Nuclear Spectroscopy of Ba^{131} and Cs^{131}

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The spectra of Ba^{131} and Cs^{131} have been investigated in a magnetic lens spectrograph. The 12-day Ba^{131} decays by orbital electron capture. Gamma-rays at 0.497, 0.371, 0.241, 0.213, 0.196, and 0.122 Mev have been observed. Cs^{131} (10-day) decays entirely by orbital electron capture. No gamma-rays are associated with this transition. In the particle spectrum only Auger electrons are found There are no internal conversion lines which could arise from the 0.080- and 0.163-Mev states of Xe^{131}. It is concluded that Cs^{131} decays to the ground state of Xe^{131}.

I. INTRODUCTION

IN nuclear spectroscopy it is particularly advantageous to study a radioactive substance whose end product is a stable element, the energy levels of which have been ascertained by measurements on some other radioactive element. For example, the energy levels of Te^{124} have been determined[1] by measurements on I^{124}, which decays by positron emission and K-capture, and also by measurements[2,3] on Sb^{124}, which decays by the emission of beta-rays. The levels of Te^{124}, determined in these two ways, agree. Numerous other examples are known.[4] If, in addition, the product nucleus is known to have a metastable state, certain conclusions about the configurations of the various states involved may be obtained with the help of the shell model of nuclear structure.[5] This is true since the shell model has been particularly helpful in explaining regions of isomerism and in predicting the configurations of ground states and metastable states.

With this in mind we have made a study of the radiations of Cs^{131}. Cs^{131} goes to Xe^{131} by orbital electron capture. The levels of Xe^{131} are known from a study[4] of I^{131}. Furthermore, a metastable state of 12-day half-life is known[6,6a] in Xe^{131}. Since Ba^{131} is the parent of Cs^{131}, this nuclide was also studied.

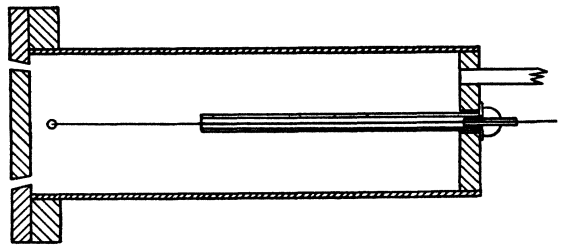

FIG. 1. Diagram of counter with annular opening allowing the use of thin film windows with ring type focusing.

II. APPARATUS

The measurements were made with a magnetic lens type spectrometer which has been described[7] previously and which has been modified to use ring focusing. The position of the ring focus was located in the following manner. Three cones of electrons were defined by placing a baffle with three annular slits at the central plane of the lens. Essentially a "point source," 1.3 mm in diameter, of thorium active deposit was used to produce a line of internal conversion electrons. When the coil current was set to focus the "F" line from ThC ($H\rho$ = 1385 gauss-cm), sharp patterns of concentric circles were obtained on an electron sensitive film exposed at positions near the counter end of the spectrometer chamber. Six such exposures were made, from which it was possible to plot the trajectories of electrons from the inner, outer, and center regions of the acceptance zone. The crossing of these trajectories located the position of the ring focus. The annulus of best focus was found to be 3.76 cm in diameter and located 9.2 cm from the plane of axial focus. The width of the annulus was found to be 3 mm when the usual sized sources were used.

In order to have ring focusing and still be able to use thin film counter windows, a 5.08 cm diameter counter was constructed so that an annular counter window could be employed to define the focus ring. Zapon films laid down on the window plate provided a window which held without leaking and transmitted electrons having energies down to 11 kev. The counter is shown in Fig. 1.

III. EXPERIMENTS ON Ba^{131}

Ba^{131} has a half-life of 12 days and can be formed by neutron capture in barium. The properties of the radiations from Ba^{131} were first investigated by Yu, Gideon, and Kurbatov[8] using absorption and cloud-chamber techniques. These investigations showed that Ba^{131} emits no positrons but decays by orbital electron capture accompanied by gamma-rays and internal conversion electrons. The energy of the gamma-rays have been measured by absorption experiments in lead by

