IL NUOVO CIMENTO **46 C** (2023) 59
DOI 10.1393/ncc/i2023-23059-0

Communications: SIF Congress 2022

The KAMEO proposal: Investigation of the E2 nuclear resonance effects in kaonic atoms

L. De Paolis(1) on behalf of M. Bazzi(1), D. Bosnar(2), M. Bragadireanu(3),
M. Cargnelli(4), M. Carminati(5), A. Clozza(1), G. Deda(5),
R. Del Grande(6)(1), K. Dulski(1)(8)(9), C. Fiorini(5), I. Friščič(2),
C. Guaraldo(1), M. Iliescu(1), M. Iwasaki(7), A. Khreptak(1)(8),
S. Manti(1), J. Marton(4), M. Miliucci(1), P. Moskal(8)(9), F. Napolitano(1),
S. Niedz̀wiecki(8)(9), O. Ohnishi(10), K. Piscicchia(11)(1), Y. Sada(10),
A. Scordo(1), F. Sgaramella(1), H. Shi(4), M. Silarski(8)(9),
D. L. Sirghi(11)(1)(3), F. Sirghi(1)(3), M. Skurzok(8)(9), S. Wycech(12),
A. Spallone(1), K. Toho(7), M. Tüchler(4)(13), C. Yoshida(10), J. Zmeskal(4)
and C. Curceanu(1)

(1) *INFN, Laboratori Nazionali di Frascati - Via E. Fermi 54, I-00044 Frascati (RM), Italy*

(2) *Department of Physics, Faculty of Science, University of Zagreb - 10000 Zagreb, Croatia*

(3) *Horia Hulubei National Institute of Physics and Nuclear Engineering,*
Str. Atomistilor No. 407, P.O. Box MG-6 Bucharest-Măgurele, Romania

(4) *Stefan Meyer Institute for Subatomic Physics - Kegelgasse 27, 1030 Wien, Austria*

(5) *Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria and INFN*
Sezione di Milano - I-20133 Milano, Italy

(6) *Physik Department E62, Technische Universiät München - James-Franck-straße 1, 85748*
Garching, Germany

(7) *RIKEN, Institute of Physical and Chemical Research - Wako, Tokyo 351-0198, Japan*

(8) *Faculty of Physics, Astronomy, and Applied Computer Science, Jagiellonian University*
Lojasiewicza 11, Krakow, 30-348, Poland

(9) *Center for Theranostics, Jagiellonian University - Kopernika 40, Krakow, 31-501, Poland*

(10) *Research Center for Electron Photon Science (ELPH), Tohoku University*
Sendai, Japan

(11) *Centro Ricerche Enrico Fermi–Museo Storico della Fisica e Centro Studi e Ricerche*
"Enrico Fermi" - Via Panisperna 89a, I-00184 Roma, Italy

(12) *National Centre for Nuclear Research - 02-093, Pasteura, Warsaw Poland*

(13) *University of Vienna, Vienna Doctoral School in Physics - Vienna, Austria*

received 6 February 2023

Summary. — The E2 nuclear resonance effect is a phenomenon that occurs when the energy of an atomic de-excitation state closely matches that of a nuclear excitation state, resulting in the attenuation of certain atomic X-ray lines in the resonant isotope target. The study of this effect in kaonic atoms can provide important insight into the mechanisms of the strong kaon-nucleus interaction. In 1975, Goldfrey, Lum, and Wiegand at Lawrence Berkeley Laboratory observed the effect in $^{98}_{42}$Mo, but they did not have enough data to reach a conclusive result. The E2 nuclear resonance effect is expected to occur in four kaonic molybdenum isotopes ($^{94}_{42}$Mo, $^{96}_{42}$Mo, $^{98}_{42}$Mo, and $^{100}_{42}$Mo) with similar energy values. The KAMEO (Kaonic Atoms Measuring Nuclear Resonance Effects Observables) proposal plans to study this effect in these isotopes at the DAΦNE Φ factory during the SIDDHARTA-2 experiment. KAMEO will use four solid strip targets, each enriched with a different molybdenum isotope, and expose them to negatively charged kaons produced by Φ meson decays. The X-ray transition measurements will be performed using a high-purity germanium detector, and an additional solid strip target of non-resonant $^{92}_{42}$Mo isotope will be exposed and used as a reference for standard non-resonant transitions.

