LA-5994-MS
Informal Report

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UC-34c
Reporting Date: May 1975
Issued: June 1975

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UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

In the interest of prompt distribution, this report was not edited by the Technical Information staff.

Based on an invited paper presented at the Washington, DC, APS Meeting, April 28 - May 1, 1975.

Printed in the United States of America. Available from
National Technical Information Service
U S Department of Commerce
5285 Port Royal Road
Springfield, VA 22151
Price: Printed Copy $4.00 Microfiche $2.25

HADRONIC ATOMS AND TICKLISH NUCLEI: THE E2 NUCLEAR RESONANCE EFFECT*

by

M. Leon

ABSTRACT

The E2 nuclear resonance effect in hadronic atoms offers a way to increase the hadronic information that can be obtained from hadronic x-ray experiments. The effect occurs when an atomic deexcitation energy closely matches a nuclear excitation energy, so that some configuration mixing occurs. It shows up as an attenuation of some of the hadronic x-ray lines from a resonant versus a normal isotope target.

The effect was observed very clearly in pionic cadmium in a recent LAMPF experiment. A planned LAMPF experiment will use the nuclear resonance effect to determine whether the p-wave π-nucleus interaction does indeed become repulsive for $Z \gtrsim 35$ as predicted. The effect also appears in the kaonic molybdenum data taken at LBL because several of the stable molybdenum isotopes are resonant.

A number of promising cases for π^-, K^-, $\bar{p}$, and Σ^- atoms are discussed and a spectacular and potentially very informative experiment on $\bar{p}$ - ^{100}Mo is proposed.

The motive underlying this subject is the desire to increase the strong interaction information that can be extracted from the study of hadronic atoms. In muonic atoms, information about the size and shape of the nucleus comes from the x rays from transitions between the most tightly bound levels, for which the overlap with the nucleus is significant. In hadronic atoms, in contrast, the corresponding x rays are nearly all missing because the hadron reacts with the nucleus. In fact it is only last remaining hadronic x-ray transition that has any strong interaction information at all. The situation is sketched in Fig. 1. The most we can hope for is some information on (1) the absorptive width of the upper level, since the ratio of absorptive width and radiative width determines the yield of the last x ray compared to the preceding one; and (2 and 3) the hadronic energy shift (from the purely electromagnetic value) and width of the lower level, since these are also the shift and width of the last x ray. As the Z of the nucleus increases so do the shift and width, while the yield decreases, until the line melts into the background. Then there is a gap in Z until the next higher transition begins to show a decreased yield, etc. Thus any additional hadronic information is very welcome, and at least for a few nuclei, the E2 nuclear resonance

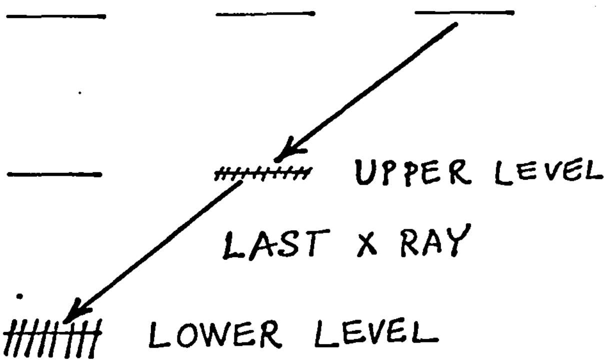

Fig. 1. The last, i.e., lowest, x-ray transition which contains the strong interaction information.

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[*] Based on an invited paper presented at the Washington, D.C. APS Meeting, 28 April-1 May 1975.

effect offers an opportunity for just that.

Having set the stage, I can now introduce the main theme. Nuclear excitation by negative muons bound in atomic orbits is a familiar topic. Since the muon in its lowest orbits gets quite close to, or even inside, the nucleus, the tidal forces are extremely strong, and thus the probability of exciting a "tidal wave" on the nuclear surface is quite large. The situation for negative hadrons is different because the hadron is absorbed while most of its wave function is far outside the nucleus; only a small tail penetrates the classically forbidden region (centrifugal barrier) to reach the nucleus itself. As a result, the tidal forces from hadrons are always very weak, so that the probability of nuclear excitation is, as a rule, extremely small

But not always, and it is these exceptional cases that I refer to as "ticklish nuclei." These exceptions occur for the most part when a resonance condition is satisfied, that is, when an atomic deexcitation energy is closely matched by a nuclear excitation energy. The situation is pictured in Fig. 2 for the particular example of $\pi^- \, ^{112}$Cd. Here the predicted energy difference between the atomic 5g and 3d levels, 618.8 keV, is very nearly equal to the ^{112}Cd nuclear excitation energy of 617.4 keV. The classical analogy would be to have the period of the hadron in its elliptical orbit match the natural vibration frequency of the nucleus, so that at every pass through its perigee the hadron strokes the nucleus at just the right time, and hence builds up a large nuclear oscillation.

