30B, 39 (1969).
[6]J. C. Vanderleeden and F. Boehm, to be published; E. Bodenstedt, L. Ley, H. O. Schlenz, and U. Wehman, Phys. Letters 29B, 165 (1969); D. W. Cruse and W. D. Hamilton, Nucl. Phys. A125, 241 (1969); F. Boehm and E. Kankeleit, Nucl. Phys. A109, 457 (1968); V. M. Lobashov, V. L. Nazarenko, L. F. Saenko, L. M. Smotritskii, and G. I. Kharkevitch, Zh. Eksperim. i Teor. Fiz. – Pis'ma Redakt. 3, 268 (1966) [transl.: JETP Letters 3, 173 (1966)]; B. Jenschke and P. Bock, Phys. Letters 31B, 65 (1970).
[7]Yu. G. Abov, P. A. Krupchitsky, M. I. Bulgakov, O. N. Yermakov, and I. L. Karpikhin, Phys. Letters 27B, 16 (1968); E. Warming, F. Stecher-Rasmussen, W. Ratynski, and J. Kopecký, Phys. Letters 25B, 200 (1967).
[8]Taken from C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed.
[9]R. E. Gegenwarth, J. I. Budnick, S. Skalski, and J. H. Wernick, Phys. Rev. Letters 18, 9 (1967).
[10]Model No. 440K, Opamp Laboratories, 172 S. Alta Vista Blvd., Los Angeles, California 90036.
[11]Furane Plastics, 5121 San Fernando Road West, Los Angeles, California 90039.
[12]See, for instance, R. D. Evans, *The Atomic Nucleus* (McGraw Hill Book Company, New York, 1955), p. 214.
[13]Here $[Nn_z\Lambda\uparrow]$ is the usual notation for a single particle and a deformed core. N is the number of nodes in the single-particle wave function, n_z is its number of nodes along the z axis, and Λ is the projection of the single-particle angular momentum along the symmetry axis of the deformed core. $\uparrow$ or $\downarrow$ indicates that the single-particle intrinsic spin is parallel or antiparallel, respectively, to Λ.
[14]These assignments are from R. M. Diamond, B. Elbek, and F. S. Stephens, Nucl. Phys. 43, 560 (1963).
[15]See Table III of F. C. Michel, Phys. Rev. 133, B329 (1964). This early paper discusses many of the concepts necessary in the selection of appropriate transitions for study. These ideas are also discussed by S. Wahlborn, Phys. Rev. 138, B530 (1965).
[16]S. R. DeGroot, H. A. Tolhoek, and W. J. Huiskamp, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, The Netherlands, 1965), Vol. II, p. 1199.
[17]W. Henning, D. Huenemann, W. Weber, P. Kienle, and H. H. Korner, in *Hyperfine Structure and Nuclear Radiations*, edited by E. Matthias and D. A. Shirley (North-Holland Publishing Company, Amsterdam, The Netherlands, 1968), p. 178.
[18]J. P. Hurrell, Brit. J. Apl. Phys. 16, 755 (1965).

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Nuclear Resonance Fluorescence in Xe^{131}†

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The 637- and 723-keV states in Xe^{131} have been investigated by employing the technique of nuclear resonance fluorecence. The angular distribution of the resonantly scattered radiation from the 637-keV level is consistent with the assignment of either spin and parity $\frac{5}{2}^+$, decaying to the ground state predominantly by an $M1$ transition, or a spin and parity of $\frac{7}{2}^+$ with the decay to the ground state being pure $E2$. Considering the results of other investigators, a $\frac{7}{2}^+$ assignment appears to be the correct choice. Assuming a spin of $\frac{7}{2}$, the mean life of the 637-keV level is found to be 1.8 ± 0.8 psec. The fact that resonant scattering from the 723-keV level was observed with a source of gaseous I^{131} is attributed to Coulomb fragmentation of the $(IXe^{131})^+$ molecular ion formed following the β decay of I^{131}. The angular distribution of the resonantly scattered 723-keV γ rays is consistent with a spin and parity assignment of $\frac{5}{2}^+$ to this level, and a pure $M1$ decay to the ground state. Our results indicate that the mean life of the 723-keV level is greater than 1.5 psec.