1. – Introduction

Kaonic atoms are created when a negatively charged kaon (K^-) is captured by an atomic system as a result of the electromagnetic interaction with the nucleus. The K^- replaces an electron in the atomic shell and then starts an electromagnetic cascade process that leads to its absorption by the atomic nucleus. As the kaon approaches the nucleus and reaches the innermost levels of the atom, the strong kaon-nucleus interaction comes into play, altering the atomic structure enough to be detected through dedicated X-ray spectroscopy techniques [1-3]. Investigations of kaonic atoms began in the 1970s [4-6] and have continued to the present day [7-13], representing a crucial tool for understanding the strong kaon-nucleon interaction in the low-energy regime. In 2023, the SIDDHARTA-2 experiment will conduct the first measurement of kaonic deuterium at the DAΦNE e^+e^- collider at the National Laboratories of Frascati (LNF) in Italy [14]. This measurement, in combination with the kaonic hydrogen measurement performed by the SIDDHARTA experiment [10], will enable the extraction of isospin-dependent antikaon-nucleon scattering lengths.

When an atomic de-excitation energy closely matches a nuclear excitation energy, a resonance condition known as the E2 nuclear resonance occurs [15]. Several kaonic atoms are predicted to be resonant [16], and four isotopes of kaonic molybdenum ($^{94}_{42}$Mo, $^{96}_{42}$Mo, $^{98}_{42}$Mo and $^{100}_{42}$Mo) are particularly interesting [17]. These Mo isotopes can provide insight into the properties of deeply bound kaonic levels, which are difficult to access through K^- cascades due to the nuclear absorption. Additionally, 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 neutrons number along the isotopes. In 1975, Goldfrey, Lum, and Wiegand were the first to measure the E2 nuclear resonance effect in $^{98}_{42}$Mo at the Lawrence and Berkeley Laboratory (LBL) in California [18, 19], but only 25 hours of data were collected, which was not enough for a definitive result. This is the only measurement of the E2 nuclear resonance effect that has been performed in kaonic atoms, but the effect has been measured in other exotic atoms such as pionic atoms [20] and anti-protonic atoms [21]. 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 [21]. An investigation of Mo isotopes could provide similar information. Additionally, the neutrinoless double beta decay of $^{98}_{42}$Mo is a rare process that violates the conservation of the lepton number. If observed, it would demonstrate that neutrinos are Majorana particles [22]. 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, which can be obtained 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. In this paper, the possibility and advantages of investigating kaonic molybdenum isotopes at the DAΦNE collider with the KAMEO (Kaonic Atoms Measuring nuclear resonance Effects Observables) setup, running in parallel with the SIDDHARTA-2 experiment, are briefly discussed.

2. – The E2 nuclear resonance effect in kaonic molybdenum isotopes

The E2 nuclear resonance occurs when a de-excitation energy of an atomic transition closely matches the energy required for a nuclear excitation. This causes the mixing of atomic states due to the electrical quadrupole excitations of nuclear rotational states. In terms of quantum mechanics, it mixes the $(n, l, 0^+)$ level with the $(n', l-2, 2^+)$ level, resulting in a wave function ϕ that includes a small mixture of excited nuclear and de-excited atomic wave functions:

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

In eq. (1), the admixture coefficient $\alpha = \pm\frac{\langle n',l-2,2^+|H_q|n,l,0^+\rangle}{E_{(n',l-2,2^+)}-E_{(n,l,0^+)}}$ is determined by the electric quadrupole interaction between the kaon and the nucleus. In kaonic atoms, the rate of nuclear absorption increases by several hundred times for each unit decrease in orbital angular momentum. For a decrease of $\Delta l = 2$, the nuclear absorption rate increases by about 10^5. This implies a very small admixture coefficient α (around 1%) and a significant induced width:

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

To summarize, the E2 nuclear resonance can lead to a significant weakening or attenuation of the involved kaonic X-ray line and of any lower lines, in resonant kaonic atoms. In the kaonic atoms' experimental investigation, the information about the strong kaon-nucleus interaction is provided by kaonic X-rays coming from the last line of the cascade series. The relative yield of this line gives the nuclear absorption width of the "upper" levels. Moreover, its shift and width are characteristics of the "lower" level. In non-resonant energy levels, where the configuration mixing is negligible, the energy levels are eigenstates of orbital angular momentum with $l = n-1$. When the E2 nuclear resonance condition occurs, the energy level is affected by the mixing condition with a normally not accessible level of the atom. This hidden level has an angular momentum $l = 2$ units smaller than the upper level, and affect the width of the resonant level. The nucleus

Table I. – *Energies and parameters of the kaonic atoms in which the E2 nuclear resonance is expected* [15]. *More details about the method used for calculations are reported in* [17].

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
$^{96}_{44}$Ru	832	(6,5)–(4,3)	875	6→5	312	0.42
$^{122}_{50}$Sn	1140	(6,5)–(4,3)	1106	6→5	403	0.42
$^{138}_{56}$Ba	1426	(6,5)–(4,3)	1346	6→5	505	0.15
$^{198}_{80}$Hg	412	(8,7)–(7,5)	406	6→5	403	0.42

is probed with a less peripheral kaon wave function. Therefore, by observing spectra emitted by E2 resonant kaonic atoms and comparing them with those of neighbouring non-resonant nuclei, one could extract unique and fundamental information about the strong kaon-nucleus interaction. Additionally, by comparing the intensities ratio (attenuated line/reference) between a resonant isotope and a non-resonant one, it is possible to directly measure the fraction of kaons absorbed by the excited nucleus.

In [15], a list of E2 resonant kaonic atoms was determined (see table I), calculating the energy levels and estimating the mixing parameters and X-ray lines attenuation with the method described in [17]. Such method was used also for the prediction of E2 nuclear resonance in pionic and anti-protonic atoms, whose effects were measured [20, 21].

As reported in table I, in four isotopes of kaonic molybdenum (94, 96, 98, and 100) the E2 nuclear resonance effect takes place by mixing $(6h, 0^+)$ and $(4f, 2^+)$ states. The wave function describing this resonance effect is

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

Here, the admixture coefficient is expressed as $\alpha = \pm\frac{\langle 4f,2^+|H_q|6h,0^+\rangle}{E_{(4f,2^+)}-E_{(6h,0^+)}}$. A diagram illustrating the effect using $^{98}_{42}$Mo as an example can be seen in fig. 1. Molybdenum isotopes offer a unique and really interesting opportunity for the investigation of strong kaon nucleus interaction properties with the E2 nuclear resonance effects, in kaonic atoms. The comparison between the measured spectra of these kaonic isotopes could reveal new fundamental information on strong interaction in the strangeness sector and the nuclear distribution.

3. – The measurement performed at the Lawrence and Berkeley Laboratory

The first measurement of the E2 nuclear resonance effects in a kaonic atom was performed on K$^-$-$^{98}_{42}$Mo at the Lawrence and Berkeley Laboratory (LBL) in California (1975) [19]. The kaons were produced by colliding a 5,6 GeV proton beam with a tungsten target, at Bevatron. The intensity averaged of the beam is 5×10^{11} per machine burst, which lasted 1 s and was repeated every 6 s. The kaons were focused and transported to the experimental target with a momentum of 500 MeV/c, by a dedicated

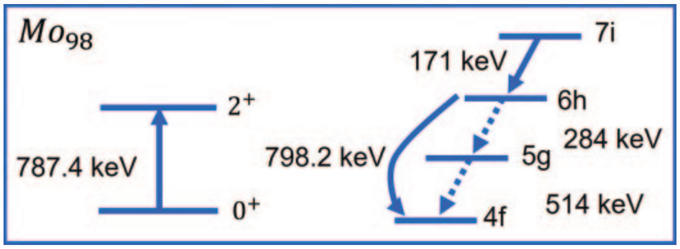

Fig. 1. – Diagrams illustrating the E2 nuclear resonance effect in kaonic molybdenum 98 are shown. The resonance mixes the $(6h, 0^+)$ and $(4f, 2^+)$ states, weakening the $6h \rightarrow 4f$ transition line and any lower lines in comparison to a non-resonant molybdenum isotope.

beam-line branching off from the tungsten target. The beam-line is described in fig. 2. The end of the beam-line was equipped with a series of counters for kaons' identification. This group of counters consisted of 3 scintillators and a water Cherenkov counter, interleaved with graphite degraders. A schematic description of the experimental apparatus is shown in fig. 3.