Quantum-mechanically the situation is much easier to analyze: the noncentral coupling between the hadron and nucleus produces configuration mixing, so that the energy eigenfunction contains a small admixture of excited nucleus-deexcited atom wave function:

$$\psi = \sqrt{1-a^2}\,\phi(5g,0^+) + a\,\phi(3d,2^+)\ .$$

The admixture coefficient a, which is always very small, is given by

$$a = \pm \frac{<3d,2^+ \ |H_Q| \ 5g,0^+>}{E(3d,2^+)-E(5g,0^+)}\ .$$

H_Q expresses the electric quadrupole interaction between hadron and nucleus, and the matrix element is in fact given in general by[1]

$$<H_Q> = \pm \frac{e^2}{2} Q_o <r^{-3}>$$
$$[(2I+1)(2I'+1)(2\ell+1)(2\ell'+1)]^{1/2}$$
$$\begin{pmatrix} 2II' \\ 0\text{-}KK \end{pmatrix}\begin{pmatrix} 2\ell\ell' \\ 000 \end{pmatrix}\begin{Bmatrix} 2II' \\ F\ell'\ell \end{Bmatrix}\ .$$

(This equation is included only to satisfy the theoretical voyeurs in the audience.) Besides the angular momentum factors, we have Q_o which is the nuclear quadrupole strength, and $<r^{-3}>$ which measures the orbital quadrupole strength. This last factor can easily and quite adequately be evaluated using point Coulomb wave functions. Q_o comes directly from the measured Coulomb excitation cross sections [B(E2↑) values], so the calculations are independent of any particular nuclear model.

Everything I have said so far about nuclear resonance applies also to muons, and indeed such effects in muonic atoms have been studied for several years.[2] Now I turn to a characteristic that is unique to hadrons. I have already mentioned that for hadrons nuclear excitation is much less likely than for muons, because the hadron is consumed by the nucleus while the hadronic wave function is still almost completely far outside it. Just this circumstance results in nuclear excitation being very much easier to detect, in much smaller amounts, for hadronic atoms. This is because the nuclear absorption rate increases very drastically (by a factor of several hundred) for each unit decrease of orbital angular momentum; thus for a decrease of two, the factor might be ~ 10^5. That means a very small admixture coefficient a (typically ~ 1%) can mean a very significant induced width:

$$\Gamma^{ind}_{n,\ell} = |a^2|\ \Gamma^0_{n',\ell-2}\ .$$

If this induced width is not small compared to the radiative width emptying the original level, we get a significant weakening or attenuation of the corresponding hadronic x-ray line and any lower lines (Fig. 2). Thus by comparing the ratio of intensities [attenuated line/reference (higher) line] from such a "ticklish: isotope to that from a nonresonant, "lethargic" isotope of the same element, we get a direct measure of the fraction of hadrons absorbed by the excited nucleus. Note that all corrections for level populations, x-ray absorption in the targets, detector efficiencies, etc., drop out when we take this ratio of intensity ratios, which of course

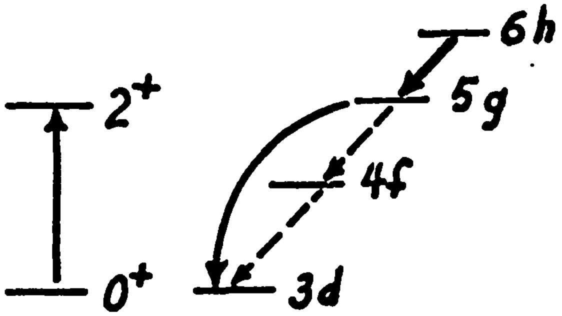

Fig. 2. The levels involved in the nuclear resonance effect for pionic ^{112}Cd. The nuclear levels are on the left, the atomic on the right. The 5→4 and 4→3 lines are attenuated, while the 6→5 line, being unaffected, serves as a reference line.

makes the experiments very easy.

