states due to electrical quadrupole excitations of nuclear rotational states. This mixing produces a wave function ϕ that includes a small mixture of excited nuclear and de-excited atomic wavefunctions, described by the equation:

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

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 determined by the electric quadrupole interaction between the kaon and the nucleus.

The rate of nuclear absorption increases significantly in kaonic atoms for each unit of decreasing in orbital angular momentum, and the induced width is determined by the equation:

$$\Gamma^{Ind}_{n,l} = |\alpha|^2\Gamma^0_{n',l-2} \tag{2}$$

In this way, the E2 nuclear resonance can lead to a significant attenuation of the involved kaonic X-ray line and of any lower lines, in resonant kaonic atoms. In kaonic Molybdenum isotopes 94, 96, 98, and 100, the E2 nuclear resonance effect occurs by mixing (6h,0$^+$) and (4f,2$^+$) states, described by the wave function:

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

where the admixture coefficient $\alpha = \pm\frac{\langle 4f,2^+|H_q|6h,0^+\rangle}{E_{(4f,2^+)}-E_{(6h,0^+)}}$. Parameters and energies of the E2 nuclear resonance effects in kaonic Mo isotopes are reported in Tab. 1. A schematic representation of the E2 nuclear resonance effect in $^{98}_{42}$Mo is presented in Fig. 1. The investigation of the E2 nuclear resonance effects in kaonic Mo isotopes represents a unique and interesting opportunity to extract fundamental information for a better understanding of the properties of kaon-nucleon strong interaction. Moreover, the comparison among the measured spectra of kaonic Mo isotopes could allow the investigation of the distribution of the neutrons in the nuclear periphery [20].

The E2 nuclear resonance effect in kaonic atoms was first measured in 1975 at Lawrence and Berkeley Laboratory in California, using a negative kaon beam and solid targets of $^{98}_{42}$Mo, with non-resonant $^{92}_{42}$Mo as reference [16, 18, 19]. Germanium detectors feeding a pulse height analyzer were used to collect the spectra, and the E2 nuclear resonance effect was observed as attenuation of X-ray lines. However, the experiment only yielded 25 hours of data, which was not enough for a conclusive result. Subsequently, no further investigations into the E2 nuclear resonance effect in kaonic atoms were conducted to today. The KAMEO experiment plans to measure the E2 nuclear resonance effects in kaonic Mo isotopes at the DAΦNE e$^+$e$^-$ collider of the LNF, in Italy. The DAΦNE collider is a ϕ factory producing low energetic K$^-$ (p=127 MeV/c), suitable for the investigation of kaonic atoms [5, 14]. The KAMEO apparatus consists of several solid target strips of enriched Mo isotopes (>99%): $^{94}_{42}$Mo, $^{96}_{42}$Mo, $^{98}_{42}$Mo, $^{100}_{42}$Mo and $^{92}_{42}$Mo (used as the reference for standard transition not affected by E2 nuclear resonance); and a High Purity Germanium (HPGe) detector. The surface of the solid target strips will be 4 cm x 8 cm. The thickness will be estimated with a dedicated Monte Carlo simulation to maximize the efficiency in kaonic Mo isotope production and measurement of the X-ray transitions. In 2023, the SIDDHARTA-2 experiment will perform the first measurement of the 2p→1s X-ray transition in kaonic deuterium, using a cylindrical target placed above the Interaction Point (IP) of the DAΦNE collider. The KAMEO experiment is able to run in parallel with SIDDHARTA-2, exploiting the horizontal plane, as shown in Figure 2. The SIDDHARTA-2 luminometer[23], consisting of plastic scintillators (80 mm × 40 mm × 2 mm each), read by pairs of Photo Multiplier Tubes (PMTs) [24, 25], will be used as trigger for the HPGe detector X-ray spectroscopy. The luminometer is placed at a distance of 110 mm from

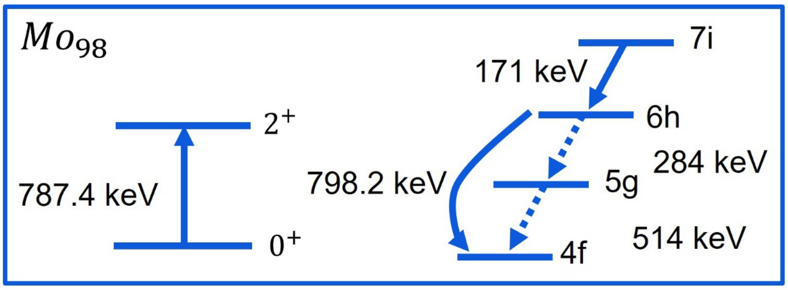

Figure 1. Schematic views of the E2 nuclear resonance effect in kaonic Molybdenum 98. The resonance mixes (6h,0+) and (4f,2+) states, attenuating the 6h→4f transition line and any lower lines with respect to a non-resonant Molybdenum isotope.