The target consisted of a pill-box–shaped vessel made from standard methyl-methacrylate tubing and containing foils of $^{98}_{42}$Mo (99% pure isotopes) in standard boxes filled at the Isotope Development Center at Oakridge. The outside diameter of the cylindrical target was 10.16 cm (8.9 cm inside diameter). The target foils were fixed using standard-sized plastic rings. The flat sides of the target vessel were made of Mylar (0.0127 cm thick). The target was 2 g/cm^2 thick (2.8 g/cm^2 along the beam-line, see fig. 3). The end of the beam-line was set to stop about 100 K$^-$ in the 2.8 g/cm^2 of the target, per burst of the kaon beam. The X-rays were detected with three different semiconductor detectors: a lithium-drifted germanium detector, a lithium-drifted silicon detector and an ultrapure germanium detector. More technical information about the detectors can be found in [23, 24].

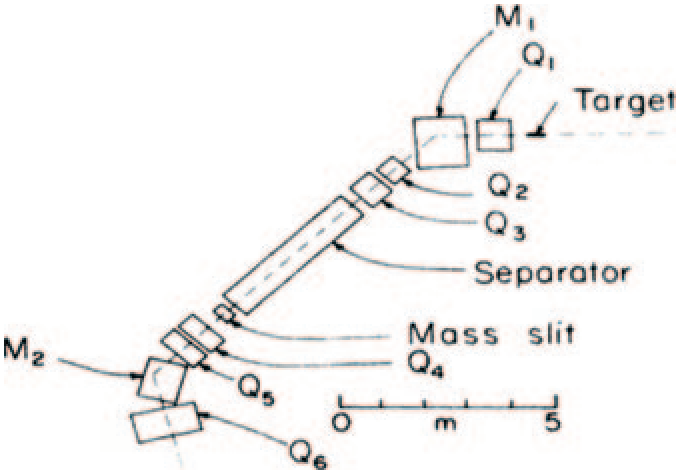

Fig. 2. – Schematic view of the kaon beam-line branching off the tungstenum target at the Bevatron, reported in [19]. Q stays for quadrupole, and M for bending magnet. A set of devices to perform the K$^-$-$^{98}_{42}$Mo measurement was installed downstream of the Q$_6$ (see fig. 3).

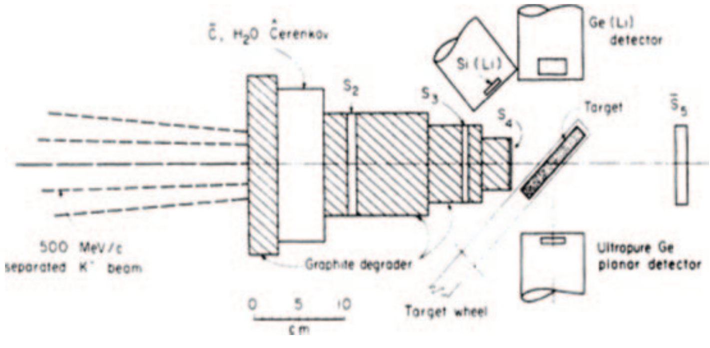

Fig. 3. – Schematic view of the kaon beam-line in the end part, downstream of the quadrupole Q_6 (see fig. 2), arranged to perform the K^--${}^{98}_{42}$Mo measurement. The S devices are scintillators. In the figure, the beam counters, the graphite degrader, the target wheel and the semiconductor detectors are shown. The target was located about 65 cm from the quadrupole Q_6. The schematic description was reported in [19].

