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SHIFTS IN XENON K X-RAY ENERGIES
FOLLOWING ELECTRON-CAPTURE BETA DECAY
AND THE ROLE OF NUCLEAR HYPERFINE STRUCTURE

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ABSTRACT

Precision measurements by a crystal-diffraction technique show shifts in the energies of K X-rays following electron-capture beta decay. For the pair $^{131,132}\text{Cs}$ the effect amounts to 0.112 ± 0.011 eV, which can be explained by taking into account shifts arising from the 1s atomic hyperfine structure, observed here for the first time.

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The K X-rays following beta decay by electron capture (EC) have lifetimes that are short (for xenon 5×10^{-17} sec) compared with those of excited nuclear levels populated in the beta decay. The X-ray energies will therefore be influenced by static properties of the excited nuclear states: radii and magnetic moments. In the following we report shifts in the energies of xenon K X-rays from EC decay of caesium isotopes.

It is essential for the interpretation of the experiment to note that associated atomic excitations ("shake-off") are expected to be of low probability for K capture relative to other mechanisms which excite the K shell. Outer-shell vacancies caused by the primary process give rise to unresolved K X-ray satellites, which change the observed energy; however, as pointed out by Primakoff and Porter [1], the almost perfect screening of the nuclear charge by the 1s electron means that the simultaneous disappearance in EC decay of a K electron and of a nuclear charge will leave the wave functions of the outer electrons essentially unchanged. For this reason K capture is expected to have much less outer-shell excitation than $\beta^\pm$ decay, internal conversion, and external excitation.

The nuclear finite-size effect in the atomic 1s state has been observed for stable isotopes by the groups of Sumbaev [2] and Boehm [3], who used curved-crystal spectrometers of the Cauchois type to detect K X-rays excited by fluorescence. It has not been possible to detect directly the shifts due to the magnetic hyperfine structure in the atomic 1s state, which in fluorescence excitation manifests itself only as a broadening of the X-ray lines [4]. For both effects, the characteristic energies are 10^{-2} to 10^{-3} of the natural linewidth; consequently, experiments with radioactive sources of X-rays require not only high intensities but also special precautions to eliminate systematic errors.

The high beam intensities at the on-line isotope separator ISOLDE-2 at the CERN Synchro-cyclotron make it possible to obtain mono-isotopic sources of up to 1 Ci implanted as a very thin layer in a metal backing and with a source area of only a few mm^2 . Such sources are ideally suited for measurements with a curved-crystal spectrometer of the DuMond type, which provides the highest obtainable

transmission. The spectrometer [5] constructed for the present experiment uses a 4 mm thick quartz crystal bent to a focal length of 4.64 m. The photons are reflected from the (110) plane in Laue transmission.

A new and essential feature of the spectrometer is its source arrangement. In order to minimize errors arising from the limited reproducibility of the crystal drive, the spectrometer measures the reflections from two different sources placed, at short distance, one above and one below the focal plane and behind a rotating shutter synchronized with the data recording. The accuracy of the placement of the sources, although high, does not suffice for a determination of the energy shift from one scan alone; the reason for this is that a 10 meV shift in energy of the Xe K X-ray is equivalent to a 0.3 μ m displacement of one source relative to the other in the direction of the dispersion. To balance out this effect the measurement was performed at both positive and negative [referred to as right (r) and left (ℓ)] Bragg angles θ . Let the sources 1 and 2 be placed, respectively, as the lower and upper sources; the apparent shift in the position x , proportional to $\sin \theta$, is then calculated as

$$S_{1-2} = \frac{1}{2} (x_{\text{low},r} - x_{\text{up},r} - x_{\text{low},\ell} + x_{\text{up},\ell}) . \quad (1)$$

In more precise statistical language, the quantities x are the position estimates based on the experimental data. Corrected for the instrumental asymmetry, to be discussed below, this expression serves as an estimate of the change in wavelength.

