nesses indicates that the Pr^{143} data are undistorted above 125 kev by any effects of source preparation.

ACKNOWLEDGMENTS

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Radiations of Xe^{127}†

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The radiations of Xe^{127} have been examined. The energies of previously observed gamma rays were found to be 58±1, 146±0.5, 173.0±0.5, 204.5±0.5, and 377.5±0.5 kev. Conversion electron intensities relative to gamma-ray intensities and internal conversion coefficients were measured. The experiment indicates that electron capture to the ground state is suppressed. Spin and parity assignments are proposed for the 204- and 377-kev excited states of I^{127}.

I. INTRODUCTION

XENON–127 decays by electron-capture to I^{127} with a half-life of 36.4 days.[1] The isotope was first identified by Creutz *et al.*[2] by using a (p,n) reaction on I^{127}. Since then its radiations have been investigated by several workers, the most recent being Mathur[3] whose scintillation spectrometry and gamma-gamma coincidence work supported a decay scheme proposed by Bergström.[4] Bergström's work was done principally on the electron spectrum of Xe^{127}, and his work plus that on the gamma-ray spectrum by Mathur comprise the most complete investigations of the radiations of Xe^{127} to the present time.

The present investigation was undertaken in order to provide further information on the decay of Xe^{127} and the resulting excited states of I^{127} through the use of both scintillation and magnetic spectrometers.

II. SOURCE PREPARATION

Xe^{127} was produced in potassium iodide targets by a (p,n) reaction using 10-Mev protons and by a $(d,2n)$ reaction using 20-Mev deuterons. The Xe^{127} was separated from the target and transferred to 0.25-mil aluminized Mylar films by a glow discharge using a method similar to that described by Mathur and Hyde.[5] The aluminized side of the film formed the cathode surface. The discharge was operated for approximately two minutes at an initial pressure of the order of 200 μ. The cathode-anode potential difference was 1000 v which produced a current of 0.5 mil distributed over a cathode area of the order of 3 cm^2.

Radio-autographs of the films revealed two sharply delineated areas of activity, both of which were of consistently uniform activity. Brown and Leck[6] have investigated some properties of adsorbed gas layers created on metallic surfaces under similar physical conditions. Their results along with an order of magnitude calculation of the activity indicate that the Xe^{127} is present on the surface of the films in a form approaching a monolayer. The decay of the activity from one of the sources used in the investigation was followed for 82 days resulting in a measured half-life of 36±0.5 days indicating negligible evaporation of Xe^{127} atoms from the aluminized Mylar films. This supports observations of Mathur and Hyde[5] and Brown and Leck.[6]

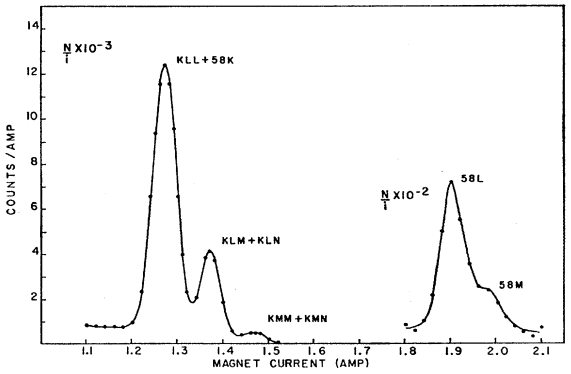

FIG. 1. K Auger electron spectrum and 58 K, L, and M internal conversion electron spectrum.

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[1] S. J. Balestrini, Phys. Rev. **95**, 1502 (1954).
[2] E. C. Creutz *et al.*, Phys. Rev. **58**, 1481 (1940).
[3] H. B. Mathur, Phys. Rev. **97**, 707 (1955).
[4] I. Bergström, Arkiv Fysik **5**, 191 (1952).
[5] H. B. Mathur and E. K. Hyde, Phys. Rev. **96**, 126 (1954).
[6] E. Brown and J. H. Leck, Brit. J. Appl. Phys. **6**, 161 (1955).

TABLE I. Experimental results.

