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Observation of the $E2$ Nuclear Resonance Effect in Pionic Cadmium*

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Nuclear resonance effects in mesonic atoms result from near degeneracy of nuclear excitation and atomic de-excitation energies. The $E2$ nuclear resonance effect was observed in pionic cadmium by comparing selected pionic x-ray intensity ratios from ^{112}Cd with those from ^{111}Cd. The effect for hadronic atoms is now unambiguously established and the results are in close agreement with the theoretical predictions.

Nuclear resonance effects in mesonic atoms result from "accidental" near degeneracy of nuclear excitation and atomic de-excitation energies. Given such an energy matching, even a relatively weak coupling—such as that provided by the electric quadrupole moment of the nucleus—can produce significant configuration mixing. Thus, in effect, the mesonic atom de-excites by exciting the nucleus. It has recently been pointed out[1,2] that this $E2$ nuclear resonance effect should be easy to observe in a few *hadronic* atoms: those for which the absorption of the hadron by the excited nucleus weakens one or two hadronic x-ray line intensities relative to the intensities from another isotope of the same element.[3] This effect is intrinsically interesting and also provides an important test of our knowledge of the hadron-nucleus interaction.

In this Letter we report the observation of the nuclear resonance effect in pionic cadmium. While this effect has been seen[4] in muonic Bi and Tl, this is, to our knowledge, the first such observation for hadronic atoms.

For pionic cadmium the predicted[5] $5g \rightarrow 3d$ (complex) atomic energy difference is $618.8 + i1.0$ keV, while both ^{112}Cd and ^{111}Cd have $E2$ excitable states near that energy: 617.4 ± 0.3[6] and 619.9 ± 0.3 keV,[7] respectively. Thus pionic atoms of these isotopes are choice candidates for exhibiting the nuclear resonance effect; in each, the induced

width in the (mixed) $5g$ state implies an attenuation of the $5g \rightarrow 4f$ (194 keV) and $4f \rightarrow 3d$ (425 keV) pionic x rays. (The predicted π^- absorption from the $5g$ and higher levels is completely negligible in the absence of this configuration mixing.) The $6h \rightarrow 5g$ (105 keV) line, being unaffected, can serve as an intensity reference. The situation for ^{112}Cd is pictured in Fig. 1.

The experiment consisted of comparing the relative intensities of pionic $6 \rightarrow 5$, $5 \rightarrow 4$, and $4 \rightarrow 3$ x-ray lines from ^{112}Cd and ^{111}Cd.[8] No corrections were necessary for detector efficiency or for x-ray absorption in the target because the targets were essentially identical in terms of absorption (same mass and geometry). Each separated isotope (as CdO powder) was contained in a thin copper holder and placed in the π^- beam at the biomedical channel at the Los Alamos Meson Physics Facility (LAMPF). Sufficient moderator was included in the 171-MeV/c ($\Delta p/p \simeq 3\%$) beam to put the peak of the π^- stopping distribution within the CdO sample; resultant stopping rates were about 5×10^4 sec^{-1}. The x-ray detector,[9] protected by Cu shielding, was about 10 cm from the sample. To minimize background there was essentially no extraneous material in the vicinity of the sample; no stopping telescope was required. Data were accumulated in a multichannel analyzer in the standard way. A ^{133}Ba source, which has five lines in the region of interest, was used for energy calibration.[10]

The ^{111}Cd and ^{112}Cd samples were each exposed to the π^- beam for two hours, which was sufficient to accumulate about 10^4 counts above background in the $5 \rightarrow 4$ lines. A run with a dummy sample of TiO_2 in the target holder showed no peaks in the energy regions of interest. Natural CdO was exposed for a shorter time to provide a consistency check. Parts of the ^{111}Cd and ^{112}Cd spectra are shown in Fig. 2. The background and line shapes were fitted using the nuclear-γ analyzing code GAMANAL.[11] The results are given in Table I. The ratio of intensity ratios for the two isotopes is thus found to be

$$R_\alpha \equiv \left(\frac{5 \rightarrow 4}{6 \rightarrow 5}, {}^{112}\mathrm{Cd}\right)\left(\frac{5 \rightarrow 4}{6 \rightarrow 5}, {}^{111}\mathrm{Cd}\right)^{-1} = 0.65 \pm 0.06, \quad (1)$$

and

$$R_\beta \equiv \left(\frac{4 \rightarrow 3}{6 \rightarrow 5}, {}^{112}\mathrm{Cd}\right)\left(\frac{4 \rightarrow 3}{6 \rightarrow 5}, {}^{111}\mathrm{Cs}\right)^{-1} = 0.78 \pm 0.11. \quad (2)$$

The errors in Table I include the statistical errors in the line and in the background and errors reflecting the goodness of fit of the peak shape, as generated by the GAMANAL code; those shown in Eqs. (1) and (2) include, in addition, a small contribution (~5%) to allow for possible sample misalignment of $\pm 5°$. Since R_α and R_β differ significantly from 1, we are confident that the nuclear resonance effect has been observed.

