New possible investigation on strong interaction in kaonic atoms:

The E2 nuclear resonance effect

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High Precision Measurement on kaonic atoms

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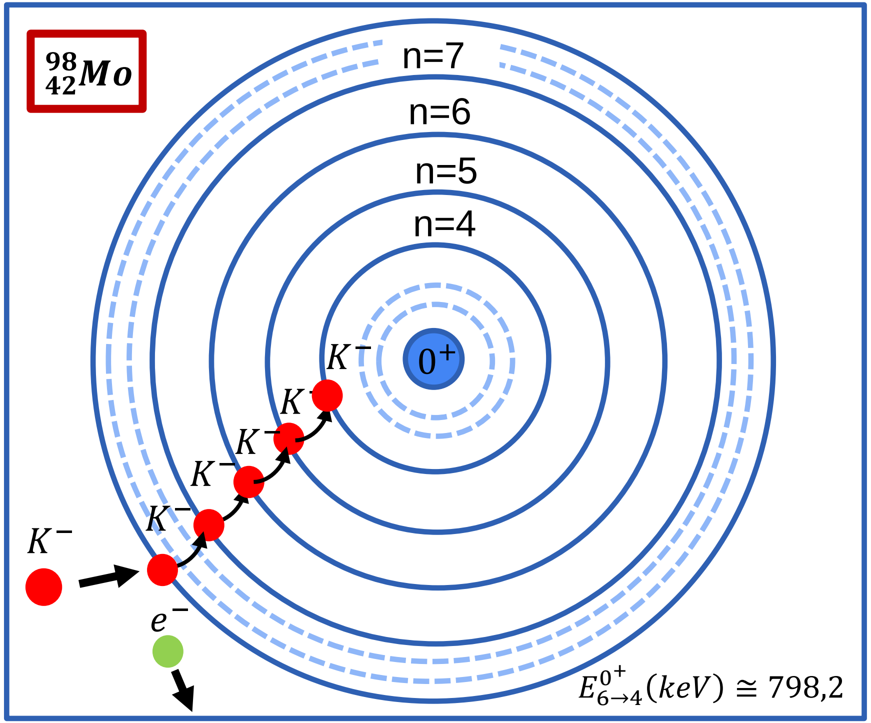
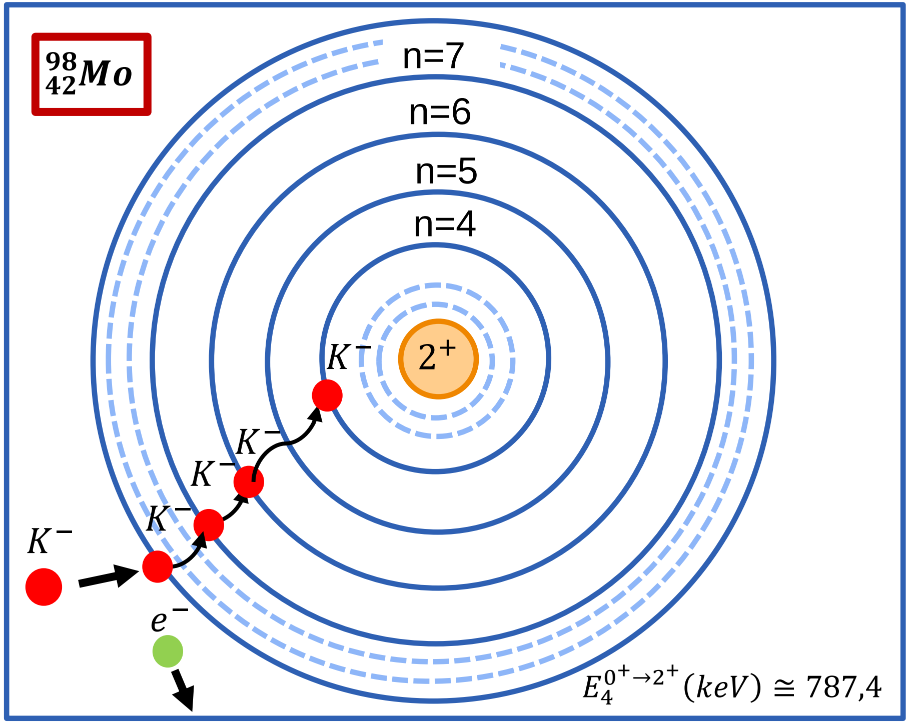
The E2 Nuclear Resonance Effect

In “thicklish nuclei” kaonic atoms, when an atomic de-excitation energy is closely matched by a nuclear excitation energy, a resonance condition occurs, which produces an attenuation of some of the atomic x-ray lines from a resonant versus a normal isotope target.