Transition (kev)	Transition energy in kev	Relative K x-ray and gamma intensity	Relative K Auger electron and internal conversion electron intensities	Electron intensity ratios	K fluorescence yield and internal conversion coefficients
K x-ray		1170±70	75±13[a] (KLL) 38±2 (KLM+KLN) 2.6±0.1 (KMM+KMN)		ω_K=0.91 ±0.03[a]
58	58.0±1.0	21±2	58±10[a] (K) 6.7±0.2 (L) } K/L 1.59±0.06 (M) } L/M	8.6±2.0[a] 4.2±0.3	α_K=2.7 ±1.0[a] α_L=0.32 ±0.07
146	146.5±0.5	64±10	19.6±0.5 (K)		α_K=0.31 ±0.09
173	173.0±0.5	342±17	43±1.0[b] (K)		α_K=0.13 ±0.02[b]
204	204.5±0.5	1000±40	85±2[b] (K) 15.4±0.4 (L+M) } K/(L+M)	5.5±0.4[b]	α_K=0.085 ±0.014[b] α_L=0.015 ±0.002[c]
377	377.5±0.5	301±12	3.8±0.2 (K) 0.78±0.06 (L+M) } K/(L+M)	4.9±0.3	α_K=0.012 ±0.002 α_L=0.0025±0.0005[c]

[a] Experimental ratio of KLL to $KLM+KLN$ for xenon used to separate KLL and 58 K lines (see text).
[b] Theoretical K/L value used to subtract L component of preceding transition; M component ignored (see Table II and text).
[c] Includes α_M.

III. AUGER AND CONVERSION ELECTRON SPECTRA

The electron spectrum of Xe^{127} was investigated with a 180° spectrograph and a thick-lens magnetic spectrometer.[7] The spectrometer was equipped with a Geiger counter having a nylon window with a cutoff of approximately 5 kev. Correction factors for window absorption were determined empirically using the beta spectrum of S^{35}.

An Auger spectrum corrected for window absorption and counter dead time is shown in Fig. 1. A conversion spectrum is shown in Figs. 1 and 2. The 146 L and 173 K and the 173 L and 204 K lines are not resolved by the thick-lens spectrometer. Energy measurements of the conversion and Auger electron lines were made with the thick-lens spectrometer; the values determined were consistent with those which could be measured with the 180° spectrograph. The results are listed in Table I.

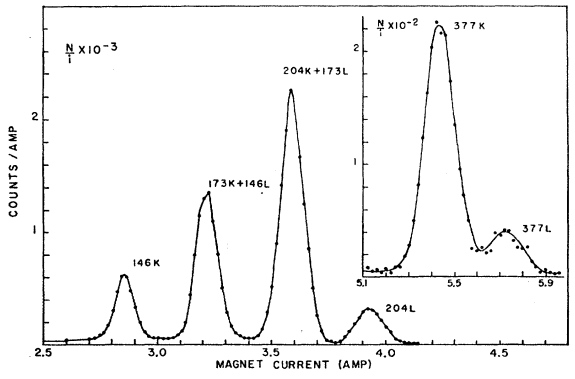

FIG. 2. Internal conversion electron spectrum.

[7] B. Crasemann and D. L. Manley, Phys. Rev. 98, 66 (1955).

IV. X-RAY AND GAMMA-RAY SPECTRA

A scintillation spectrum of Xe^{127} is reproduced in Fig. 3. These spectra were obtained with Harshaw $1\frac{1}{2}\times1$-in. NaI(Tl) crystals having 1-mil and 30-mil aluminum, and 5-mil beryllium windows. A 5-cm source-crystal separation was found to be sufficient to reduce K x-ray plus gamma-ray sum peaks to a negligible value. Intensity measurements presented in Table I were made using appropriate photopeak efficiency values taken from the curves of Kalkstein and Hollander.[8]

The complex scintillation spectrum was decomposed into its components by an empirical method; the pulse distribution produced by gamma rays of a single energy was plotted on an energy scale, and a graphical interpolation of the Compton distribution and backscatter peaks was made for the Xe^{127} gamma rays. Sn^{113}, Hg^{203}, Co^{57}, and Cd^{109} were used to cover the energy region of interest. The results are shown in Fig. 3. X-ray intensity relative to the 204-kev gamma-ray intensity was measured with 5-mil beryllium and 1-mil aluminum window crystals using collimated and uncollimated sources at various distances in order to reduce systematic errors resulting from the use of window-absorption and crystal-efficiency correction factors. The gamma-gamma coincidences performed were in agreement with Mathur's[3] results. No annihilation radiation was observed.