Let me add that, in contrast to the muon case, there is no chance of observing nuclear γ emission by the excited nucleus because the hadron destroys it much too quickly.

Having presented the main theme, let me now show you how it works in a variety of specific cases. In order to make predictions for this effect, one needs to have some knowledge of the hadronic shifts and widths of the "inner," $n',\ell-2$ eigenstates; this is obtained by integrating the Klein-Gordon equation with a phenomenological hadron-nucleus potential. Our predictions for negative pions (for which the phenomenological potential is fairly well known) capturing on even-even nuclei are shown in Table I.[3] The last column gives the expected attenuation of the line in question. This is defined as

$$\text{Attn.} \equiv 1 - \frac{I_Q}{I_o}$$

where I_Q is the line intensity for the ticklish nucleus, I_o for a normal one. Experimentally, I_Q/I_o is just the ratio of intensity ratios mentioned above.

Since the largest attenuation is predicted for ^{112}Cd, a group of us at Los Alamos (J. N. Bradbury, H. Daniel, J. J. Reidy, and myself) ran an experiment[4] on cadmium isotopes at the biomedical π^- beam of LAMPF. The experiment involved little more than putting the enriched isotope targets in turn into the beam, viewing them with a germanium detector feeding a pulse height analyzer, and comparing the results. Part of the spectra for ^{112}Cd and ^{111}Cd are shown in Fig. 3. If you look at these spectra long enough, you can see that the ratio 5→4/6→5 is smaller in the upper spectrum (^{112}Cd) than in the lower one (^{111}Cd), which demonstrates the effect. Since ^{111}Cd is also ticklish (as we discovered somewhat late in the game), we made a second run comparing ^{111}Cd and ^{110}Cd. The excitation energies are given in Table II. You can see that the energy matching is nearly as good for ^{111}Cd as for ^{112}Cd. Fortunately, the ground state spin of 1/2 for ^{111}Cd means that the resonance effect is only about half as strong as in ^{112}Cd. The results are compared with theory in Table III. These results first of all demonstrate very clearly the existence of the nuclear resonance effect: the ratios are very significantly different from one. In addition, the agreement with calculation is very good, so that we can be quite confident that we understand the physics.

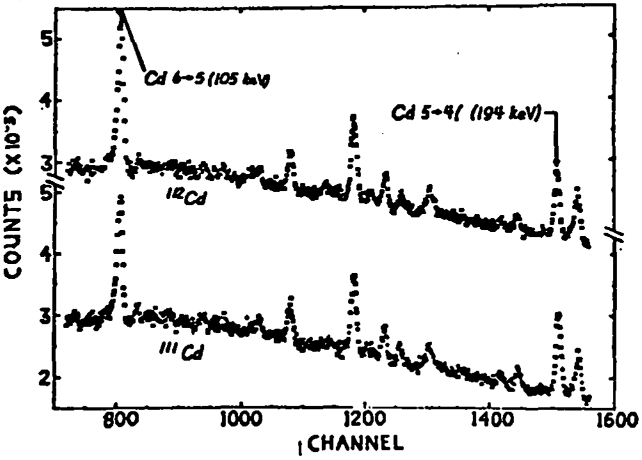

Fig. 3. Part of the pulse height spectra for pionic ^{112}Cd (above) and ^{111}Cd (below). The relevant lines are marked.

What strong interaction information can we obtain from this kind of nuclear resonance experiment? An attenuation measurement places a constraint on the <u>complex energy difference</u>, and therefore on the shift and width produced by the hadron-nucleus potential. This is illustrated in Fig. 4, where we show the sensitivity of the attenuation to the energy shift for the ^{112}Cd/^{111}Cd pair, along with the measured value.[4] If the nuclear excitation energies were known more precisely, the constraint imposed by the experiment would be much more stringent.

In some cases, this type of experiment can give <u>unique</u> information on the strong interaction by giving us a glimpse of a normally "hidden" level.