TABLE II. – *Results got in 1975 at Bevatron, measuring the attenuation of the* $6h \to 5g$ *X-ray line in* K^--${}^{98}_{42}$Mo *due to the* E2 *nuclear resonance, concerning the same transition measured in non-resonant* K^--${}^{92}_{42}$Mo. α *is the attenuation coefficient expressed in eq.* (2), *whilst* $R_\alpha = (\frac{7\to6}{6\to5}, K^-\text{-}{}^{98}_{42}\text{Mo})/(\frac{7\to6}{6\to5}, K^-\text{-}{}^{92}_{42}\text{Mo})$.

Target	$E^{K^-\text{-}{}^{x}_{42}\text{Mo}}_{(6,5)\to(4,3)}$ (keV)	$E^{Nucl}_{0^+\to2^+}$ (keV)	$\lvert a\rvert$	R_a
${}^{98}_{42}$Mo	798.2	787.4	0.033	0.16 ± 0.16
${}^{92}_{42}$Mo	799.1	1540	0.001	1.00 (ref)

The experiment was performed in 1975. The $7i \to 6h$ and $6h \to 5g$ X-ray transitions of ${}^{98}_{42}$Mo were measured with germanium detectors. The same transitions of the non-resonant ${}^{92}_{42}$Mo isotope were measured, to be used as a reference. The E2 nuclear resonance effect was observed in K^--${}^{98}_{42}$Mo, expressed as the attenuation of X-ray lines, but only 25 hours of data taken resulted not being enough for a conclusive result. The final spectra collected are shown in fig. 4. Results obtained by the analysis of data collected are shown in table II.

4. – The KAMEO proposal: measurement of the E2 nuclear resonance effects in kaonic molybdenum isotopes

From 1975 to today, the experiment performed at Bevatron by Goldfrey, Lum and Wiegand [18] remains the only measurement of the E2 nuclear resonance effect in kaonic atoms. Moreover, this measurement was inconclusive due to the insufficient amount of data accumulated in the 25 hours of data taking. In the last about 50 years, technological progress has accompanied the experimental physics of kaonic atoms allowing the development of dedicated devices for more precise measurements. The SIDDHARTA-2 experiment will perform in 2023 the first measurement of the $2p \to 1s$ X-ray transition in kaonic deuterium, at the DAΦNE e^+e^- collider. The DAΦNE collider is a Φ factory, that produces low-energetic K^- ($p = 127\,\text{MeV}/c$), suitable for kaonic atoms investiga-

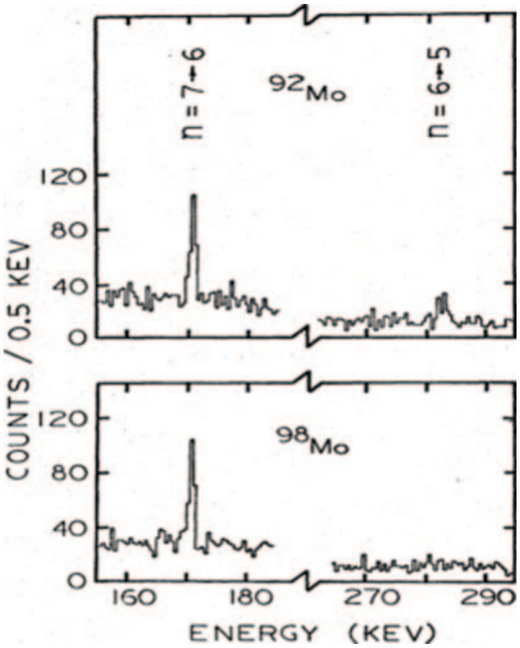

Fig. 4. – Spectra collected measuring the $7i \to 6h$ and $6h \to 5g$ transitions emitted by the E2 resonant K$^-$-$^{98}_{42}$Mo and the non-resonant K$^-$-$^{92}_{42}$Mo isotope at Bevatron, in 1975 [18]. The E2 nuclear resonance effect was observed in K$^-$-$^{98}_{42}$Mo, expressed as the attenuation of X-ray lines, but only 25 hours of data taken resulted not being enough for a conclusive result.