Owing to the smallness of the shift S_{1-2} , we have applied different methods of estimation to the data. In a preliminary presentation [5] of the present work, three consistent methods were used for extracting S_{1-2} ; we adopt in the present work a fourth method [6], which gives essentially identical results but which has the advantage of being simpler and mathematically more transparent. This method is based on a bias correction to the centroid of the truncated line; it is insensitive to details of the line shape and statistically > 95% efficient.

Following the preliminary measurements [5], more detailed and systematic studies have revealed a substantial instrumental asymmetry defined as $A = \frac{1}{2}(S_{1-2} + S_{2-1})$.

The data yield $A = 52 \pm 7$ meV (xenon, first order), a result which was confirmed by comparing the X-rays in second-order from two identical ^{169}Yb sources. For K_{β_1} the asymmetry term was assumed to be proportional to the energy, corresponding to a value of 57 meV.

The corrected data for the isotopes $^{127,129,131,132}\text{Cs}$ are shown in Table 1. The results for K_{α_1} are internally consistent (i.e. they satisfy all relations of the type $E_{ab} + E_{bc} - E_{ac} = 0$) and clearly demonstrate the presence of large shifts between the X-ray energies from different isotopes. One further notes that within the experimental errors the shift for the 131-132 pair is the same for K_{α_2} , K_{β_1} and K_{α_1} .

We now try to calculate the shifts and concentrate the analysis on the isotope pair $^{131,132}\text{Cs}$, which has very simple decay schemes: ^{131}Cs ($g, I^\pi = 5/2^+$) $\rightarrow$ ^{131}Xe ($g, I^\pi = 3/2^+$, $\mu/\mu_N = 0.692$) and ^{132}Cs ($g, I = 2$) $\rightarrow$ ^{132}Xe (668 keV, $I^\pi = 2^+$, $\mu/\mu_N = 0.74 \pm 0.10$ [7]; 2% to other levels). The parity of the ^{132}Cs ground state is not certain, but the magnetic moment of $\mu/\mu_N = +2.219$ points to a positive-parity assignment ($\pi g_{7/2} \nu d_{3/2}$ or $\pi d_{5/2} \nu s_{1/2}$), so that the beta transition is allowed (and, consequently, of pure multipolarity 1). Four types of contributions are considered.

- i) The nuclear finite-size effect. From the optical isotope shifts [8] in the xenon isotopes one has $\langle r^2 \rangle_{132} - \langle r^2 \rangle_{131} = 0.05 \pm 0.04$ fm. The increase in $\langle r^2 \rangle$ for the 2^+ vibrational level in ^{132}Xe may be estimated from the model of harmonic vibrations of a liquid drop [9]; on the basis of a 2^+ lifetime of 7 psec one obtains $\Delta \langle r^2 \rangle \approx 0.05$ fm². The corresponding total energy shift $E_{131} - E_{132}$ calculated from Seltzer [10] is +13 meV.
- ii) The magnetic hyperfine effect. The magnetic hyperfine effect [11] leads to shifts $A I/2$ and $-A(I+1)/2$ for the states $F = I + 1/2$ and $F = I - 1/2$, respectively, where A is the usual hyperfine-interaction constant proportional to the nuclear g-factor and F is the combination of the nuclear spin I with the atomic angular momentum $1/2$ of the $1s$ shell. (It is permissible here to neglect the weak couplings to outer electrons.) If the population of the hyperfine states is

in the so-called statistical ratio $(I+1)/I$, the resulting shift is zero as in fluorescence excitation [4]. For allowed and (quasi-allowed) first forbidden electron-capture beta decay, however, only $\frac{1}{2}$ unit of angular momentum is carried away by the neutrino so that one has the selection rule $\Delta F = \pm \frac{1}{2}$. If there is a spin change of 1, a transition with $\Delta I = \mp 1$ can only populate the single hyperfine level $F = I \pm \frac{1}{2}$. For the case of no spin change, a beta transition of multipolarity 1 populates both hyperfine states in the (non-statistical) ratio $I/(I+1)$ so that there is a resulting shift of $-A/2$. The intensity rules and resulting shifts are summarized in Table 2. Calculating the A parameter according to Kopfermann [11] with relativistic corrections (+37%), finite nuclear-size correction (-3%) and correction for the Bohr-Weisskopf effect (-1.5%), one finds that the K X-rays from ^{131}Cs and ^{132}Cs are shifted by +75 and -38 ± 6 meV, respectively; consequently the total contribution to $E_{131} - E_{132}$ is expected to be +113 meV.