V. CONVERSION COEFFICIENTS AND SPIN AND PARITY ASSIGNMENTS

Conversion coefficients and the K-fluorescence yield given in Table I were measured using the ratio of the effective solid angles of the scintillation and thick-lens spectrometer found by comparing the gamma-ray

[8] M. I. Kalkstein and J. M. Hollander, University of California Radiation Laboratory Report UCRL-2764, 1954 (unpublished).

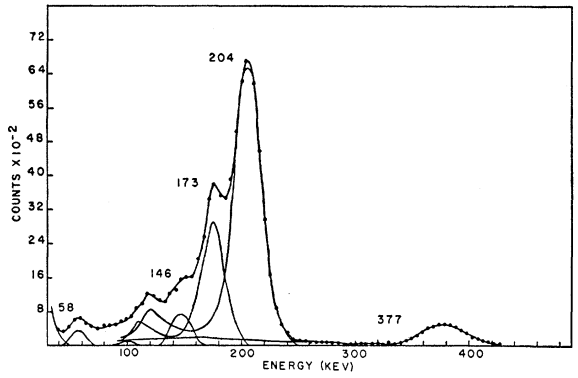

FIG. 3. Scintillation spectrum. The filled circles are experimental points. The contribution of the 377-, 204-, 173-, 146-, and 58-kev gamma rays to the total is indicated.

intensity with conversion electron intensity resulting from a transition with a known conversion coefficient. Gamma rays and conversion electrons from a Hg^{203} source were compared using Nordling's[9] value of 0.159 ± 0.004 for the 279-kev transition.

Theoretical values of K and L conversion coefficients and K/L ratios are listed in Table II. The K conversion coefficients were taken from the tables of Sliv and Band[10] and the L conversion coefficients from the tables of Rose.[11]

Assuming the ratio of the intensities of the KLL to $KLM+KLN$ Auger lines to be a slowly varying function of Z, the value of 0.50 ± 0.04 found by Bergström[4] for xenon can be used to determine the intensity of the 58 K conversion electron line and the KLL Auger line. The resulting K/L ratio and K conversion coefficient along with the experimental L conversion coefficient indicate the 58-kev transition to be $M1$. This is consistent with the characterization of the spin and parity of the 58-kev excited state of I^{127} by Knight *et al.*[12] as $g_{7/2}$ and with the $d_{5/2}$ ground state. On the basis of the experimental $K/(L+M)$ ratio, the character and multipolarity of the 377-kev transition can be specified as predominantly $E2$. Use of either an $M1$ or $E2$ theoretical K/L ratio for the 173-kev transition for the separation of the 173 L and 204 K conversion electron lines to determine the 204 K conversion electron intensity labels the 204-kev transition as primarily $M1$. With the same procedure applied to the 146-kev and 173-kev transitions one finds the latter to be $M1$. The characterization of the 146-kev transition is the most uncertain because of the lack of an experimentally determined K/L ratio and the difficulty in separating the 204-kev and 173-kev Compton distribution and back scatter peaks from the 146-kev photopeak in the scintillation spectra. On the basis of the experimental K conversion coefficient, it would be characterized as an $M1$–$E2$ mixture.

TABLE II. Theoretical conversion coefficients and K/L ratios.

Transition (kev)	αK		αL		K/L		Assignment
	$M1$	$E2$	$M1$	$E2$	$M1$	$E2$	
58	2.85	5.5	0.34	4.4	8.38	1.25	$M1$
146	0.225	0.350	0.0285	0.096	7.91	3.65	$E2$
173	0.137	0.205	0.0177	0.048	7.74	4.27	$M1$
204	0.088	0.120	0.011	0.025	8.00	4.8	$M1$
377	0.018	0.016	0.00221	0.00255	8.14	6.28	$E2$

[9] Nordling, Siegbahn, and Sokolowski, Nuclear Phys. **1**, 329 (1956).
[10] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57 ICCK1, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].
[11] M. E. Rose (privately circulated tables).
[12] J. D. Knight *et al.*, Phys. Rev. **102**, 1592 (1956).