Values for these ratios have been calculated using the strong-interaction parameters of Anderson, Jenkins, and Powers,[5] including the electric quadrupole contribution to the pionic isomer shift,[2] and correcting for the slight isotopic impurity of the samples.[8] The results are

$$R_\alpha(\text{theory}) = 0.64^{+0.06}_{-0.11} \quad (3)$$

$$R_\beta(\text{theory}) = 0.72^{+0.05}_{-0.09}. \quad (4)$$

The errors attached to these ratios arise from the uncertainties in the nuclear excitation and in the $B(E2)$ values[7,12]; by far the largest contribution comes from the ^{112}Cd nuclear excitation energy. The calculated ratios agree very well with the measured values.[13]

The observed intensity ratio for natural Cd, which contains 24% ^{112}Cd and 13% ^{111}Cd, yields

$$R_\gamma \equiv \left(\frac{5 \rightarrow 4}{6 \rightarrow 5}, \mathrm{Cd}\right)\left(\frac{5 \rightarrow 4}{6 \rightarrow 5}, {}^{111}\mathrm{Cd}\right)^{-1} = 1.14 \pm 0.18, \quad (5)$$

which is consistent with the predicted value of

$$R_\gamma(\text{theory}) = 1.08. \quad (6)$$

What are the implications of hadronic-atom nuclear-resonance-effect measurements like the present one? In fact, the effect is most sensitive to the precise value of the complex energy difference [in this case $E(5g, 0^+) - E(3d, 2^+)$], so that these measurements in general provide constraints in the complex energy-difference plane. The comparison of the cadmium-111 and -112

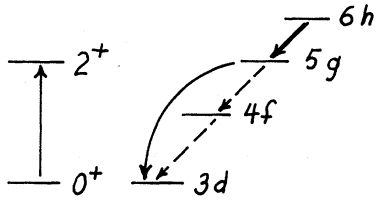

FIG. 1. Nuclear and atomic energy levels relevant to the mixing of the $(5g, 0^+)$ and $(3d, 2^+)$ levels in pionic ^{112}Cd.