The E2 Nuclear Resonance Effect

Quanto-mechanically, the noncentral coupling between the hadron and the nucleus produces configuration mixing (E2), so that the energy eigenfunction contains a small admixture of excited nucleus-deexcited atom wavefunction:

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

where the admixture coefficient $a = \pm \frac{\langle 4f,2^+ | H_q | 6h,0^+ \rangle}{E_{(4f,2^+)} - E_{(6h,0^+)}}$ is very small, and Hq expresses the electric quadrupole interaction between hadron and nucleus, and the matrix element is in fact given in general by:

$$\langle H_q \rangle = \pm \frac{e^2}{2} Q_0 \langle r^{-3} \rangle$$

$$[(2I+1)(2I'+1)(2\ell+1)(2\ell'+1)]^{\frac{1}{2}}$$

$$\begin{pmatrix} 2 & I & I' \\ 0 & -K & K \end{pmatrix} \begin{pmatrix} 2 & \ell & \ell' \\ 0 & 0 & 0 \end{pmatrix} \begin{Bmatrix} 2 & I & I' \\ F & \ell & \ell' \end{Bmatrix}$$

$\langle r^{-3} \rangle$	quadrupole orbital radius
Q_0	nuclear quadrupole strength

H.L. Acker, Nucl. Phys. **87**, *153*, 1966

The E2 Nuclear Resonance Effect

The classical analogy would be to have the period of a hadron in its elliptical orbital match the natural vibration frequency of the nucleus, so that every pass through perigee the hadron strokes the nucleus at just the right time, and hence builds up a large nuclear oscillation

The nuclear absorption rate increases very drasically (by a factor of several hundred) for each unit decrease of orbital angular momentum; thus for a decrease of $\Delta l = 2$, the factor may be around 10^5.

INDUCED WIDTH: $\Gamma_{n,l}^{Ind} = |a^2|\Gamma_{n',l-2}^{0}$

A very small admixture coefficient a (typically 1%) can mean a significant induced width!

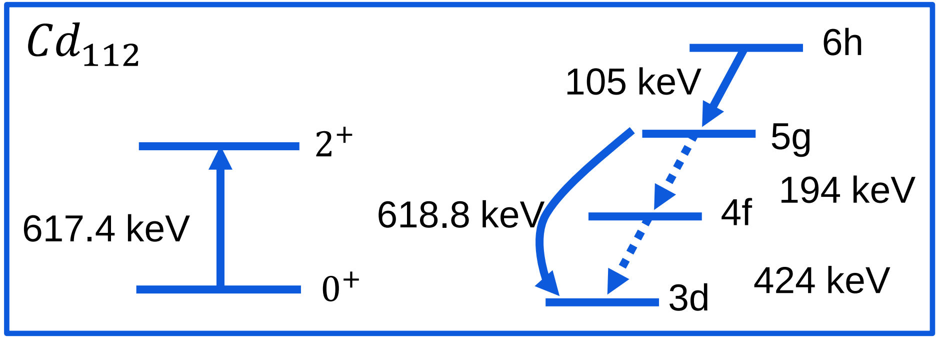
A significant weakening/attenuation of corresponding hadronic x-ray line and any lower lines can be observed.

Moreover, comparing the ratio of intensities (attenuated line/reference) from the resonant isotope (thicklish) to a non resonant one, we have the **direct measure of the fraction of hadrons absorbed by the excited nucleus**.

The pionic cadmium 112 experiment

An experiment measuring E2 resonance effect cadmium 112 was performed in 1975 by J. N. Bradbury, H.Daniel, J. Reidy and M. Leon at the biomedical pion beam of Los Alamos Meson Physics Facility (LAMPF).

In pionic cadmium (112), the energy difference between 5g and 3d levels, 618.8 keV, is very nearly equal to the nuclear excitation energy of 617.4 keV.