- iii) The shake-off effect. The changes in K X-ray energies arising from outer-shell excitations may be calculated as $\sum P_i \Delta E_i$, where P_i is the probability of obtaining a vacancy in the state i together with the primary excitation, and where ΔE_i is the energy shift of the corresponding X-ray satellite. The P_i have been calculated for xenon in the sudden approximation (corresponding to very large transition energy) by Nestor et al. [12], while the satellite energies were obtained by the method of Rosén and Lindgren [13]. The sum runs over unresolved satellite lines only, and gives for xenon K_{α_1} an increase in energy of +1.5 meV and, in the approximation used here, a resulting shift of zero. The same calculation yields a 150 meV increase for K_{α_1} in fluorescence excitation. In this connection it is interesting to note a recent experiment by Hahn et al. [14], according to which the Ta K_{α} X-rays induced by fluorescence in tantalum oxide have 0.8 eV larger energy than those arising from electron capture in a $^{181}\text{WO}_3$ source. Those authors prefer to attribute the difference to a selective shake-off of 4f electrons in the electron-capture process. In line with the discussion above, we expect that sizeable effects arise in shake-off in the fluorescence excitation and in the hyperfine effect, for which we calculate a contribution of -0.4 eV.

iv) Chemical shifts. These are believed to be unimportant in the present experiment, since the measurements have been made on sources prepared by ion implantation of one element into identical backings. Radiation damage caused by the implantation could give rise to chemical shifts, but does not seem likely as the experiments have been repeated under very different conditions of focusing and implanted dose, and as identical results were obtained with copper and aluminium backings [5].

Our calculated resulting shift for the masses 131-132 of 126 ± 9 meV agrees well with the experimental value of 112 ± 11 meV. The information on the $^{127,129}\text{Cs}$ decay schemes is insufficient to permit a quantitative comparison in those cases. The present experiment constitutes the first experimental observation of energy shifts associated with the 1s electronic hyperfine splitting, and it points to a new possibility for measuring magnetic moments of extremely short-lived nuclear states.

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Table 1

Energy shifts ^{*)} of the xenon K X-rays
measured in first order of reflection

X-ray	Source 1	Source 2	$E_1 - E_2$ (meV)
K_{α_1}	^{127}Cs	^{129}Cs	-12 ± 9
K_{α_1}	^{127}Cs	^{131}Cs	-132 ± 20
K_{α_1}	^{127}Cs	^{132}Cs	36 ± 20
K_{α_1}	^{129}Cs	^{131}Cs	-108 ± 21
K_{α_1}	^{129}Cs	^{132}Cs	53 ± 12
K_{α_1}	^{131}Cs	^{132}Cs	112 ± 11
K_{α_2}	^{131}Cs	^{132}Cs	170 ± 40
K_{β_1}	^{131}Cs	^{132}Cs	120 ± 60

*) Each result represents an average over several independent measurements with different sources, and each measurement is an average over 6-20 consistent scans of the four lines (two sources, positive and negative Bragg reflections). The experimental errors are the statistical errors only; the bias correction introduces an additional scale error estimated at 5%. Errors arising from the non-overlap of the reflections are negligible in the cases studied here.

Table 2

Branching ratios and energy shifts of K X-rays
from EC beta decay

ΔI	Relative intensity		Resulting shift
	$F = I + \frac{1}{2}$	$F = I - \frac{1}{2}$	
-1	1	0	$\frac{1}{2} A \cdot I$
+1	0	1	$-\frac{1}{2} A(I + 1)$
$0(\lambda = 1)$	I	$I + 1$	$-\frac{1}{2} A$
$0(\lambda = 0)^*)$	$I + 1$	I	0

*) The case $\lambda = 0$ is equivalent to statistical excitation.