tion. The SIDDHARTA-2 experiment is equipped with a cylindrical target placed above the Interaction Point (IP) of the collider [25]. The KAMEO experiment plans to exploit the horizontal plane, running in parallel with the SIDDHARTA-2 experiment (see fig. 5). The target will consist of several solid 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). The solid strip surface being about 4 cm × 8 cm. the thickness of the targets will be estimated with a dedicated Monte Carlo simulation, to get the highest efficiency in kaonic Mo isotope production and measurement. The target strips are placed 5 mm outer the SIDDHARTA-2 luminometer, which consists of plastic scintillators 80 mm × 40 mm × 2 mm read by pairs of Photo Multiplier Tubes (PMTs). The luminometer is placed at 110 mm from the IP and is used to measure the luminosity of the DAΦNE collider. In KAMEO, the luminometer will be used as a trigger for the X-ray spectroscopy with a High-Purity Germanium (HPGe) detector. The HPGe detector is produced by Baltic Scientific Instruments and is placed at about 115 mm from the target strips (depending on the thickness of the strips). This detector is ideal for the measurement of the $7i \to 6h$ and $6h \to 5g$ atomic transitions of the kaonic Mo isotopes, at energies: ∼170 keV and ∼280 keV, respectively. The *p*-type HPGe detector has a cylindrical active part with a base diameter of 59.8 mm and a height of 59.3 mm. This HPGe detector was designed to work under high-rate conditions (to 150 kHz), with slight degradation of the resolution. The energy resolutions (FWHM) of the HPGe detector, measured using low-activity sources ^{133}Ba and ^{60}Co (activity $< 1\ \mu$Ci) and analog electronics, are 0.87 keV at 81 keV, 1.06 keV at 302.9 keV, 1.11 keV at 356 keV, and 1.67 keV

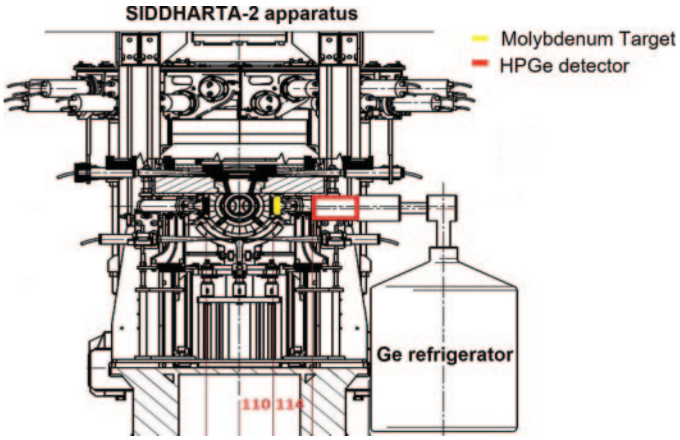

Fig. 5. – Schematic view of the KAMEO installed on the horizontal line close to the interaction point of the DAΦNE collider, running in parallel with the SIDDHARTA-2 experiment.

at 1330 keV. The efficiency of the HPGe detector for Mo isotopes will be estimated with the Monte Carlo simulation. At a preliminary estimate, based on the DAΦNE performance during the SIDDHARTA-2 kaonic helium measurement [25], in 2022, and the data of the experiment performed in 1975, the attenuation produced by the E2 nuclear resonance effect in kaonic molybdenum isotopes 94, 96, 98 and 100 should be measured in 10–15 days of data taking for each isotope, plus 10–15 days of measurement on 92 Mo isotope (used as reference).

5. – Goals of the KAMEO experiment

The main goal of KAMEO is to measure the mixing coefficient α due to the E2 nuclear resonance effect in the ${}^{94}_{42}$Mo, ${}^{96}_{42}$Mo, ${}^{98}_{42}$Mo, ${}^{100}_{42}$Mo resonant isotopes, achieving a precision better than 10%. The α coefficient is extracted from the attenuation of the $6h \to 5g$ transition in the spectra of resonant Mo isotopes, in comparison with the spectrum of non-resonant ${}^{92}_{42}$Mo, used as a reference. Moreover, 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, as well as 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 might turn out to be a “Coulomb assisted nuclear quasi-bound state of K^- meson”. The shifts and broadenings of atomic levels in kaonic molybdenum isotopes are extracted by comparing X-ray transitions in kaonic molybdenum isotopes with purely electromagnetic values determined using QED. This can be done using a procedure similar to that used for anti-protonic tellurium isotopes [21]. The expected precision is of the order of some keV. Finally, the measurements performed by KAMEO allow the study of the neutron density in the nuclear periphery of kaonic Mo isotopes. This study is performed by determining the difference between neutron and proton *rms* radii with a precision of 0.1 fm, as well as by determining the precise value of the neutron *rms* radius, similar to the method used in [21]. 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, a process that violates lepton number conservation, and the observation of which would demonstrate that the neutrino is a Majorana particle [22].