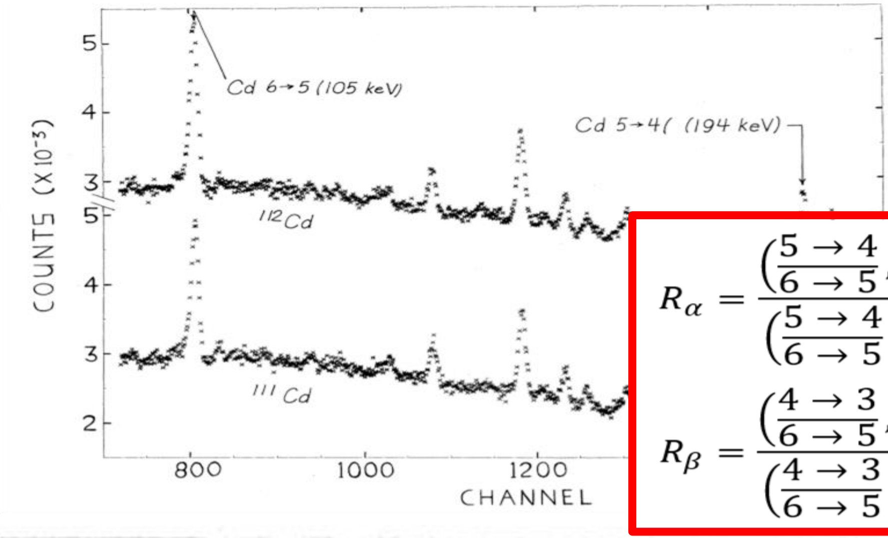


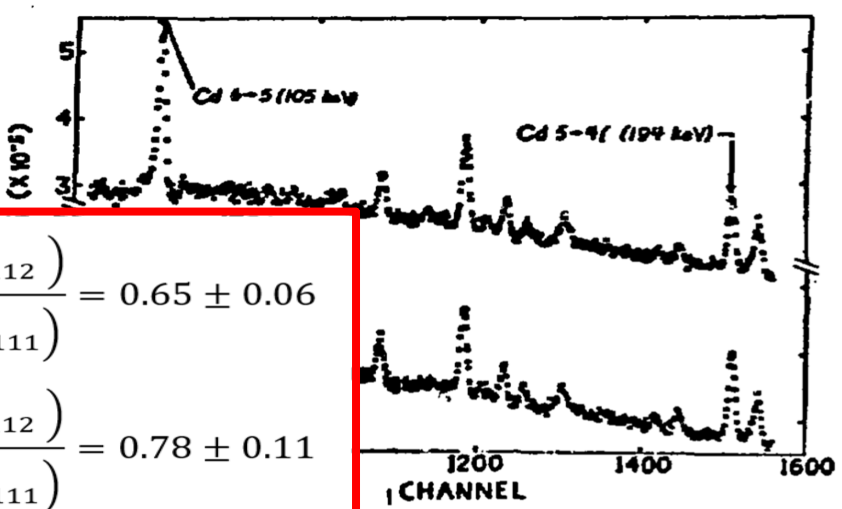
Experimental apparatus and measurement features:

- The experiment consisted of placing enriched isotope targets of Cd(111) e Cd(112) in turn into the negative pion beam for **2 hours**.
- The spectra were collected using a **germanium detector** feeding a pulse height analyzer.
- Natural Cadmio was exposed for a shorter time to provide consistency check.

Pionic cadmium 112 measurement

These results demonstrate the existence of the Nuclear Resonance Effect: the ratios are very significantly different from one.





$$R_\alpha = \frac{\left(\frac{5\to 4}{6\to 5}, Cd_{112}\right)}{\left(\frac{5\to 4}{6\to 5}, Cd_{111}\right)} = 0.65 \pm 0.06$$

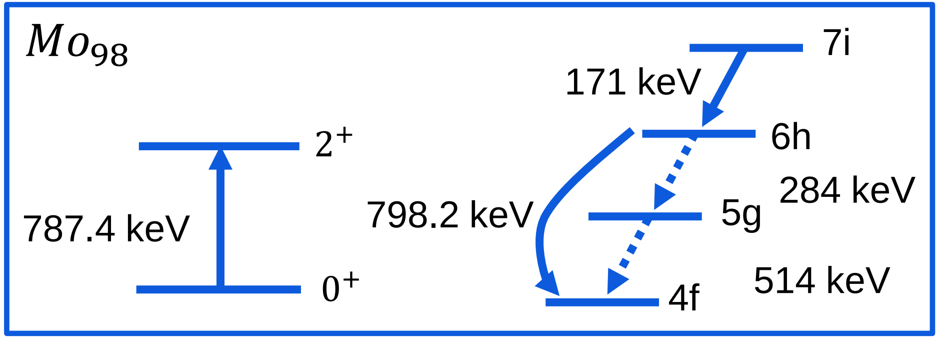
$$R_\beta = \frac{\left(\frac{4\to 3}{6\to 5}, Cd_{112}\right)}{\left(\frac{4\to 3}{6\to 5}, Cd_{111}\right)} = 0.78 \pm 0.11$$