Table 1. Table with energies and parameters of the E2 resonant Molybdenum isotopes. [15]

Atom	$E_{0^+\to 2^+}[keV]$	Mixing(n,l)	$E_{(n,l)\to(n',l-2)}[keV]$	Line	E[keV]	Atten.
$^{94}_{42}Mo$	871	(6,5) ÷ (4,3)	799	6→5	284	0.18
$^{96}_{42}Mo$	778	(6,5) ÷ (4,3)	799	6→5	284	0.71
$^{98}_{42}Mo$	787	(6,5) ÷ (4,3)	798	6→5	284	0.81
$^{100}_{42}Mo$	536	(6,5) ÷ (4,3)	798	6→5	284	0.04

the Interaction Point (IP) of the DAΦNE collider. The Mo target strips will be positioned 5 mm outside the luminometer. The p-type HPGe detector is designed by Baltic Scientific Instruments to work under high-rate conditions (to 150 kHz). It has a cylindrical active volume having 59.3 mm of height and 59.8 mm of base diameter. The energy resolution of the HPGe detector, tested with ^{133}Ba and ^{60}Co sources (activity < 1 μCi), are 0.87 keV at 81 keV, 1.06 keV at 302.9 keV. These parameters make the HPGe detector ideal to perform the measurement of the 7i→6h and 6h→5g atomic transitions in kaonic Mo isotopes (having energies of ∼170 keV and ∼280 keV, respectively) in the high-rate environment of the DAΦNE collider. The HPGe detector will be positioned 115 mm far from the Mo target strips. The detection efficiency will be estimated with a dedicated Monte Carlo simulation.

The KAMEO experimental proposal aims the measurement of the mixing coefficient α in the $^{94}_{42}$Mo, $^{96}_{42}$Mo, $^{98}_{42}$Mo, and $^{100}_{42}$Mo resonant isotopes, caused by the E2 nuclear resonance effect, with a precision better than 10%. The mixing coefficient is obtained from the attenuation of the 6h→5g transition in the spectra of resonant Mo isotopes, compared to non-resonant $^{92}_{42}$Mo, used as a reference. Additionally, KAMEO will provide the first measurement of the shift ($\epsilon_{6h,0^+}$) and width ($\Gamma_{6h,0^+}$) of the 6h atomic level in kaonic resonant Mo isotopes due to the E2 nuclear resonance effect, and the first extraction of the shift ($\epsilon_{4f,2^+}$) and width ($\Gamma_{4f,2^+}$) of the 4f atomic level in excited-nucleus isotopes of kaonic Mo due to the kaon-nucleus strong interaction. The 4f state could be a Coulomb-assisted nuclear quasi-bound state of K^- meson [20]. To extract the shifts and broadenings of atomic levels, the X-ray transitions in kaonic Molybdenum E2-resonant isotopes are compared to purely electromagnetic values determined using QED. This procedure is similar to that used for antiprotonic Tellurium isotopes [20], with an expected precision of some keV. Finally, the high-precision measurements performed by KAMEO enable the study of the neutron density in the nuclear periphery of kaonic Mo isotopes, whose number of nucleons in the nucleus growth of pairs of neutrons from the lightest resonant isotope. The difference between neutron and proton *rms* radii can be determined with a precision of 0.1 fm, and the neutron *rms* radius can be precisely estimated (following a similar procedure used in [20]). The extraction of the neutron *rms* radius in $^{98}_{42}$Mo would be crucial for research on the neutrinoless double beta decay of $^{98}_{42}$Mo, which violates lepton number conservation. Observing this decay would demonstrate that the neutrino is a Majorana particle [21].

3 Conclusion and outooks

The experimental investigation of the E2 nuclear resonance effect in the resonant isotopes of kaonic Molybdenum (94, 96, 98, and 100) presents a novel perspective into the strangeness sector's strong interaction at low energies. KAMEO could perform the best measurement of the E2 nuclear resonance effects in kaonic Mo isotopes. Moreover, this measurement could enhance the understanding of the neutron distribution in the nuclear periphery, providing also important information for the investigation of the neutrinoless double beta decay in $^{98}_{42}$Mo. Finally, the first measurement of shifts and widths of the 4f energy level in kaonic Mo E2-resonant isotopes, which could be a Coulomb-assisted nuclear quasi-bound state of K^- meson, could reveal fundamental details of the strong kaon-nucleus interaction, providing parameters which allow updates of the theoretical models. The KAMEO experiment plans precise measurements of the E2 nuclear resonance effects in kaonic molybdenum isotopes 94, 96, 98 and 100