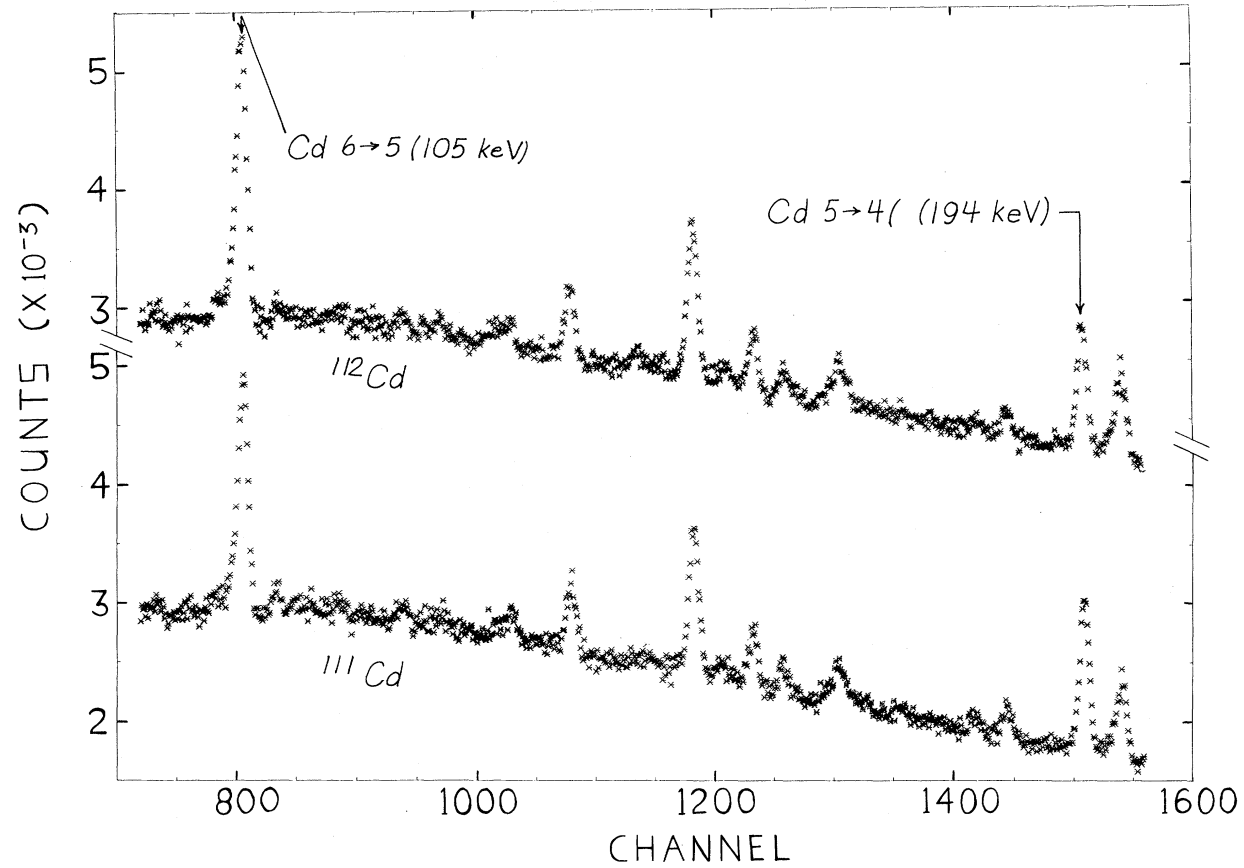

FIG. 2. Part of the experimental spectra (unnormalized), showing the 6 → 5 (105 keV) reference line and the 5 → 4 (194 keV) attenuated line.

isotopes is particularly sensitive to the real part of this energy difference because it lies between the two nuclear excitation energies. This sensitivity is apparent in Fig. 3, in which we have plotted the *attenuation* $(1 - R_\alpha)$ of the 5 → 4 line from ^{112}Cd as compared to ^{111}Cd as a function of $\mathrm{Re}[E(5g) - E(3d)]$; here $\Gamma(3d)$ is fixed at the value predicted with the Anderson, Jenkins, and Powers strong-interaction parameters. Furthermore, since the 5 → 4 attenuation predicted using the Tauscher[5] parameters is 0.11, the present measurement strongly favors the Anderson, Jenkins, and Powers set of strong-interaction parameters.

In addition, our data give the 4 → 3 energy directly as 424.5 ± 0.2 keV. This result is completely consistent both with the observed resonance effect and with the Anderson, Jenkins, and Powers parameters.

We are indebted to R. J. Powers and G. L. Godfrey for providing their computer programs, to M. E. Schillaci for calculating the absorption in the samples, and to A. G. Chavez for performing the data analysis. The detector was provided by R. Pehl, and A. Harper constructed the sample holder. One of us (H.D.) acknowledges the hospi-

TABLE I. Fitted counts and ratios.

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	...	...

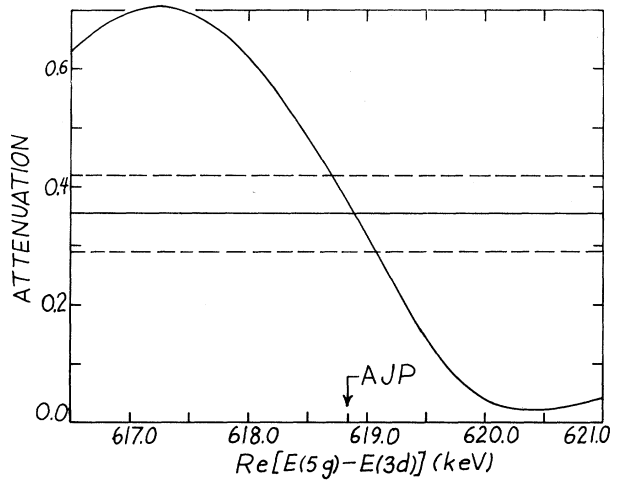

FIG. 3. Predicted attenuation $[1-R_{\alpha}(\text{theory})]$ as a function of the real part of the atomic $5g$-$3d$ energy difference. The horizontal lines show the result of this experiment. The value corresponding to the Anderson, Jenkins, and Powers (Ref. 5) (AJP) set of strong-interaction parameters is indicated.

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Note added.—In a subsequent experiment x-ray intensities from targets of metallic ^{111}Cd and ^{110}Cd were compared. ^{110}Cd should not exhibit the nuclear resonance effect since its 2^+ nuclear energy level is at 257.9 keV. We find $R_{\alpha}(111/110) = 0.69 \pm 0.09$ and $R_{\beta}(111/110) = 0.81 \pm 0.10$, in reasonable agreement with the predicted values (corrected for sample impurity): $R_{\alpha}(\text{theory}) = 0.81 \pm 0.04$ and $R_{\beta}(\text{theory}) = 0.85 \pm 0.03$.

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