Sample	6 → 5 (105 keV) (%)	5 → 4 (194 keV) (%)	Ratio $\frac{5\to 4}{6\to 5}$	4 → 3 (425 keV) (%)	Ratio $\frac{4\to 3}{6\to 5}$
^{112}CdO	26647 ± 3.6	9968 ± 5.5	0.374 ± 0.025	2446 ± 8.2	0.092 ± 0.008
^{111}CdO	21432 ± 3.7	12408 ± 5.1	0.579 ± 0.036	2526 ± 8.8	0.118 ± 0.011
Natural CdO	1953 ± 12	1293 ± 7.8	0.662 ± 0.096	···	···

The Molybdenum 98 experiment

An experiment measuring E2 Nuclear Resonance Effects in Molybdenum 98 was performed in 1975 by G. L. Goldfrey, G- K. Lum and C. E. Wiegand at Lawrence Berkeley Laboratory (LBL) in California.

In kaonic molybdenum (98), the energy difference between 6h and 4f levels, 798.2 keV, is very nearly equal to the nuclear excitation energy of 787.4 keV.

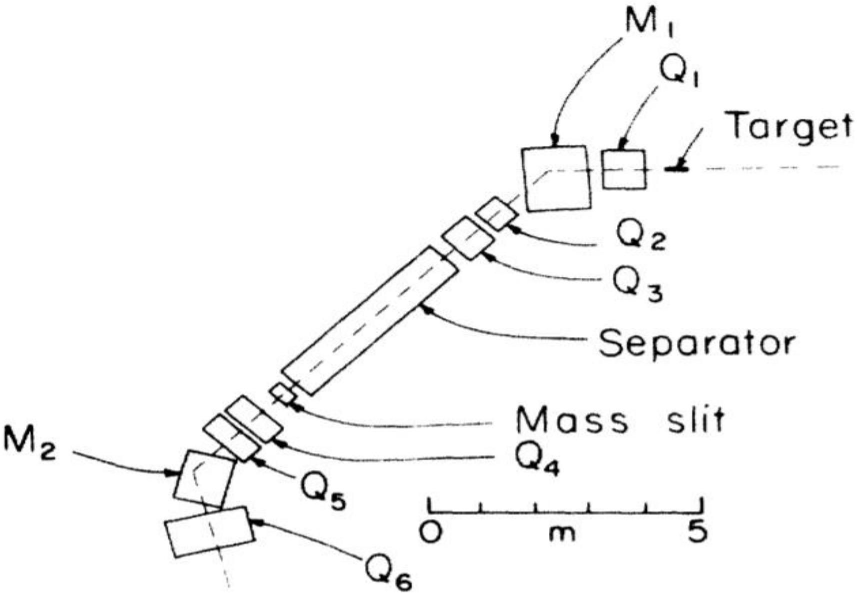


Experimental apparatus and measurement features:

- The experiment was performed with a negative kaon beam, turning the targets of Mo(98), and Mo(92) as reference.
- The spectra were collected using **germanium detectors** feeding a pulse height analyzer.

The kaon beam at Bevatron

Negative kaons were produced in a tungsten target (5.08 cm in legth along the beam, 0.50 cm high and 0.76 cm wide) by a proton beam with 5.6 GeV energy and 5×10^{11} of proton intensity per machine burst. The duration of each burst was 1 second and it was repeated for 6 seconds.



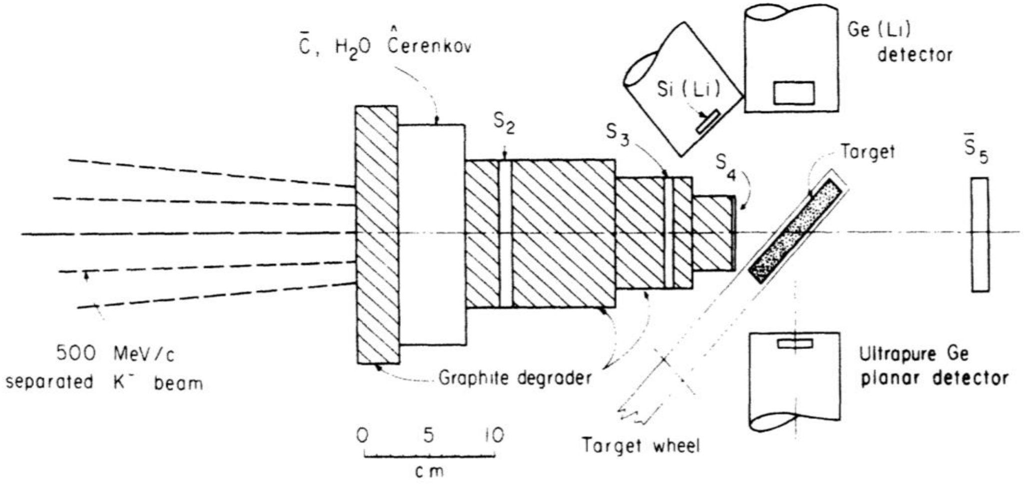
Kaons and other particles produced in the forward diections entered a mass spectrometer, consisting of 6 Quadrupoles (Q) two bending magnets (M), a separator and a «mass» slit.

