New possible investigation on strong interaction in kaonic atoms: The E2 nuclear resonance effect

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Symposium - Nuclear E2 resonance effects in kaonic molybdenum isotopes



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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

The E2 Nuclear Resonance effect is a mixing of the atomic states due to the electrical quadrupole excitations of nuclear rotational states.

Quanto-mechanically, the effect mixes $(n, l, 0^+)$ levels with $(n', l - 2, 2^+)$ levels producing a wave function which contains a small admixture of excited nucleus-deexcited atom wavefunctions:

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

where the admixture coefficient $\alpha = \pm \frac{\langle n, l, 2^+ | H_q | n', l - 2, 0^+ \rangle}{E_{(n,l,2^+)} - E_{(n,l,0^+)}}$ (very small), and H_Q

expresses the *electric quadrupole interaction* between hadron and nucleus.

As example, for the nuclear E2 resonance effect in $K^- - Mo$ isotopes:

$$\psi = \sqrt{1 - |\alpha|^2} \phi(6h, 0^+) + \alpha \phi(4f, 2^+) \text{ with } \alpha = \pm \frac{\langle 4f, 2^+ | H_q | 6h, 0^+ \rangle}{E_{(4f, 2^+)} - E_{(6h, 0^+)}}$$

The E2 Nuclear Resonance Effect

HADRONIC ATOMS ARE VERY SENSITIVE TO QUITE AMOUNTS OF CONFIGURATION MIXING

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 .

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

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INDUCED WIDTH: \Gamma_{n,l}^{Ind} = |a^2|\Gamma_{n',l-2}^0
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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 <u>2 hours</u>.
- 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.



Pionic cadmium 112 measurement

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E2 effect in antiprotonic Te atoms

The nuclear E2 resonance effect was recently studied in even-A Te atoms for several reasons:

• The E2 effect allows to obtain informations on the properties of deeply bound antiprotonic atoms, not accessible by the antiprotonic cascade, in ticklish nuclei.

The attenuation of the $n = 8 \rightarrow n = 6$ x-ray transition affected by the E2 resonance measured in several even-A Te isotopes can lead to a precise determination of shift and width of the n = 6 level.





 The search for isotope effects in the level shift (ε) and width (Γ) would reveal sign of changes in the nuclear periphery when pair of neutrons are added to the lighest isotope (¹²²₅₂Te).

SAME TOPICS COULD BE INVESTIGATED WITH KAONIC MOLYBDENUM ATOMS (4 even-A ISOTOPES)

The antiprotonic Te experiment

Five even-A tellurium isotopes were investigate in two experiments conducted in 1995 and 1996 using antiprotons with momenta 300 MeV/c (${}^{124}_{52}Te$, ${}^{128}_{52}Te$, ${}^{130}_{52}Te$) and 106 MeV/c (${}^{122}_{52}Te$, ${}^{126}_{52}Te$).

High Purity Germanium (HPGe) detectors were employed for the x-ray measurement. The energy resolution was about 1 keV at 200 keV (relative efficiency was about 19%)





The antiprotonic Te experiment

The $|n = 8, l = 7, 0^+\rangle$ states in tellurium are mixed with the $|n = 6, l = 5, 2^+\rangle$ states. The small ratio of mixing strenght and level spacing (respectively $\cong 1 \text{ keV}$ and $\cong 15 \text{ keV}$) allows a perturbative treatment and the E2-induced, complex energy shift due to this mixing is approximately given by:

$$\varepsilon(E2; 8,7) - i \frac{\Gamma(E2; 8,7)}{2} \cong \frac{\langle 8,7; 0^+ | H_q | 6,5; 2^+ \rangle}{E_{(8,7,0^+)} - E_{(6,5,2^+)}}$$

where:

- $E_{(8,7,0^+)}$ is the energy of the $|n = 8, l = 7, 0^+$ state
- $E_{(6,5,2^+)} = E(2^+) + E_{em}(6,5) + \varepsilon(6,5) i\Gamma(6,5)/2$ is the energy of the state $|n = 6, l = 5, 2^+\rangle$

TABLE VIII. Shifts and widths of the deeply bound $n, l=6, 5$ level in ¹³⁰ Te.					
State (n, l)	Experimen	tal ε (keV)	Experimen	tal Γ (keV)	Calculated $\varepsilon - i\Gamma$ (keV)
(n,l)	j = l + 1/2	j = l - 1/2	j = l + 1/2	j = l - 1/2	
(6,5)	6.6 ± 3.8	3.6 ± 1.1	17.0 ± 4.4	11.8 ± 4.4	6.8- <i>i</i> 18.2

B. Klos, S. Wycech et al., PHYS. REV. C 69, 044311 (2004)

The antiprotonic Te experiment

The measured level shifts (ϵ) and widths (Γ) of the energy levels n=8,6 in even-A antiprotonic tellurium isotopes allowed the investigation toward the **neutron density in nuclear periphery**.