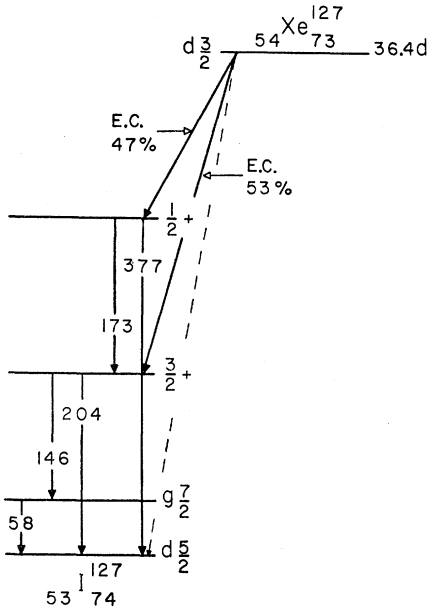

FIG. 4. Decay scheme for Xe^{127}. The electron capture percentages are for transitions to excited states only. Decay to the ground state is discussed in the text.

In their paper reporting the discovery and investigation of the beta decay of Te^{127} to excited states of I^{127}, Knight *et al.*[12] have presented arguments based on experimental evidence limiting the 204-kev level to either 3/2+ or 5/2+. Specifying the 377-kev transition to be $E2$ limits the spin and parity of the 377-kev excited state to 1/2+ or 9/2+. The absence of the 319-kev transition connecting the 377-kev and 58-kev excited states in the observed conversion electron, scintillation or coincidence spectra indicate 1/2+ to be correct. The assignment of $M1$ as the character and multipolarity of the 173-kev transition shows the 204-kev level to be 3/2+. This assignment determines the 146-kev transition to be $E2$. The spin and parity assignments are indicated in Fig. 4 and the character and multipolarity of the transitions are listed in Table II.

The ground state of Xe^{127} is presumed to be $d_{\frac{3}{2}}$.[13] This assignment plus those shown in Fig. 4 indicate that electron capture from the ground state of Xe^{127} to the 377- and 204-kev excited states and to the ground state of I^{127} is allowed: $\Delta I=0, \pm 1$ (no).

VI. DISINTEGRATION ENERGY AND LOG *ft* VALUES

The excited states of I^{127} resulting from the decay[3,4] of Xe^{127} are shown in the decay scheme of Fig. 4. No evidence of a transition to the 418-kev excited state of I^{127}, discovered by Knight *et al.*,[12] was found in the scintillation, conversion or gamma-gamma coincidence spectra. Using this decay scheme and the experimentally determined conversion coefficients, the frequency of transitions from the 204-kev level to the 58-kev level was found to be equal to that from the 58-kev level to the ground state of I^{127} within the experimental errors. From this, one concludes that the probability of a transition from Xe^{127} to the 58-kev level of I^{127} is negligible.

An upper limit on the disintegration energy can be estimated by using the following argument. From the decay scheme and experimental results, the percentage of electron capture transitions going to states other than the 377-kev or 204-kev excited states or to the ground state is negligible. The rate of creation of K-shell vacancies (the sum of the K x-ray intensity, $I_{K\text{ x-ray}}$, and K Auger electron intensity, $I_{K\text{ Auger}}$) is, therefore, equal to the K conversion electron intensity, I_{Ke}, plus the sum of the fraction of the electron capture transition intensities $I_{377\text{ E.C.}}$, $I_{204\text{ E.C.}}$ and $I_{0\text{ E.C.}}$ which result from K capture. This can also be expressed by the following relation:

$$\frac{I_{K\text{ x-ray}}+I_{K\text{ Auger}}-I_{Ke}}{I_{377\text{ E.C.}}+I_{204\text{ E.C.}}+I_{0\text{ E.C.}}}=\frac{1}{1+(\Sigma/K)_t}, \quad (1)$$