* Supported by the joint program of the ONR and AEC.
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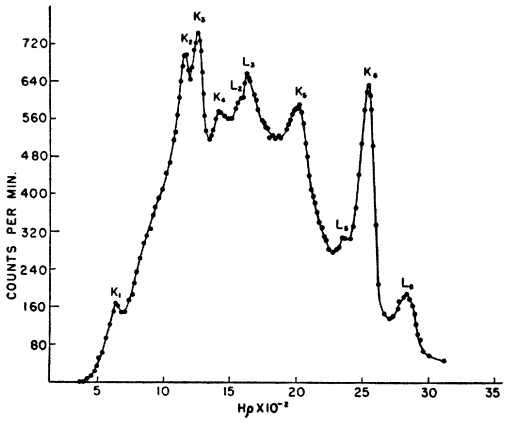

FIG. 2. Spectrum of secondary electrons ejected from lead by gamma-rays of Ba^{131}. (K_1—0.122 Mev); (K_2 and L_2—0.196 Mev); (K_3 and L_3—0.213 Mev); (K_4—0.241 Mev); (K_5 and L_5—0.371 Mev); (K_6 and L_6—0.497 Mev).

the above-mentioned authors and by Katcoff[9] who found gamma-rays at approximately 0.26, 0.5, and 1.2 Mev. In addition Katcoff measured the absorption of the electrons in aluminum and found two groups at energies of 0.42 and 0.24 Mev. Finally, Dale *et al.*[10] and Zimmerman *et al.*[11] have measured the spectrum of the gamma-rays and have found two lines—one at 0.496 and the other at 0.213 Mev.

Ba^{131} was prepared by neutron bombardment of barium in the Oak Ridge pile. The sample, in the form of $Ba(NO_3)_2$ was dissolved in water and Cs carrier added. The barium was then precipitated with $(NH_4)_2CO_3$ from a hot solution. The $BaCO_3$ was then dissolved in dilute HNO_3 and, after the addition of other alkaline earth carriers, was precipitated as the nitrate with fuming nitric acid.

The specific activity of the source was quite low. In order to get a sufficient counting rate, the source was packed into a large cylindrical capsule, made of copper, approximately 1 cm in diameter by 1 cm deep. A lead radiator of surface desity 20 mg/cm^2 covered the ends of the capsule. The spectrum of the photoelectrons ejected from the lead radiator was measured in the lens. The counting rate was quite low, so that long counts for each point had to be taken.

The results are shown in Fig. 2 in which the number of counts per minute is plotted against the magnetic rigidity in gauss-cm. The following photoelectric peaks are to be seen: a K peak for a gamma-ray of 0.122 Mev; K and L for 0.196 Mev; K and L for 0.213 Mev; K for 0.241 Mev; K and L for 0.371 Mev; and K and L for 0.497 Mev. It will be seen that the curve does not go to the background immediately beyond the line for the 0.497 gamma-ray. Presumably, a low intensity, high energy gamma-ray is also present. Cuffey[12] determined the energy of a high energy gamma-ray, by coincidence counting methods, and found a gamma-ray of 0.82 Mev.

In order to determine whether the peak of lowest energy is a K line for a gamma-ray of energy 0.12 Mev or an L line for some gamma-ray of lower energy, a beta-ray source was examined. Since the specific activity of the material was extremely low, the source had to be thick in order to obtain any counting rate above the background. An experiment, taking very long counts, showed two internal conversion lines corresponding to K and L lines from a gamma-ray at 0.120 Mev.

It is difficult to estimate the relative intensity of the various gamma-rays from the results shown in Fig. 2 on account of the low specific activity of the source. A rough estimate was made, using Gray's[13] empirical formula, and the results are shown in Table I. It is possible that the estimate of the intensity of the line at 0.122 Mev is too low since this line is internally converted. At the present time it is not possible to give a complete disintegration scheme for Ba^{131}. From energy considerations it appears likely that the lines of energy 0.122 and 0.371 Mev are in series, and both are in parallel with the line at 0.497 Mev.

While these experiments were in progress a similar investigation was carried out by Kondaiah[14] who found lines at 0.122, 0.206, 0.372, and 0.494 Mev. The present experiments confirm the lines at 0.122, 0.371, and 0.497 Mev, but, in addition, show a line at 0.241 Mev and indicate that the line reported by Kondaiah at 0.206 Mev is really two lines at 0.196 and 0.213 Mev.

IV. EXPERIMENTS ON Cs^{131}

Cs^{131}, the daughter of Ba^{131}, has a half-life of 10 days. This substance has been investigated by Yu, Gideon, and Kurbatov,[8] Katcoff,[9] and Yaffe *et al.*[15] Yu, Gideon, and Kurbatov, on the one hand, and Yaffe *et al.* on the other, find x-rays of xenon and in addition internal conversion electrons for a gamma-ray of energy 0.145 Mev. Katcoff finds only x-rays and Auger electrons.