A scintillator (S1) was placed behind the mass slit for kaon identification.

At the end of the mass spectrometer (Q6) a **500 MeV/c separated K^- beam is produced.**

The kaon beam at Bevatron

Downstream from Q6, a group of counters consisting of water Cerenkov counter, and 4 scintillators (S2, S3, S4, S5) were installed to discriminate kaons from pions, with the use of time of flight and anticoincidence with Cerenkov counter, and from background.



The target consists in a pill-box-shaped vessel made from stock methyl-methacrylate tubing 10.16 cm outside diameter (8.9 cm inside diameter).

Target thickness was 2 g/cm^2 (2.8 g/cm^2 along the beam)

The target was filled with 99% pure isotopes of Molybdenum 92 and 98, alternatively.

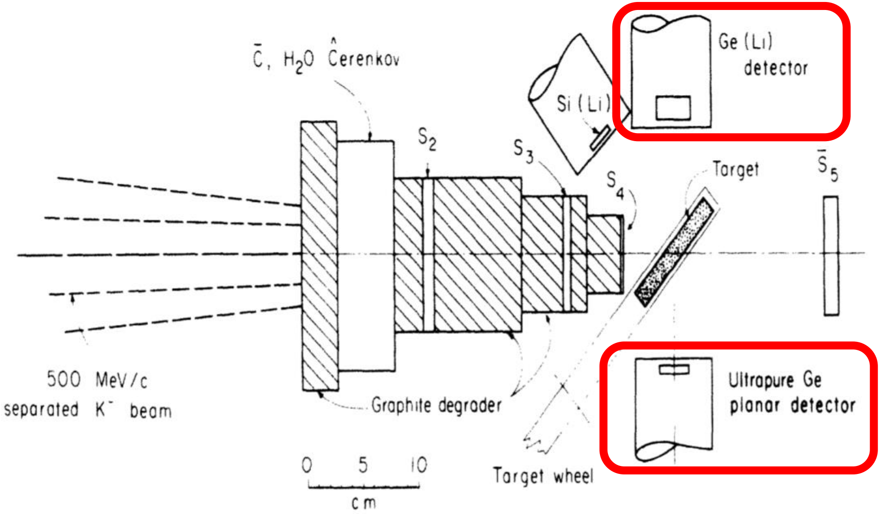
The flat sides of the container was of Mylar, less than 0.0127 cm thickness

The Germanium Detectors

The x-ray spectra coming from $K^{-} - {}^{98}_{42}Mo$ and $K^{-} - {}^{92}_{42}Mo$ were collected with ultrapure Germanium and Ge(Li) detectors, whose resolutions was estimated with the formula:

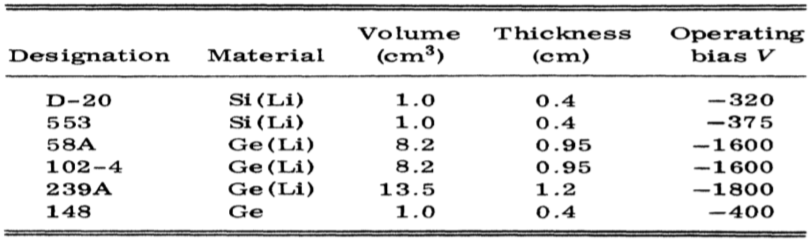
$$\Delta E(FWHM) = [P^2 + (2.36)^2 E\epsilon F]^{1/2}$$

where F=0.08 is the Fano Factor, $\epsilon = 2.94\ \mathrm{eV}$ is the average energy to make an electron-gole in Germanium, E is the energy deposited in the detector and P is the random noise



The ultrapure Ge detector is 0.4 cm thickness and has 1.8 cm of diameter, and provides a resolution of 580 eV FWHM at 85 keV