where $(\Sigma/K)_t$ is the intensity ratio of total L and higher shell to K capture. The minimum value of $(\Sigma/K)_t$ is found by assuming the intensity of electron capture to the I^{127} ground state is zero. Putting $I_{0\text{ E.C.}}=0$ in (1) gives a value of 0.40 ± 0.12 for $(\Sigma/K)_t$. $(\Sigma/K)_t$ can also be written as follows:

$$\frac{1}{1+(\Sigma/K)_t}=\rho_{377}\frac{1}{1+(\Sigma/K)_{377}}+\rho_{204}\frac{1}{1+(\Sigma/K)_{204}}+\rho_0\frac{1}{1+(\Sigma/K)_0}, \quad (2)$$

where $(\Sigma/K)_{377}$, $(\Sigma/K)_{204}$, and $(\Sigma/K)_0$ are the ratios for electron capture transitions to the 377- and 204-kev excited states and to the ground state, respectively, and ρ_{377}, ρ_{204}, and ρ_0 are the respective branching ratios. Under the present assumption of $\rho_0=0$, ρ_{377} and ρ_{204} are equal to the values indicated in Fig. 4.

The transition probability for allowed electron capture is discussed by Brysk and Rose.[14] Using their tables for the L_{I} and L_{II} to K electron wave function ratios and the indicated approximations for s electron capture from shells higher than the L shell, Σ/K can be expressed as a function of the disintegration energy. Substituting this expression for $(\Sigma/K)_{377}$ and $(\Sigma/K)_{204}$ in (2) along with the experimental value of $(\Sigma/K)_t$ listed above, one obtains an estimate for the upper limit on the disintegration energy of 450_{-20}^{+50} kev. With this disintegration energy, log*ft* values for the K capture transition to the 377-kev and 204-kev level are found to be 4.8 ± 0.4 and 6.1 ± 0.2, respectively. The Coulomb field term in the expression for f was taken from the graph of Moszkowski[15] and t was corrected for L and higher shell capture as well as for the branching ratio.

A lower limit for the log*ft* value for the K capture transition to the ground state can be estimated by assuming the transition to the 377-kev level goes entirely by L and higher shell capture. The energy difference between the ground state of Xe^{127} and the 377-kev level then lies between the L- and K-shell binding energy of xenon. Choosing the disintegration energy so that the difference is equal to the former limit, strictly for the sake of a minimum estimate of log*ft*, one can compute the value of $(\Sigma/K)_{204}$ and $(\Sigma/K)_0$ using the expression mentioned above. Using these values with (1) and (2) plus the definition of the branching ratios, one obtains an estimate for the maximum value of $I_{0\text{ E.C.}}$ which is equal to 26% of the total electron capture intensity. From this a minimum value of 6.8 for log*ft* for the K capture transition to the ground state can be calculated. The results of the above arguments can be summarized in the following estimates: (1) Disintegration energy <500 kev. (2) Log*ft* for K capture to the ground state >6.8.

Beta-decay systematics[16] predicts a value in the neighborhood of 500 kev for the disintegration energy, in agreement with an estimate of the threshold energy of the $(d,2n)$ reaction on I^{127} made by Balestrini.[1]

VII. DISCUSSION

The experimental data indicates that electron capture from the ground state of Xe^{127} to the ground state of I^{127} is suppressed, which on the basis of the $d_{\frac{3}{2}}$ ground state assignment of Xe^{127} is contrary to the definitely "allowed" $d_{\frac{3}{2}}\rightarrow d_{\frac{3}{2}}$ transition expected; however, this result has been anticipated. Knight *et al.*[12] have applied the discussion of nuclear core effects by de-Shalit and Goldhaber[17] to explain the abnormally large log*ft*

[13] H. B. Mathur and E. K. Hyde, Phys. Rev. **95**, 708 (1954).

[14] H. Brysk and M. E. Rose, Oak Ridge National Laboratory Report ORNL-1830, 1955, and errata (unpublished).

