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Abstract. The nuclear E2 resonance effect occurs when an atomic de-excitation energy is closely matched by a nuclear excitation energy. It produces an attenuation of some of the atomic X-ray lines in the resonant isotope target. Investigating the nuclear E2 resonance effect in kaonic atoms, important information about kaon-nucleus strong interaction can be provided. The only $K^- - ^{98}_{42}Mo$ nuclear resonance effect was measured by G. L. Goldfrey, G- K. Lum and C. E. Wiegand at Lawrence Berkeley Laboratory, in 1975. The nuclear E2 resonance effect was observed in 25 hours of data taking, not enough to provide a conclusive result. 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 at the same transition, with similar energy values. The KAMEO (Kaonic Atoms Measuring nuclear resonance Effects Observables) experiment plans to study the E2 nuclear resonance effect in kaonic Molybdenum isotopes at the DAΦNE e^+e^- collider, during the SIDDHARTA-2 experiment. The experimental strategy consists of exposing four solid strip targets, each enriched with one Molybdenum isotope, to negatively charged kaons, using a germanium detector for X-ray transition measurements. A further exposure of a non-resonant $^{92}_{42}Mo$ isotope solid strip target will be used as reference for standard non-resonant transitions.

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1. Introduction

Kaonic atoms are exotic atoms formed whenever a negatively charged kaon (K^-) is captured by an atomic system due to the electromagnetic interaction with the nucleus and replaces an electron in the atomic shell. After capture, the K^- begins an electromagnetic cascade process that will culminate with its absorption by the atomic nucleus. As the kaon approaches the nucleus, jumping into the innermost levels of the kaonic atom, the strong kaon-nucleus interaction enters into play, turning out in affecting the atomic structure enough to be experimentally measured with a dedicated X-ray spectroscopy [1, 2, 3]. The experimental investigation of kaonic atoms started in 1970s [4, 5, 6] and has continued until these days [7, 8, 9, 10, 11, 12, 13], representing a fundamental tool to investigate 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 National Laboratories of Frascati (LNF), Italy [14], so allowing, in combination of the kaonic hydrogen measurement performed by the SIDDHARTA experiment [10], to extract the antikaon-nucleon scattering lengths.

In an atomic system, whenever a nuclear excitation energy closely matches an atomic de-excitation energy, a resonance condition occurs, which is known as E2 nuclear resonance [15]. Several atoms are predicted to be resonant to kaons [16]. Among them, 4 isotopes of kaonic Molybdenum ($^{94}_{42}$Mo, $^{96}_{42}$Mo, $^{98}_{42}$Mo and $^{100}_{42}$Mo) are really interesting [17]. In these Mo isotopes, the E2 resonance effect might allow to obtain information on the properties of deeply bound kaonic levels, not easily accessible by the kaon cascade, due to the nuclear absorption. Moreover, the comparison between these measurements might allow the extraction of information on the strong nuclear potential by investigatibg the variation of the resonance's parameters with the growing of neutron numbers among the isotopes. In 1975, G. L. Goldfrey, G. K. Lum and C. E. Wiegand performed the first measurement of the E2 nuclear resonance effect in $^{98}_{42}$Mo, at Lawrence and Berkeley Laboratory (LBL) in California [18, 19]. The E2 nuclear resonance was measured, but only 25 hours of data were collected, not enough for a conclusive result. This is the only measurement of the E2 nuclear resonance effect performed in kaonic atoms. The E2 nuclear resonance was measured in other exotic atoms, such as pionic atoms [20] and anti-protonic atoms [21]. In particular, the measurement of the E2 nuclear resonance effect in even-A anti-protonic tellurium isotopes was used to determine properties of the neutron density in the nuclear periphery [21]. A similar investigation could be performed on Mo isotopes. Furthermore, neutrinoless double beta decay of $^{98}_{42}$Mo is a rare researched process violating the lepton number conservation. Its observation would demonstrate that neutrino is a Majorana particle [22]. The $\beta\beta$-decay nuclear matrix elements are calculated using models depending 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 relative distance among neutrons in the isotope. In this paper, the possibilities and the advantages of the kaonic Molybdenum isotopes investigation at DAΦNE collider, in parallel with the SIDDHARTA-2 experiment, are briefly presented.

2. The E2 Nuclear resonance effects in kaonic Molybdenum isotopes

The E2 nuclear resonance occurs in atoms for which a nuclear excitation energy closely matches an atomic de-excitation energy. The effect turns out in a mixing of the atomic states due to the electrical quadrupole excitations of nuclear rotational states. Quantum-mechanically, the effect mixes $(n, l, 0^+)$ level with $(n', l-2, 2^+)$ level, producing a wave function ϕ which contains a small admixture of excited nucleus-deexcited atom wavefunctions:

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

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

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

In conclusion, due to the E2 nuclear resonance, a significant weakening/attenuation of the involved kaonic X-ray line and any lower lines can be observed. Moreover, comparing the ratio of intensities (attenuated line/reference) between the resonant isotope and a non-resonant one, is it possible to directly measure the fraction of kaons absorbed by the excited nucleus.
In kaonic Molybdenum isotopes 94, 96, 98 and 100, the E2 nuclear resonance effect occurs by mixing (6h,0^+) and (4f,2^+) states. The wave function describing the resonance effect is:

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

where the admixture coefficient $\alpha = \pm\frac{\langle 4f,2^+|H_q|6h,0^+\rangle}{E_{(4f,2^+)}-E_{(6h,0^+)}}$. A schematic representation of the effect is shown, using $^{98}_{42}$Mo as an example, in Fig. 1.