TABLE I

ISOTOPES FOR WHICH LARGE PIONIC ATOM NUCLEAR RESONANCE EFFECTS ARE PREDICTED

Nucleus	$E_{2^+}-E_{0^+}$ (keV)	Levels mixed	$E_{nl}-E_{n',l-2}$ (keV)[b]	$\Gamma_{n',l-2}$ (keV)	Atten. line(s)	Energy (keV)	Reference line	Energy (keV)	Atten. (%)
$^{112}_{48}$Cd	617.4	5g–3d	618.8	2.0	5 → 4 4 → 3	194 424	6 → 5	105	52
$^{150}_{62}$Sm	334.1	5g–4d	337.6	8.4	5 → 4 4 → 3	326 721	6 → 5	176	11
$^{110}_{46}$Pd	373.8	4f–3p	377.7	29.9	4 → 3	389	5 → 4	178	11
$^{48}_{22}$Ti	983	3d–1s	1037.8	95.4	3 → 2	254	4 → 3	88	8
$^{104}_{44}$Ru	357.7	4f–3p	349.6	26.5	4 → 3	355	5 → 4	163	11

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[b] Including the strong interaction, finite size, and lowest order vacuum polarization corrections.

TABLE II

NUCLEAR EXCITATION AND ATOMIC DEEXCITATION ENERGIES FOR PIONIC CADMIUM

Levels	Energy Difference (keV)
π-Cd 5g → 3d	618.8 + i 1.0
^{112}Cd $0^+ \rightarrow 2^+$	617.4 ± 0.3
^{111}Cd $\frac{1}{2} \rightarrow \frac{5}{2}^+$	619.9 ± 0.3
^{110}Cd $0^+ \rightarrow 2^+$	657.7 ± 0.3

TABLE III

OBSERVED AND PREDICTED INTENSITY RATIOS FOR PIONIC CADMIUM

$$R_\alpha \equiv \left(\frac{5\rightarrow4}{6\rightarrow5},\ ^{112}\text{Cd}\right) \Big/ \left(\frac{5\rightarrow4}{6\rightarrow5},\ ^{111}\text{Cd}\right)$$

$$R_\beta \equiv \left(\frac{4\rightarrow3}{6\rightarrow5},\ ^{112}\text{Cd}\right) \Big/ \left(\frac{4\rightarrow3}{6\rightarrow5},\ ^{111}\text{Cd}\right)$$

	Experiment	Theory
R_α	0.65 ± 0.06	$0.72\ {}^{+\,0.07}_{-\,0.13}$
R_β	0.78 ± 0.11	$0.77\ {}^{+\,0.05}_{-\,0.10}$
$R_\alpha\left(\frac{111}{110}\right)$	0.69 ± 0.09	0.73 ± 0.05
$R_\beta\left(\frac{111}{110}\right)$	0.81 ± 0.10	0.79 ± 0.03

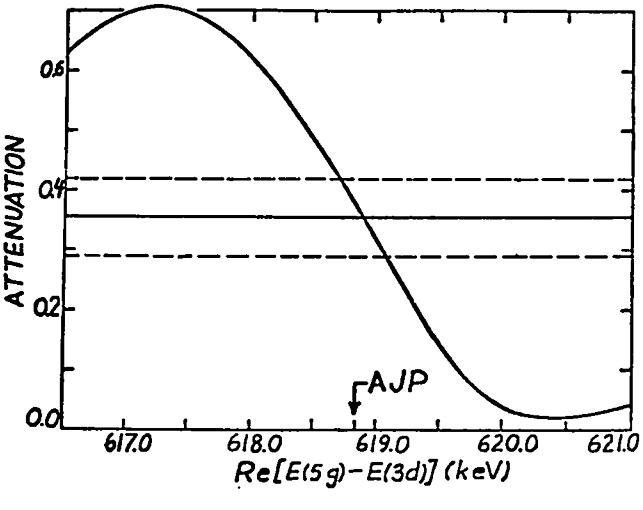

Fig. 4. Attenuation as a function of the 5g-3d energy difference for ^{112}Cd as compared with ^{111}Cd.

Thus quite some time ago Ericson et al.[5] predicted that the p-wave pion-nucleus interaction would change from attractive to repulsive as Z increased through about 36; the expected behavior is shown in Fig. 5.[6] This is because the s-wave pion-nucleon interaction (which is repulsive) overwhelms the attractive p-wave pion-nucleon interaction for larger Z's. This change of sign cannot be observed directly because the absorption in the 3d level means the 3d → 2p transition fades out for Z ≳ 30. However, for both ^{104}Ru and ^{110}Pd there is a predicted nuclear resonance with the 3p state, so this effect will allow us to determine whether the p-interaction is attractive or repulsive. The heart of the matter for Pd is shown in Fig. 6.[3] There we have plotted contours of fixed attenuation (in percent) in the complex energy-difference plane. The large circle to the right is the prediction of naive extrapolation of the observed p-wave energy shifts, while the point at the left is the predicted energy difference including the p-wave repulsion. There should be no difficulty in telling 11% from about 2% attenuation and therefore in deciding whether the p-wave force is attractive or repulsive. We hope to perform the experiment and answer this question during the next LAMPF running cycle.