[15] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).

[16] K. Way and M. Wood, Phys. Rev. **94**, 119 (1954).

[17] A. de-Shalit and M. Goldhaber, Phys. Rev. **92**, 1211 (1953).

found for the beta decay from the ground state of Te^{127} to the 204-kev excited state of I^{127}. A result of this explanation is the prediction that electron capture from the ground state of Xe^{127} to the ground state of I^{127} should be suppressed.

Assuming that the assigned character and multipolarities are correct, the comparison of theoretical and experimental conversion-coefficient values seems to indicate a systematic error resulting in an increase of gamma-ray intensities. If the K fluorescence yield value for iodine were better known,[18] its use in comparing the relative efficiencies and solid angles of the thick-lens and scintillation spectrometers would eliminate a number of errors inherent in the method employed; however, the accuracy of the window correction factor and the uncertainty in the intensity ratio of the $KLM+KLN$ to KLL Auger line for iodine[19] as well as errors in measuring Auger intensities due to increased back scatter effects would probably make such a technique less accurate than the one used. An increase in the relative electron intensities would decrease the difference between the observed K fluorescence yield and the value for $Z=53$ of 0.86 taken from the semiempirical curve of Burhop.[20] However, the increase necessary to make these values equal is not consistent with the other experimental data even with an added increase in the Auger electron intensities. A decrease in the relative K x-ray intensity causes difficulties in the interpretation of the value found for the Σ/K capture ratio and it seems unlikely from an experimental point of view. There is some experimental evidence that the values for K fluorescence yields predicted from the semiempirical curve of Burhop may be low in the region of $Z=55$.[21]

The authors wish to thank Professor A. C. Helmholz of the University of California for generously providing the cyclotron bombardments. Thanks are due Professor Bernd Crasemann of this laboratory for a number of helpful discussions.

[18] C. E. Roos, Phys. Rev. **105**, 931 (1957).
[19] C. D. Broyles *et al.*, Phys. Rev. **89**, 715 (1953).
[20] E. H. S. Burhop, J. phys. radium **16**, 624 (1955).
[21] Charles H. Pruett and Roger G. Wilkinson, Phys. Rev. **96**, 1340 (1954).

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Structure of the Nuclear Mass Surface*

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The nuclear mass surface is analyzed in terms of its observed structural properties, and a formula is developed for the binding energy which is easy to use and is accurate, over all, to ± 0.54 Mev, and, for $A>214$, to ± 0.27 Mev.

1. INTRODUCTION

AT the present time, no truly satisfactory representation of the whole nuclear mass surface is available. Smooth formulas of the Weizsäcker type seem to have a limited accuracy of about ± 2–3 Mev.[1] The work of Cameron[2] furnishes as good a fit to the experimental data as might reasonably be expected for medium and heavy nuclei. However to obtain these results he is forced to use a large number (over 200) of empirical constants which do not appear to be very smoothable if accuracy is retained.

Much of the difficulty in constructing a satisfactory mass surface arises from the problem of comprehending a two-dimensional surface with no closely satisfied structural properties. We sought to determine if there is, in fact, some structural property of the nuclear surface.

In the next section we point out that there is evidence that such structure does exist. In the third section we describe how a mathematical model based on this structure may be fitted to the experimental data. In the fourth section we describe this fit in detail and quote our results.

Our results indicate that a formula which is a function of atomic number, plus a function of neutron excess, plus atomic number times a function of neutron excess, plus a pairing term gives, within a shell, a fit of accuracy ± 0.2 Mev. It gives an over-all fit of within ± 0.5 Mev. There appear to be discontinuities at the shell boundaries of about 1 Mev, which are not accounted for by this type of formula. We remark that, except in the region of very light nuclei, these fits (aside from shell discontinuities) are as close as present experimental error will allow.

2. EVIDENCE FOR STRUCTURE

Several different lines of evidence indicate that the binding energies of atomic nuclei may be represented

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
[1] A. E. S. Green, Revs. Modern Phys. **30**, 569 (1958).
[2] A. G. W. Cameron, Can. J. Phys. **35**, 1021 (1957).