Cs^{131} grows from Ba^{131} and can be prepared by separating cesium from the parent Ba^{131}. The chemical

TABLE I. Relative intensities of gamma-rays of Ba^{131}.

E_γ (Mev)	Relative intensity
0.497	1.00
0.371	0.12
0.241	0.014
0.213	0.053
0.196	0.044
0.122	0.013

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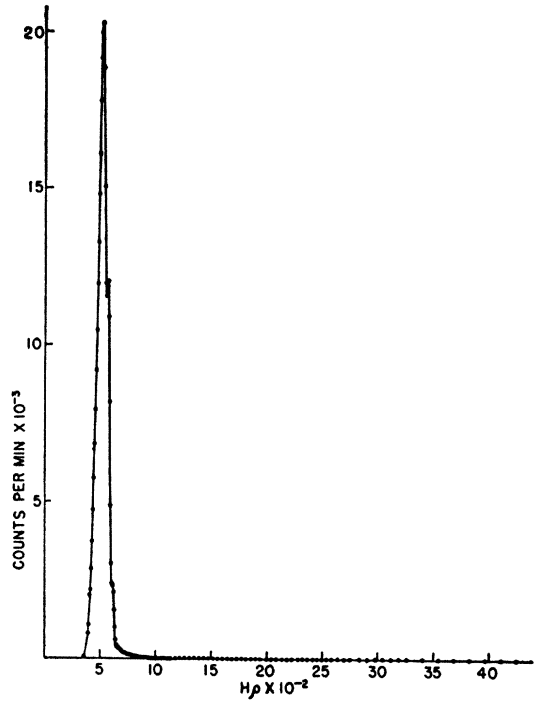

FIG. 3. Electron spectrum of Cs^{131} showing Auger electrons from xenon K_α x-rays.

procedure was carried out in the following way. The filtrates from the barium precipitation were united, additional alkaline earth carrier added, and the alkaline earths were reprecipitated by the addition of $(NH_4)_2CO_3$ and $(NH_4)_2C_2O_2$. The filtrate contained the active cesium and the cesium carrier which had been added, any alkali impurities, together with ammonium salts. The ammonium salts were destroyed with aqua regia and the solution evaporated nearly to dryness. The solution was then made 0.2N in HCl and placed in an ion exchange column. The column was eluted with 0.2N HCl and counts taken on aliquots of the effluent solution at frequent intervals. The curve, showing counting rate per cubic centimeter of the effluent against the time, exhibited three maxima. The first two maxima were quite small, probably arising from potassium and rubidium impurities, and the third one contained most of the activity. That part of the solution corresponding to the cesium peak was then evaporated to a small volume and used in the preparation of sources.

A very thin beta-ray source was mounted on a Zapon film and measured in the magnetic lens. The results are shown in Fig. 3, in which the number of counts per minute is plotted as a function of the magnetic rigidity in gauss-cm. From an inspection of Fig. 3 it will be seen that only Auger lines appear. Two of these lines are at 24.0 and 27.5 kev, respectively, with an indication of a third at 31 kev. The two strong Auger lines found correspond to the lines K-2L and K-L-M. No other internal conversion lines appear out to energies of 1 Mev. It is also clear that no positrons are emitted. A careful search was made for internal conversion lines known to occur in the I^{131} spectrum which arise from transitions in Xe^{131}. In particular a careful search was made for a conversion line corresponding to a gamma-ray at 0.163 Mev arising from the 12-day metastable Xe^{131} as well as for conversion lines from the gamma-rays at 0.080, 0.282, and 0.363 Mev observed as internal conversion lines in I^{131}. None was found.

In order to be sure that no xenon was escaping from the source, it was covered with a thin zapon film and allowed to stand for two weeks. The source was then examined again in the spectrometer and no internal conversion lines were found. It is, therefore, clear that Cs^{131} goes by orbital electron capture to the ground state of Xe^{131}.

In order to be sure that no high energy gamma-rays were present, the source was tested with a lead lined Geiger-Müller counter (insensitive to soft x-rays) and no counts above the background were obtained. It is probable that the gamma-ray of energy 0.145 Mev found by some investigators[8,15] is an impurity.