Proceeding now to heavier hadrons, we first consider kaons; Table IV shows some promising ticklish isotopes.[7] (The K-nucleus potential is only known rather approximately, so there is a corresponding uncertainty in the attenuation predictions.) In particular several isotopes of molybdenum are resonant to kaons. Tables V to VII consider K^- molybdenum in more detail. The attenuations appearing in five of the seven stable isotopes mean that even natural molybdenum should show some attenuation of the 6→5 line. And indeed if one goes back to the K^- x-ray survey of Wiegand and Godfrey[8] and compares molybdenum with the surrounding elements, the 6→5 line does appear to be depressed by the right amount (Table VI).

More recently, Godfrey, Lum, and Wiegand[9] attempted an experiment at LBL on separated molybdenum isotopes to see the effect. Unfortunately they had only 25 hours of K^- beam which is not enough for conclusive results. In their data (Table VI), the effect appears to show up for ^{98}Mo, but even more so for ^{95}Mo, which just shouldn't be! I am willing to bet that when more data are taken, ^{95}Mo will behave itself and show a higher 6→5/7→6 ratio. If not, then there is something very drastically wrong with our understanding of the situation, and perhaps the only way to fix things up would be to change the spin and B(E2↑) value assignments. The values shown in Table VII are from the recent experiment of Barrette et al.,[10] and you can see that the predicted attenuations would have to be increased by an order of magnitude to agree with Godfrey et al.[9] In any case, it is clear that the isotopes of molybdenum will be very interesting to investigate further, and that ultimately a lot of strong interaction information will emerge.

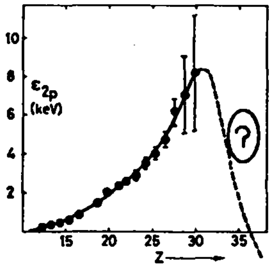

Fig. 5. Behavior of the p-wave energy shifts as a function of Z, showing the predicted sign change (from Ref. 6).

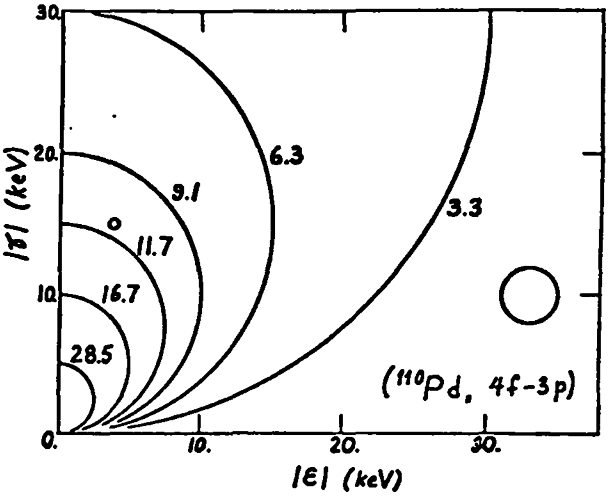

Fig. 6. Contours of fixed attenuation of the 4f→3d line in ^{110}Pd in the complex energy difference plane. The abscissa is the real part, the ordinate the imaginary part of the complex energy denominator.

When the K^- reacts with the nucleus, a Σ^- is released about 10% of the time. These Σ's stop in the target and emit x rays of their own. Thus Σ^- x-ray experiments are feasible, and Table VIII lists some promising cases for nuclear resonance effects. Essentially nothing is known about the Σ^--nucleus interaction at present, so that actual attenuations will certainly not come out to be precisely these numbers. Here we see that selenium has many ticklish isotopes and should be a very instructive system to study. I had hoped to find a case where the energy matching is so close as to be sensitive to the fine structure splitting and hence to the Σ^- magnetic moment, but unfortunately there do not seem to be any. That is too bad.

TABLE IV

ISOTOPES FOR WHICH LARGE KAONIC ATOM NUCLEAR RESONANCE EFFECTS ARE PREDICTED.

INTERACTION PARAMETER - $\bar{A} = (0.44 + 0.83\ i)F$.