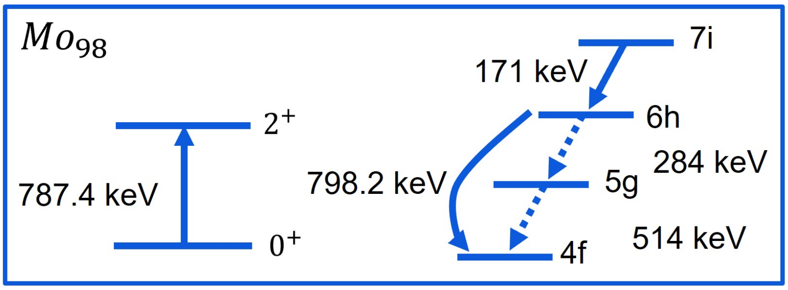

Figure 1. Schematic views of the E2 nuclear resonance effect in kaonic Molybdenum 98. The resonance mixes (6h,0^+) and (4f,2^+) states, attenuating the 6h→4f transition line and any lower lines with respect to a non-resonant Molybdenum isotope.

The first measurement of the E2 nuclear resonance effects was performed on K^-–$^{98}_{42}$Mo at LBL (California), in 1975 [18]. The experiment was performed with a negative kaon beam and solid targets of $^{98}_{42}$Mo, and non-resonant $^{92}_{42}$Mo as reference. The spectra were collected using germanium detectors feeding a pulse height analyzer. 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 to be not enough for a conclusive result. After this experiment, the E2 nuclear resonance effect was not investigated anymore in kaonic atoms. Today, about 50 years after, the KAMEO experiment (Kaonic Atoms Measuring nuclear resonance Effects Observables) plans to measure the E2 resonance effect in kaonic atoms at the DAΦNE collider, during the SIDDHARTA-2 data-taking period. The KAMEO apparatus consists of enriched solid targets of Molybdenum isotopes 94, 96, 98, 100 and 92 (as reference) exposed to the K^- emitted in the horizontal direction (not collected by SIDDHARTA-2), with a germanium detector placed behind the solid targets, for the X-ray spectroscopy. The KAMEO experiment has many goals:

- The measurement of the mixing coefficient α due to the E2 nuclear resonance effect in the four resonant Mo isotopes with a precision better than 10%. The α coefficient can be extracted from the attenuation of the 6h→4f and lower transitions (6h→5g and 5g→4f) in resonant Mo isotopes spectra, in comparison with the spectrum of a non-resonant Mo isotope used as reference ($^{92}_{42}$Mo).

- The first measurement of 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 shift ($\epsilon_{4f,2^+}$) an width ($\Gamma_{4f,2^+}$) of the 4f atomic level in excited-nucleus isotopes of kaonic Mo, due to the kaon-nucleus strong interaction. Shifts and broadenings of atomic levels in kaonic Molybdenum isotopes are extracted by measuring X-ray transition in kaonic Molybdenum isotopes and comparing them with purely electromagnetic values determined with QED. The procedure adopted is the same used with antiprotonic tellurium isotopes [21]. The expected precision should be of the order of keV.
- The investigation of neutron density in the nuclear periphery of kaonic Mo isotopes, through the determination of the difference between neutron and proton *rms* radii (with the precision of the order 0.1 fm) and the precise determination of the neutron *rms* radius, as performed in [21]. The extraction of neutrons *rms* radius in 98_{42}Mo would have an important role in the research of the neutrinoless double beta decay of $^{98}_{42}$Mo, a process violating the lepton number conservation and whose observation would demonstrate that the neutrino is a Majorana particle [22].

3. Conclusions and outlooks

The measurement of the E2 nuclear resonance effect in kaonic Molybdenum 94, 96, 98 and 100 isotopes is a new source of information on the strong interaction in the strangeness sector, at low energy. Moreover, by measuring this effect with high precision, a detailed description of the distribution of the neutrons in the nuclear periphery of the isotopes could be provided, enriching our knowledge and providing important constraints for the measurement of neutrinoless double beta decay of $^{98}_{42}$Mo. The KAMEO experiment plans to perform the measurement of the E2 nuclear resonance effect in kaonic Molybdenum isotopes at DAΦNE collider, at LNF-INFN, in parallel with the SIDDHARTA-2 experiment. A dedicated Monte Carlo simulation is being produced to optimize the experimental setup and estimate the achievable precision of the measurements. In conclusion, kaonic Molybdenum, characterized by 4 stable isotopes in which the E2 nuclear resonance effect occurs and a non-resonant stable isotope as reference ($^{92}_{42}$Mo), offers a unique and really interesting opportunity for the investigation of the strong interaction and the nuclear peripherical neutrons distribution.

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