V. DISCUSSION

The behavior of the transition $Cs^{131} \rightarrow Xe^{131}$ is, at first sight, to some extent surprising. The levels of Xe^{131} are now quite well known from the study of I^{131}. Excited states of Xe^{131} are found at 80, 163, 363, and 717 kev. The fact that none of the low-lying states of Xe^{131} is excited when Cs^{131} decays by orbital electron capture has two possible explanations. In the first place the mass of Cs^{131} may not be sufficiently greater than that of Xe^{131} to allow transitions to any states higher than the ground state of Xe^{131}. This would fix the mass of Cs^{131} with respect to that of Xe^{131} to within 80 kev.

Another possible explanation may arise if one assumes that transitions to any of the low-lying states of Xe^{131} are forbidden by selection rules. While the energy levels of Xe^{131} are now quite well established and the internal conversion coefficients for the three low energy lines have been measured,[16] it turns out to be impossible to make self-consistent assignments of spin and parity to the three levels involved. The shell model predicts the configuration $d_{3/2}$ for the ground state of Xe^{131}, which agrees with the known spin of 3/2. The half-life and energy of the gamma-ray of the 12-day metastable state[6a] of Xe^{131} is in good agreement with the assumption that this transition is characterized as magnetic 2^4 pole radiation. The configuration of the state at 163 kev is probably $h_{11/2}$. The configuration of the state at 80 kev is not known from experiment. The shell model

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predicts $g_{7/2}$ for the configuration of Cs^{131} but $d_{5/2}$ may also be possible. If the configuration of Cs^{131} is $g_{7/2}$ and enough energy is available, one would expect the transition to $h_{11/2}$ to be more probable than that to $d_{3/2}$. If slightly less than 80 kev is available for the K capture process, the value of log $ft \sim 5$. This would indicate an allowed transition and would suggest $d_{5/2}$ as the configuration of the ground state of Cs^{131}.

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The Internal Conversion Coefficients. I: The K-Shell*

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The internal conversion coefficients for electric and magnetic multipole radiation have been computed for the K-shell in the relativistic case with the unscreened coulomb field acting on the electron. The numerical results, which are obtained to four-significant-figure accuracy, were computed on the automatic sequence relay calculator (Mark I) and are given here for 12 values of Z in the range $10 \leqslant Z \leqslant 96$ and 6 gamma-ray energies (between 0.3 mc^2 and 5.0 mc^2) for the first five electric and first five magnetic multipoles.

I. INTRODUCTION

THE results of the calculation of the K-shell internal conversion coefficient (defined as the ratio of conversion electrons to quanta) which are presented herein were very briefly described in a previous communication.[1] Subsequent to May, 1949, tables of these coefficients together with an extensive interpolation were circulated privately. Inasmuch as plans for the calculation of the L-shell coefficients were instituted very soon after the completion of the K-shell work, publication of the present material was held up in the hope of presenting all of the numerical results together. This does not seem to be feasible, and this paper is written in the interest of making the K-shell results more readily available.

At the time of completion of this work the only existing accurate calculations of the K-shell internal conversion coefficients were those of Hulme[2] (for electric dipole, $Z=84$), of Taylor and Mott[3] (electric quadrupole, $Z=84$) and of Fisk and Taylor[4] (magnetic dipole, quadrupole, and octupole, $Z=84$). Shortly afterward, Griffith and Stanley[5] made calculations of the K-shell electric dipole coefficients for five values of Z in the range 69–89. Subsequently, the coefficients for electric dipole, quadrupole, and magnetic dipole for Cu, In, Po, and U at low energies were obtained by Reitz.[6] Here screening was taken into account by numerical integration of the Dirac radial equations with a Thomas-Fermi-Dirac potential. In the present work where $k \geqslant 0.3$ (kmc^2 is the gamma-ray energy) no effect of screening is considered. Comparison with Reitz's results where our calculations overlap fully justifies this procedure. Calculations of the L_I-shell coefficients with unscreened wave functions have been carried out by Gellman *et al.*[7] for the same multipoles, and the same Z and k-values as appear in Reitz's work. However, these results are primarily of orientation value, since the neglect of screening cannot be justified in this case. In fact, in the calculation of the L-shell coefficients[8] (including all sub-shells) which are now under way, screening is taken into account in the same manner as was done by Reitz. In addition, low energy K-shell coefficients for all important multipoles and for essentially the same range of values of Z as in the K-shell work are being carried out with screened wave functions in parallel with the L-shell computation.

Until the L-shell and low energy K-shell results become available, it is necessary to supplement the present values of the coefficients with low energy extrapolations based on a comparison of these values and those obtained from the nonrelativistic formulas of Uhlenbeck and Hebb[9] and the essentially nonrelativistic

* This document is based on work performed for the AEC at the Oak Ridge National Laboratory.

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