Neutron and proton distribution in the Te nuclei were described with two-parameter Fermi model.

The *rms* neutron radius was adjusted through experimental data.

THE DIFFERENCE BETWEEN NEUTRON AND PROTON RMS RADII Δr_{np} WAS DETERMINE.



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 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 $K^- - \frac{98}{42}Mo$ and $K^- - \frac{92}{42}Mo$ 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, $\epsilon = 2.94 \text{ eV}$ is the average energy to make an electrongole 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 provided a resolution of 580 eV FWHM at 85 keV

Ge(Li) detectors provided 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 $K^- - \frac{98}{42}Mo$, expressed as the attenuation of x-ray line .



Target	$E_{(6,5)\to(4,3)}^{K-Mo}(keV)$	$E_{0^+ \rightarrow 2^+}^{Nucl}(keV)$	<i>a</i>	R _α
⁹⁸ 42	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!!**



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	$E_{n,l} - E_{n,l-2}[keV]$	$\Gamma_{n,l-2}[keV]$	Atten lines	Energy [keV]	Ref lines	Energy [keV]
⁹⁴ 42Mo	871	(6,5)+(4,3)	798.8	24.8	6 → 5	284.3	7 →6	171.1
⁹⁶ ₄₂ Mo	778	(6,5)+(4,3)	798.5	25.2	6 → 5	284.3	7 →6	171.1
⁹⁸ ₄₂ Mo	787.4	(6,5)+(4,3)	798.2	25.5	$6 \rightarrow 5$	284.3	7 →6	171.1
$^{100}_{42}Mo$	535.5	(6,5)+(4,3)	797.9	25.8	$6 \rightarrow 5$	284.3	7 →6	171.2
96 44 Ru	832.3	(6,5)+(4,3)	874.9	29.8	$6 \rightarrow 5$	312.1	7 →6	187.9
¹²² ₅₀ Sn	1140.2	(6,5)+(4,3)	1105.8	70.4	6 → 5	403.5	7 →6	243.1
¹³⁸ ₅₆ Ba	1426.0	(6,5)+(4,3)	1346.3	126.1	$6 \rightarrow 5$	505.7	7 →6	305.4
¹⁹⁸ ₈₀ Hg	411.8	(8,7)+(7,5)	406.1	7.8	8 → 7	403.2	9 →8	276.1

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

K⁻Mo Predicted Nuclear Resonance effects

Isotope	Abundance [%]	Energy [keV]	Attenuation [%]
⁹² ₄₂ Mo	15.8	1540	NONE
⁹⁴ ₄₂ Mo	9.0	871	18
⁹⁵ ₄₂ Mo	15.7	786	7
96 42Mo	16.5	778	71
⁹⁸ ₄₂ Mo	23.8	787	81
$^{100}_{42}Mo$	9.6	536	4.5

The molybdenum costs 45 \$ per Kg. Some experiments carried out in Warsaw used ${}^{98}_{42}Mo$ and ${}^{100}_{42}Mo$ targets. Informations about enriched Mo isotopes target could be found.

M. Leon, Phys. Rev. A260, 461-473 (1976)

WHY INVESTIGATE NUCLEAR RESONANCE EFFECTS IN KAONIC MOLYBDENUM?

- To obtain informations on the properties of deeply bound kaonic atoms, not accessible by the kaonic cascade, in ticklish nuclei \rightarrow shift and width of the n = 4 level!
- In $K^- \frac{98}{42}Mo$ the attenuation coefficient (α) due to the nuclear resonance effect can be measured with higher precision, definitively.
- The α coefficient can be measured in ${}^{94}_{42}Mo$, ${}^{96}_{42}Mo$ and ${}^{100}_{42}Mo$ for the first time, providing new reference value for theorical models.
- The comparison of the α coefficients in ${}^{94}_{42}Mo$, ${}^{96}_{42}Mo$, ${}^{98}_{42}Mo$ and ${}^{100}_{42}Mo$ could reveal new properties of strong kaon-nucleon interaction.
- The search for isotope effects in the level shift (ϵ) and width (Γ) would reveal sign of changes in the nuclear periphery when pair of neutrons are added to the lighest isotope (${}^{94}_{52}Mo$)
- 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

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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 isotope	Abundance	Half-Time
⁹⁴ 42Mo	9%	stable
⁹⁶ 42 ^{Mo}	16%	stable
⁹⁸ 42Мо	24%	stable
¹⁰⁰ ₄₂ Mo	10%	$7.7 \times 10^{18} y$

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 $\frac{92}{42}Mo$.

THANK YOU FOR YOUR ATTENTION!!!