I. INTRODUCTION

Much effort has been devoted to both experimental and theoretical investigations[1,2] of the excited states in Xe^{131} populated by the β decay of I^{131}. The properties of various levels, however, are still not well understood. In particular, the spin and lifetime of the 637-keV level, as well as the multipolarity of its transition to the ground state, were still in question at the inception of the work described here. A spin and parity assignment of $\frac{5}{2}^+$, and a pure $E2$ transition to the ground state were indicated by the results of an electric hfs alignment experiment on oriented iodine nuclei.[3] The results of internal-conversion measurements[4] were consistent with a $\frac{7}{2}^+$ assignment and a pure $E2$ ground-state transition or a $\frac{5}{2}^+$ assignment decaying 98% $E2$ ($\delta = 7.4$) to the ground state. Other authors[5,6] have proposed a $\frac{7}{2}^+$ assignment coupled with an $E2$ transition to the ground state.

The lifetime of the 637-keV level has been previously measured by means of nuclear-resonance-

fluorescence scattering.[5] However, in that work, $N(E_R)$, the relative number of γ rays emitted from the source having the correct energy to be resonantly scattered, could only be roughly estimated and there was a correspondingly large uncertainty in the resulting lifetime for the level. The lifetime obtained in the present work is about five times larger than the value given in Ref. 5.

The primary goal of our investigation was to make a new determination of the lifetime and spin of the 637-keV state and also the multipolarity of its transition to the ground state by means of nuclear-resonance-fluorescence scattering and absorption experiments. The interpretation of the angular distribution of resonantly scattered γ rays is particularly simple when the initial and final states are identical. In addition, a knowledge of $N(E_R)$ is not necessary with a resonance self-absorption measurement. See, e.g., the works of Metzger, Ofer, and Schwarzschild.[7,8]

During the course of this work it was observed that resonant scattering from both the 637- and 723-keV levels was greatly enhanced when a gaseous source of II^{131} was used compared with the effect obtained with a gaseous source of CH_3I^{131}. The enhanced resonant scattering is ascribed to the effects of Coulomb fragmentation[9-12] of the $(IXe^{131})^+$ molecular ion produced following the β decay of I^{131}.

The decay scheme for I^{131} is given in Fig. 1. The diagram is based mainly on the work of Graeffe and Walters,[2] although results of the present investigations are shown for the 637- and 723-keV levels of Xe^{131}, and other half-life values were taken from the *Table of Isotopes*.[13]

II. EXPERIMENTAL DETAILS

1. Self-Absorption Measurements

Figure 2 illustrates the basic arrangement employed in the self-absorption measurements. The I^{131} source was contained in a cylindrical pyrex ampoule placed within a coil heater. Sources of either CH_3I^{131} or II^{131} were used. In each case the temperature was held at a value above the boiling point of the source material.

It was desirable to have the scatterer and absorber consist of solid xenon in order to obtain an observable number of resonantly scattered γ rays. This was accomplished by condensing xenon gas, of natural isotopic abundance, into thin-walled containers of either brass or stainless steel. The general procedure followed has been previously described.[14] The matched scatterers and absorbers contained a mixture of NaI and Sb powders in such proportion as to provide a good match for the nonresonant scattering background in the energy region above 500 keV. Counts were accumulated in 20-min intervals on a continuous 24-h basis. The xenon and matched absorbers and scatterers were alternated to minimize corrections for source decay and the effects of possible background varia-