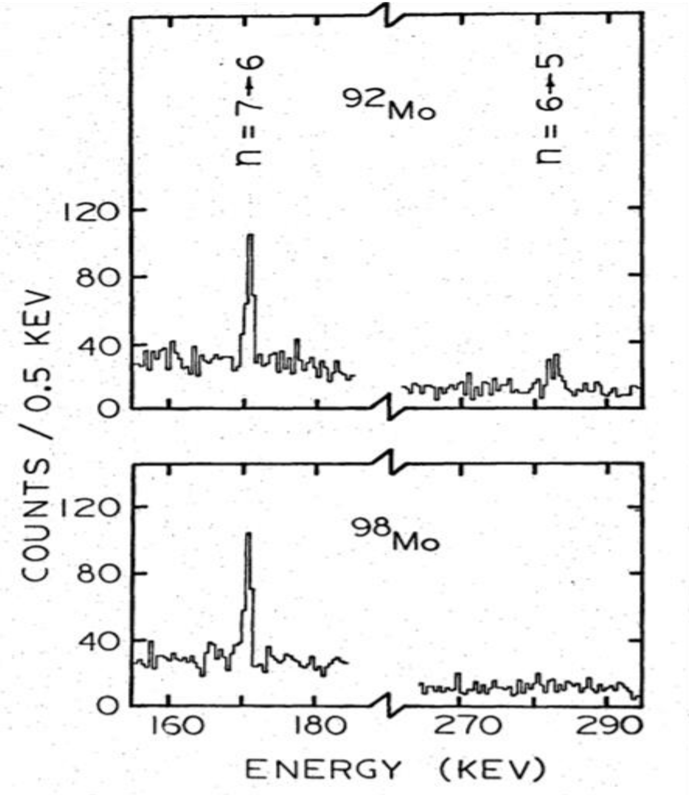
Ge(Li) detectors provide a resolution of 400 eV FWHM at 100 keV



Designation	Material	Volume (cm^3)	Thickness (cm)	Operating bias V
D-20	Si (Li)	1.0	0.4	−320
553	Si (Li)	1.0	0.4	−375
58A	Ge (Li)	8.2	0.95	−1600
102-4	Ge (Li)	8.2	0.95	−1600
239A	Ge (Li)	13.5	1.2	−1800
148	Ge	1.0	0.4	−400

The Molybdenum 98 experiment

The E2 Nuclear Resonance effect was observed $K^- - {}^{98}_{42}Mo$, expressed as the attenuation of x-ray line .



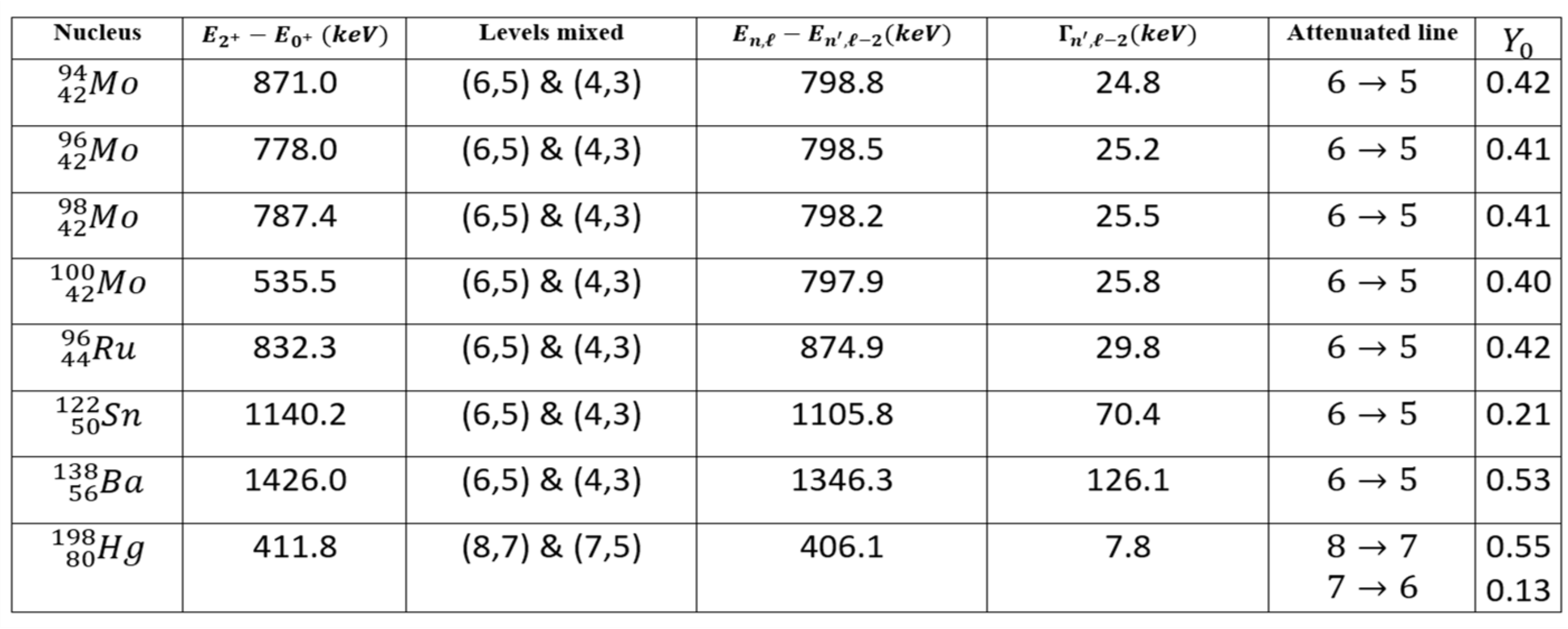
Target	$E^{K-Mo}_{(6,5)\to(4,3)}(keV)$	$E^{Nucl}_{0^+\to 2^+}(keV)$	$\lvert a \rvert$	R_α
${}^{98}_{42}Mo$	798.2	787.4	0.033	0.16 ± 0.16
${}^{92}_{42}Mo$	799.1	1540.0	0.001	1.00 (ref)