Nucleus	$E_{2^+}-E_{0^+}$ (keV)	Levels mixed	$E_{n\ell}-E_{n'',\ell-2}$ (keV)	$\Gamma_{n',\ell-2}$ (keV)	Atten line(s)	Y_0	Energy (keV)	Ref. line	Energy (keV)	Atten
$^{94}_{42}$Mo	871	(6,5)&(4,3)	798.8	24.8	6→5	0.42	284.3	7→6	171.1	0.18
^{96}Mo	778	"	798.5	25.2	"	0.41	"	"	"	0.71
^{98}Mo	787.4	"	798.2	25.5	"	0.41	"	"	"	0.81
^{100}Mo	535.5	"	797.9	25.8	"	0.40	"	"	171.2	0.04
$^{96}_{44}$Ru	832.3	(6,5)&(4,3)	874.9	29.8	6→5	0.42	312.1	7→6	187.9	0.42
$^{122}_{50}$Sn	1140.2	(6,5)&(4,3)	1105.8	70.4	6→5	0.21	403.5	7→6	243.1	0.42
$^{138}_{56}$Ba	1426.0	(6,5)&(4,3)	1346.3	126.1	6→5	0.53	505.7	7→6	305.4	0.15
$^{198}_{80}$Hg	411.8	(8,7)&(7,5)	406.1	7.8	8→7 7→6	0.55 0.13	403.2 622.2	9→8	276.1	0.42

TABLE V

PREDICTED NUCLEAR RESONANCE EFFECTS IN K^- MO

Isotope	Abundance (%)	E_N (keV)	Atten (%)
92	15.8	1540	---
94	9.0	871	18
95	15.7	786+...	7
96	16.5	778	71
97	9.5		< 4
98	23.8	787	81
100	9.6	536	4.5
		Natural molybdenum	34%

TABLE VI

OBSERVED LINE RATIOS AND ATTENUATIONS IN K^- MO

		$\left(\frac{6\to5}{7\to6}\right)$	Atten (%)
Ref. 8	Z = 38,39,41,45,47,48	0.78±0.08	---
	^{NAT}Mo	0.52±0.09	33±14
Ref. 9	^{98}Mo	0.35±0.21	55±27
	^{95}Mo	0.24±0.14	69±18

TABLE VII

CALCULATED CONTRIBUTIONS TO ATTENUATION IN ^{95}Mo

(Level data from Ref. 10)

Level I^P	Level Energy (keV)	B(E2↑) ($10^{-50}\ e^2\ cm^4$)	Atten (%)
$3/2^+$	204	3.80±0.24	0.1
$7/2^+$	766	< 0.013	---
$1/2^+$	786	0.325±0.020	4.2
$3/2^+$	821	0.060±0.015	0.1
$9/2^+$	948	5.25 ±0.25	2.8
$5/2^+$	1057	1.30 ±0.07	0.1

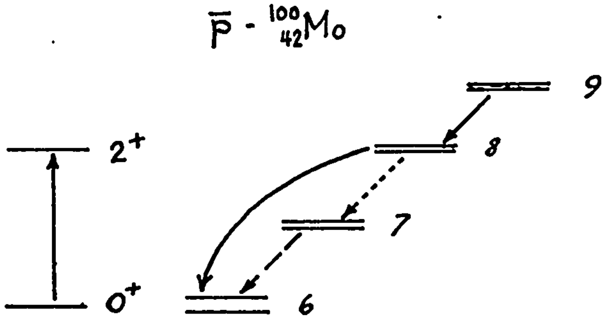

Fig. 7. Nuclear resonance effect in $\bar{p}$-^{100}Mo.

TABLE VIII

ISOTOPES FOR WHICH LARGE Σ^- ATOM NUCLEAR RESONANCE EFFECTS ARE PREDICTED.

INTERACTION PARAMETER - $\bar{A} = (0.01 + i)F$.