6. – Conclusions and outlooks

The measurement of the E2 nuclear resonance effect in kaonic molybdenum isotopes 94, 96, 98, and 100 provides new insights into the strong interaction in the strangeness sector at low energy. Additionally, by measuring this effect with high precision, a more detailed understanding of the distribution of neutrons in the nuclear periphery of these isotopes can be obtained, which would be important for the research on the neutrinoless double beta decay of $^{98}_{42}$Mo. The KAMEO experiment plans to perform measurements at the DAΦNE collider at LNF-INFN, in parallel with the SIDDHARTA-2 experiment. A dedicated Monte Carlo simulation is being developed to optimize the experimental setup and estimate the achievable precision of the measurements. Overall, kaonic molybdenum, with its 4 stable isotopes in which the E2 nuclear resonance effect occurs and a non-resonant stable isotope as a reference ($^{92}_{42}$Mo), offers a unique and exciting opportunity for the investigation of the strong interaction and the distribution of neutrons in the nuclear periphery.

* * *

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** (1994) 14.
[2] Bernard V., *Prog. Part. Nucl. Phys.*, **60** (2008) 82.
[3] Cieplý A., Mai M., Meissner U. G. and Smejkal J., *Nucl. Phys. A*, **954** (2016) 17.
[4] Davies J. D. *et al.*, *Phys. Lett. B*, **83** (1979) 55.
[5] Izycki M. *et al.*, *Z. Phys. A*, **297** (1980) 11.
[6] Baird S. *et al.*, *Nucl. Phys. A*, **392** (1983) 297.
[7] Iwasaki M. *et al.*, *Phys. Rev. Lett.*, **78** (1997) 3067.
[8] Beer G. *et al.*, *Phys. Rev. Lett.*, **94** (2005) 212302.
[9] Okada S. *et al.*, *Phys. Lett. B*, **653** (2007) 387.
[10] Bazzi M. *et al.*, *Phys. Lett. B*, **681** (2009) 310.
[11] Bazzi M. *et al.*, *Phys. Lett. B*, **704** (2011) 113.

[12] Bazzi M. *et al.*, *Phys. Lett. B*, **697** (2011) 199.
[13] Bazzi M. *et al.*, *Phys. Lett. B*, **714** (2012) 40.
[14] Curceanu C. *et al.*, *Few-Body System*, **62** (2021) 83.
[15] Leon M., *Nucl. Phys. A*, **260** (1976) 461.
[16] Leon M., *Informal Report United States: N. p., Los Alamos National Lab. (LANL), Los Alamos, NM (United States)*, LA-5994-MS (1975).
[17] Leon M., *Phys. Lett. B*, **50** (1974) 425.
[18] Goldfrey G. L., Lum G. K. and Wiegand C. E., *Phys. Lett. B*, **61** (1976) 45.
[19] Wiegand C. E. and Goldfrey G. L., *Phys. Rev. A*, **9** (1974) 2282.
[20] Bradbury J. N., Leon M., Daniel H. and Reidy J. J., *Phys. Rev. Lett.*, **34** (1975) 303.
[21] Klos B., Wycech S. *et al.*, *Phys. Rev. C*, **69** (2004) 044311.
[22] Nesterenko D. A., Jokiniemi L., Kotila J. *et al.*, *Eur. Phys. J. A*, **58** (2022) 44.
[23] Hansen W. L., *Nucl. Instrum. Methods*, **94** (1971) 377.
[24] Landis D. A., Goulding F. S. and Jaklevic M., *Nucl. Instrum. Methods*, **87** (1970) 377.
[25] Sirghi D. *et al.*, *J. Phys. G: Nucl. Part. Phys.*, **49** (2022) 055106.