Only 25 hours of data taking with K-beam was **not enough for a conclusive result!!**

IMPROVABLE WITH MODERN DETECTORS AND MORE DATA TAKING TIME

Nuclear Resonance in Kaonic atoms

Nuclear Resonances are expected also for kaonic atoms. Such predictions have been obtained by integrating the Klein-Gordon equation with a phenomenological kaon-nucleon potential.



Nucleus	$E_{2^+} - E_{0^+}$ (keV)	Levels mixed	$E_{n,\ell} - E_{n',\ell-2}(keV)$	$\Gamma_{n',\ell-2}(keV)$	Attenuated line	Y_0
${}^{94}_{42}Mo$	871.0	(6,5) & (4,3)	798.8	24.8	6 → 5	0.42
${}^{96}_{42}Mo$	778.0	(6,5) & (4,3)	798.5	25.2	6 → 5	0.41
${}^{98}_{42}Mo$	787.4	(6,5) & (4,3)	798.2	25.5	6 → 5	0.41
${}^{100}_{42}Mo$	535.5	(6,5) & (4,3)	797.9	25.8	6 → 5	0.40
${}^{96}_{44}Ru$	832.3	(6,5) & (4,3)	874.9	29.8	6 → 5	0.42
${}^{122}_{50}Sn$	1140.2	(6,5) & (4,3)	1105.8	70.4	6 → 5	0.21
${}^{138}_{56}Ba$	1426.0	(6,5) & (4,3)	1346.3	126.1	6 → 5	0.53
${}^{198}_{80}Hg$	411.8	(8,7) & (7,5)	406.1	7.8	8 → 7 7 → 6	0.55 0.13

MOLYBDENUM OFFERS A UNIQUE OPPORTUNITY TO INVESTIGATE WITH NUCLEAR RESONANCES THE STRONG $K^- - N$ INTERACTION

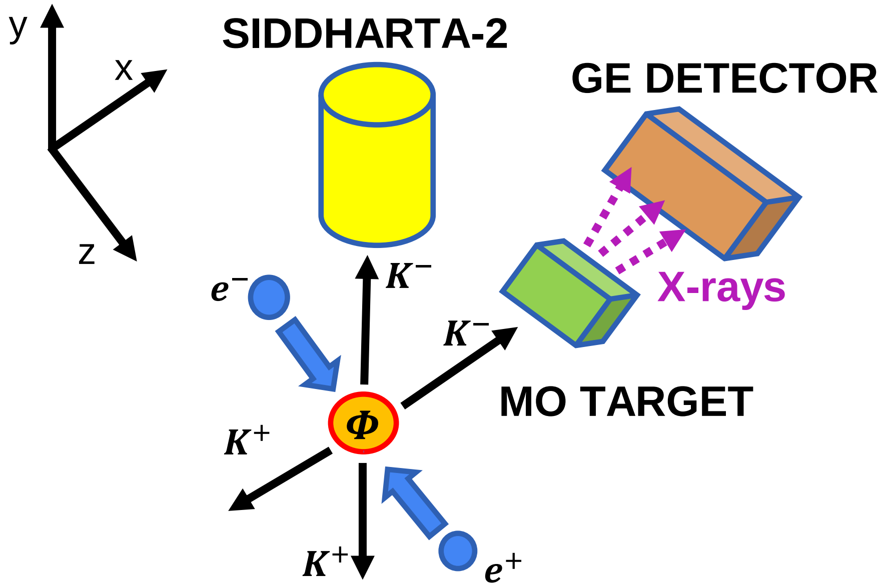
WHY INVESTIGATE NUCLEAR RESONANCE EFFECTS IN KAONIC ATOMS?