Nucleus	$E_{2^+}-E_{0^+}$ (keV)	Levels mixed	$E_{n\ell}-E_{n',\ell-2}$ (keV)	$\Gamma_{n',\ell-2}$ (keV)	Attn line(s)	Y_0	Energy (keV)	Ref. line	Energy (keV)	Attn
$^{74}_{32}$Ge	596.0	(7,6)&(5,4)	628.8	12.1	7→6	0.26	238.3	8→7	154.5	0.78
$^{74}_{34}$Se	635.0	(7,6)&(5,4)	707.6	18.1	7→6	0.21	269.0	8→7	174.5	0.59
^{78}Se	614.2	"	707.3	19.2	"	0.18	269.2	"	174.6	0.40
^{80}Se	666.2	"	707.2	19.7	"	0.17	269.3	"	174.7	0.70
^{82}Se	655.4	"	707.0	20.3	"	0.16	269.4	"	174.8	0.54
$^{102}_{44}$Ru	473.0	(9,8)&(7,6)	495.2	0.2	9→8 8→7	0.46 0.31	201.3 293.9	10→9	143.9	0.16 0.21
$^{104}_{46}$Pd	555.4	(9,8)&(7,6)	541.5	0.4	9→8 8→7	0.46 0.26	220.1 321.3	10→9	157.3	0.38 0.39
^{106}Pd	511.7	"	541.6	"	9→8 8→7	0.45 0.25	220.2 321.4	10→9	"	0.14 0.19
$^{112}_{48}$Cd	617.4	(9,8)&(7,6)	590.1	0.8	9→8 8→7	0.45 0.18	239.9 350.2	10→9	171.5	0.24
^{114}Cd	558.5	"	590.2	"	9→8 8→7	0.45 0.18	240.0 350.3	"	"	0.22
$^{126}_{52}$Te	667.0	(9,8)&(7,6)	693.4	2.3	9→8	0.42	282.1	10→9	201.6	0.54
^{128}Te	743.0	"	693.5	"	"	"	"	"	"	0.21
$^{130}_{56}$Ba	359.0	(9,8)&(8,6)	326.1	6.7	9→8	0.38	327.4	10→9	233.9	0.13
$^{168}_{68}$Er	821.1	(10,9)&(8,7)	829.9	2.4	10→9 9→8	0.42 0.08	346.1 483.8	11→10	255.8	0.67 0.61
$^{194}_{78}$Pt	328.5	(11,10)&(10,8)	338.0	1.2	11→10 10→9	0.45 0.23	337.2 456.1	12→11	256.3	0.24 0.28
$^{200}_{80}$Hg	367.9	(11,10)&(10,8)	355.6	1.8	11→10 10→9	0.44 0.18	354.9 480.0	12→11	269.7	0.13 0.14
$^{204}_{82}$Pb	899.0	(11,10)&(9,8)	877.3	1.4	11→10 10→9	0.43 0.14	372.9 504.3	12→11	283.4	0.20 0.19

Finally, antiprotons, which I have saved for last. Our favorite candidates are shown in Table IX. For ^{76}Se and ^{100}Mo the attenuation is *total*; i.e., the line is completely wiped out by the resonance effect. Note the star next to ^{100}Mo; that indicates a *hysterical* nucleus. Here the admixture parameter *a* is *not* small, but instead is ~ 1. As a result, some rather spectacular things happen. Figure 7 shows the relevant levels. In addition to the vanishing of the 8→7 line, the 9→8 line develops a complicated structure. Because of the spin of the $\bar{p}$ all the lines are *doublets* (actually they are triplets, but the third component has negligible intensity); however, because of the close-coupling the 9→8 line in ^{100}Mo becomes a *quartet*. The predicted structure of this line is shown in Fig. 8. The dotted vertical lines show the normal doublet structure (the fine structure separation is about 300 eV), the solid vertical lines the components of the quartet. The widths of the members vary drastically, and the resulting intensity pattern (not including experimental resolution) is shown. Even when the blurring produced by experimental resolution is included, much of this structure will remain. The position, widths, and relative strengths of the four components, and hence the whole line profile, depend on the hadronic $\bar{p}$-nucleus interaction. This is illustrated in Fig. 9 which shows the results when we allow the strong interaction parameter to take the values at the corners of the "error rectangle," as well as the central value (strong interaction parameter $\bar{A}$ from Barnes et al.[5]). Valuable strong interaction information could be obtained by careful measurement of this line profile. As an added bonus, the line is in a much more favorable energy region (144 keV), as far as detector efficiency and resolution are concerned, than those last x-ray lines which one normally must use to get hadronic information. Thus, in my own completely unbiased opinion this is the best and most beautiful $\bar{p}$ x-ray experiment that one could possibly do. I hope that some experimentalists will concur and do it.

In summary, I hope that I have managed to convince you that tickling nuclei is not only fun, but instructive.

TABLE IX

ISOTOPES FOR WHICH LARGE $\bar{p}$ ATOM NUCLEAR RESONANCE EFFECTS ARE PREDICTED.