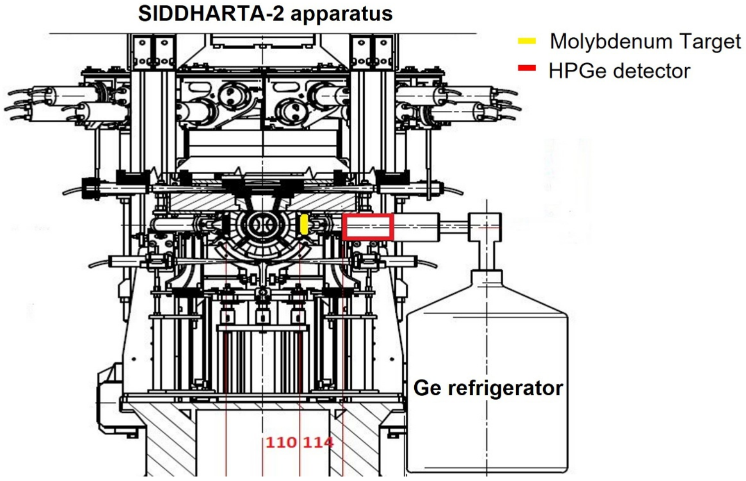

Figure 2. Schematic view of the KAMEO installed on the horizontal line close to the interaction point of the DAΦNE collider, running in parallel with the SIDDHARTA-2 experiment.

at LNF's DAΦNE collider. The measurement will be performed simultaneously with the SIDDHARTA-2 experiment and with an optimized experimental setup developed through a dedicated Monte Carlo simulation.

We thank C. Capoccia from LNF-INFN and H. Schneider, L. Stohwasser, and D. Pristauz-Telsnigg from Stefan Meyer-Institut for their fundamental contribution in designing and building the SIDDHARTA-2 setup. We thank as well the DAΦNE staff for the excellent working conditions and permanent support. Part of this work was supported by the Austrian Science Fund (FWF): [P24756-N20 and P33037-N]; the EXOTICA project of the Minstero degli Affari Esteri e della Cooperazione Internazionale, PO21MO03; the Croatian Science Foundation under the project IP-2018-01-8570; the EU STRONG-2020 project (Grant Agreement No. 824093); the EU Horizon 2020 project under the MSCA (Grant Agreement 754496); the Japan Society for the Promotion of Science JSPS KAKENHI Grant No. JP18H05402; the Polish Ministry of Science and Higher Education grant No. 7150/E-338/M/2018 and the Polish National Agency for Academic Exchange(grant no PPN/BIT/2021/1/00037); the EU Horizon 2020 research and innovation programme under project OPSVIO (Grant Agreement No. 101038099). The authors acknowledge support from the SciMat and qLife Priority Research Areas budget under the program Excellence Initiative—Research University at the Jagiellonian University.

References

[1] Lee C H, Jung H, Min D P and Rho M, Phys. Lett. B **326**, 14-20 (1994)
[2] Bernard V, Prog. Part. Nucl. Phys. **60**, 82-160 (2008)
[3] Cieplý A, Mai M, Meißner U G and Smejkal J, Nucl. Phys. A **954**, 17-40 (2016)
[4] Davies J D *et al.*, Phys. Lett. B **83**, 55 (1979)
[5] Izycki M *et al.*, Z. Phys. A **297**, 11 (1980)
[6] Baird S *et al.*, Nucl. Phys. A **392**, 297 (1983)
[7] Iwasaki M *et al.*, Phys. Rev. Lett. **78**, 3067 (1997)
[8] Beer G *et al.*, Phys. Rev. Lett. **94**, 212302 (2005)
[9] Okada S *et al.*, Phys. Lett. B **653**, 387 (2007)
[10] Bazzi M *et al.*, Phys. Lett. B **681**, 310 (2009)
[11] Bazzi M *et al.*, Phys. Lett. B **704**, 113 (2011)
[12] Bazzi M *et al.*, Phys. Lett. B **697**, 199 (2011)
[13] Bazzi M *et al.*, Phys. Lett. B **714**, 40 (2012)
[14] Curceanu C *et al.* 2021 *Few-Body System* **62** 83 (2021)
[15] Leon M, Nucl. Phys. A **260**, 461-473 (1976)
[16] Leon M, Informal Report United States: N. p. (1975)
[17] Leon M, Phys. Lett. B **50**, 425 (1974)
[18] Goldfrey G L, Lum G K and Wiegand C E, Phys. Lett. B **65**, 43-45 (1976)
[19] Wiegand C E and Goldfrey G L, Phys. Rev. A **9**, 2282 (1974)
[20] Klos B, Wycech S *et al.*, Phys. Rev. C **69**, 044311 (2004)
[21] Nesterenko D A, Jokiniemi L, Kotila J *et al.*, Eur. Phys. J. A **58**, 44 (2022)
[22] Bradbury J N, Leon M, Daniel H and Reidy J J, Phys. Rev. Lett. **34**, 303 (1975)
[23] Skurzok M *et al.*, JINST **15**, P10010 (2020)
[24] Moskal P *et al.*, Nucl. Inst. and Meth. A **764**, 317 (2014)
[25] Niedźwiecki S *et al.*, Acta Phys. Polon. B **48**, 1567 (2017)