- Investigating the E2 Nuclear Resonance Effect could provide fundamental informations about nuclear potential behavior in kaon-nucleus interaction, providing fundamental constraints for models which aim to describe kaon-nucleon interaction potential.

- For a percentage of negative kaons nuclear absorption cannot occur, thus allowing the investigation on the d- or p-wave kaon-nucleus interaction, determining its attractive or repulsive behaviour, and can provide information on kaon-nucleus nuclear interaction for nuclei with high Z and excited nucleus.
- The $K^- - {}^{98}_{42}Mo$ nuclear resonance effect can be measured with higher precision, definitively. Moreover, same effect in ${}^{96}_{42}Mo$, ${}^{94}_{42}Mo$ and ${}^{98}_{42}Mo$ can be measured for the first time and from comparison, new properties of kaon-nucleon interaction and potential can emerge.
- It would be the first measurement of nuclear resonance effects in kaonic atoms at low energies (127 Mev/c)

EXPERIMENTAL PROPOSAL

The measurement of Nuclear resonance E2 effects in Molybdenum kaonic isotopes could be performed during the SIDDHARTA-2 data taking period, exploiting the horizontal emitted kaons with dedicated targets and a Germanium detector.



The measurement don’t affect SIDDHARTA-2

Mo Transition	Energy (eV)	Intensity (%)
K_{α_1}	17479.34	100
K_{α_2}	17374.3	*52*
K_{β_1}	19608.3	*26*
L_{α_1}	2293.16	100
L_{α_2}	2289.85	11
L_{β_1}	2394.81	53
L_{β_2}	2518.3	5
L_{γ_1}	2623.5	3

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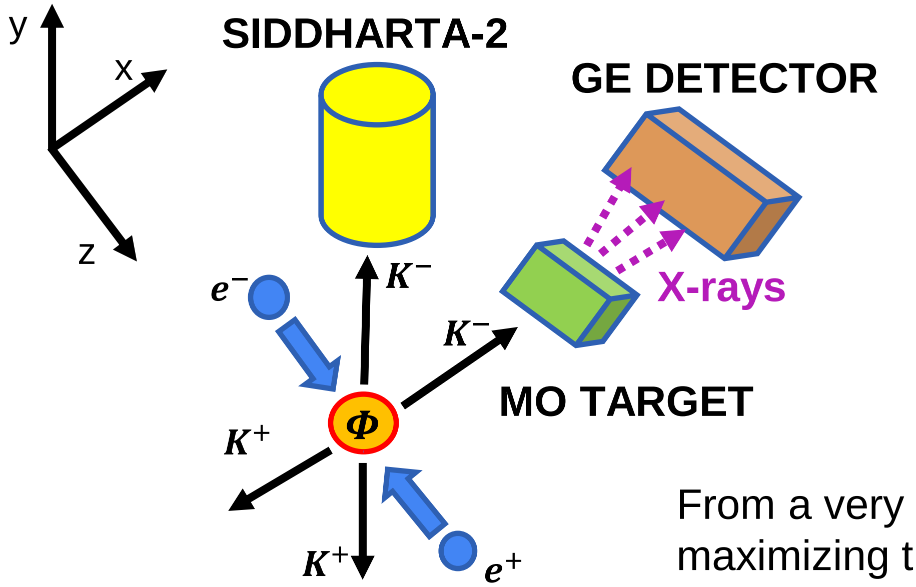

The measurement don’t affect SIDDHARTA-2

Mo isotope	Abundance	Half-Time
${}^{94}_{42}Mo$	9.19%	*stable*
${}^{96}_{42}Mo$	16.67%	*stable*
${}^{98}_{42}Mo$	24.29%	*stable*
${}^{100}_{42}Mo$	9.74%	$7.7 \times 10^{18}\ y$

From a very preliminary estimation, with a target maximizing the geometrical efficiency, **the measurements should be performed in few days for each isotope plus the standard molybdenum.**

REFERENCES

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- C. E. Wiegand and G. L. Godfrey, «Measurements of x rays and γ rays from stopped kaons», Phys. Rev. A, **9**, 2282, 1974, https://journals.aps.org/pra/abstract/10.1103/PhysRevA.9.2282

A THEORETICAL HELP IS NECESSARY

THANK YOU FOR YOUR ATTENTION!!!