INTERACTION PARAMETER - $\bar{A}$ = (2.9 + 1.5 i)F.

Nucleus	$E_{2^+}-E_{0^+}$ (keV)	Levels mixed	$E_{n\ell}-E_{n',\ell-2}$ (keV)	$\Gamma_{n',\ell-2}$ (keV)	Attn line(s)	Y_0	Energy (keV)	Ref. line	Energy (keV)	Attn
$^{76}_{34}Se$	559.3	(7,6)&(5,4)	561.4	10.4	7→6	0.34	211.6	8→7	137.2	0.99
$^{94}_{42}Mo$	871.1	(7,6)&(5,4)*	844.8	52.1	7→6	0,10	324.1	8→7	210.1	0.67
$^{100}_{42}Mo$	535.6	(8,7)&(6,5)	534.4	2.2	8→7 7→6	0.42 0.09	210.2 324.2	9→8	144.0	0.98 0.83
$^{104}_{44}Ru$	357.7	(7,6)&(6,4)	328.7	60.1	7→6	0.06	355.0	8→7	230.8	0.23
$^{130}_{52}Te$	840.0	(8,7)&(6,5)	818.2	20.0	8→7	0.25	323.4	9→8	221.4	0.78
$^{148}_{60}Nd$	300.0	(9,8)&(8,6)	295.9	5.2	9→8 8→7	0.43 0.07	295.3 431.2	10→9	221.0	0.80 0.71
$^{150}_{62}Sm$	336.0	(9,8)&(8,6)	315.8	7.3	9→8	0.42	315.4	10→9	225.4	0.26
$^{196}_{78}Pt$	355.7	(10,9)&(9,7)	358.9	5.7	10→9 9→8	0.43 0.08	357.8 500.8	11→10	264.5	0.81 0.72
$^{200}_{80}Hg$	367.97	(10,9)&(9,7)	377.5	7.7	10→9	0.42	376.5	11→10	278.3	0.43

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*Close coupled, perturbation theory inaccurate.

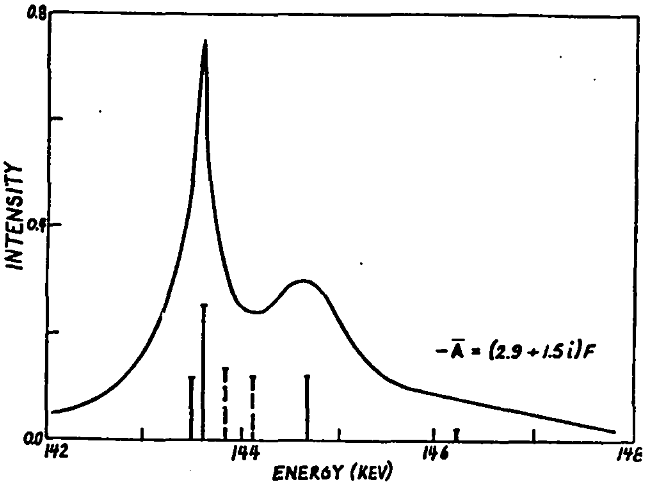

Fig. 8. Structure of the 9→8 transition in $\bar{p}$-^{100}Mo. The dotted bars show the original fine structure components in the absence of the nuclear resonance effect, the solid bars the components of the quartet produced by the nuclear resonance effect. The intensity envelope shown results when the appropriate Lorentzian natural widths are included. Units of the energy scale are arbitrary.

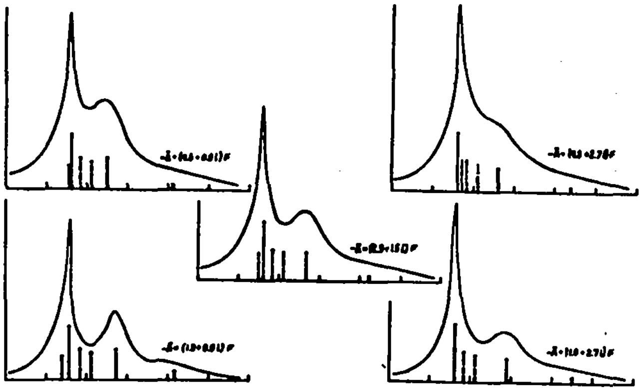

Fig. 9. Structure of the same transition when the interaction parameter $\bar{A}$ is varied to the extremes of its error bars. $\bar{A}$ is from Ref. 11.

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