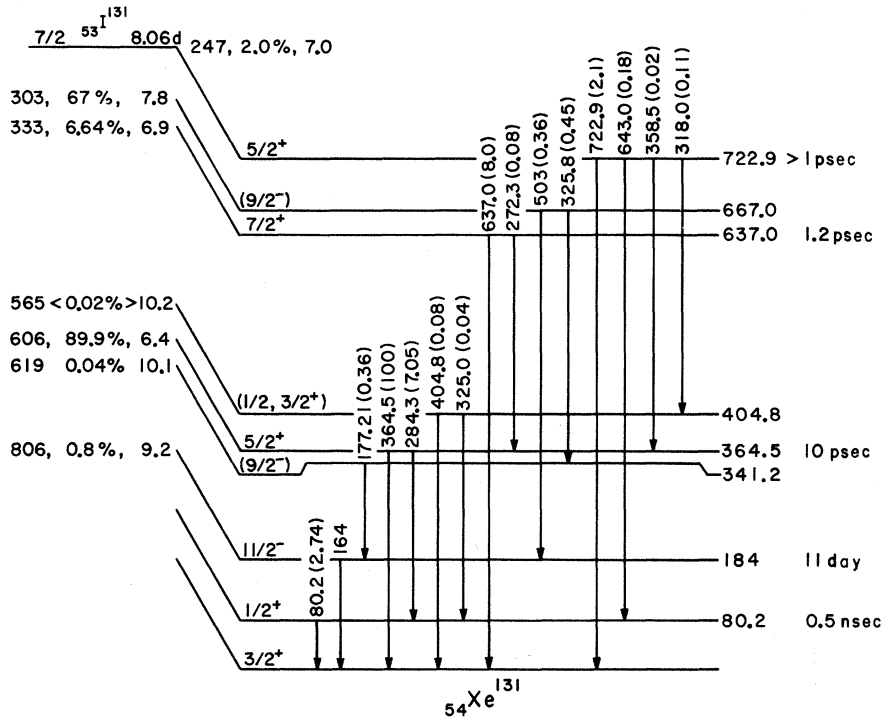

FIG. 1. Decay scheme of I^{131} taken from Ref. 2. The lifetimes are from Ref. 13 and the present work and are given as half-lives.

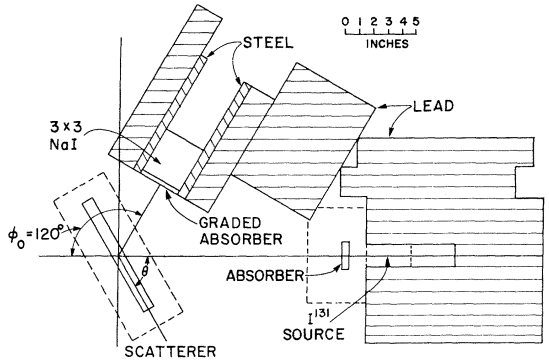

FIG. 2. Cross-sectional diagram of the experimental arrangement for resonance self-absorption and angular-distribution measurements.

tions. In all runs the resonance effect was a small fraction of the total counting rate; the majority of the recorded counts in the region of the 637- and 723-keV peaks were caused by room background.

Since Xe^{131} has a natural relative abundance of only 21%, the nonresonant absorption in the absorbers effectively limited their thicknesses to values for which the resonant self-absorption was not large. Absorber thicknesses of $\frac{7}{16}$ and $\frac{3}{2}$ in. were used. Self-absorption runs were made with three sources, one in the form of methyl iodide and two of elemental iodine, all initially ≈100 mCi.

2. Angular-Distribution Measurements

For the angular-distribution measurements the same general arrangement shown in Fig. 2 was used except that the resonant absorbers were not used. The source position remained fixed and the position of the NaI(Tl) detector was varied to change the average scattering angle over the range from 90 to 145°. Two different scatterers were used; the first was disk shaped, $8\frac{1}{2}$ in. in diameter and $\frac{5}{8}$ in. thick with faces of $\frac{1}{16}$-in. stainless-steel sheet, and the second was rectangular, 3 in. by 8 in. by $\frac{5}{8}$ in. with $\frac{1}{16}$-in.-thick brass faces. The amount of xenon in the scatterer in each case was 1.8 and 0.9 kg, respectively.

III. EXPERIMENTAL RESULTS

1. Lifetime of 637-keV Level

Figure 3 shows the resonance effect obtained by using the methyl iodide source with a xenon scatterer and $\frac{7}{16}$-in.-thick absorber after subtraction of the background counts obtained with the matched scatterer and absorber. The 637-keV resonance scattering was weak and the corresponding peak, as shown in Fig. 3, was not well defined. The result of a comparable run using an elemental iodine source is also shown in Fig. 3. A similar curve was obtained with the matched absorber and xenon scatterer. For the elemental iodine source the 637-keV peak is clearly larger and much better defined. Since the other conditions of the experiment were unchanged, the ratio of $N(E_{res})$ with the methyl iodide source to $N(E_{res})$ with the elemental iodine source can be directly obtained for the 637-keV γ ray from the normalized spectra and was found to be $\approx\frac{1}{2}$.

To a suitable approximation, the equation relating the level width Γ_0 to the transmission coefficient T_{ab} can be written[7,8]

$$T_{ab} = e^{-G\delta d_a},$$

where $G = ng\lambda^2\Gamma_0/(4D\sqrt{\pi})$ and $D = (E_\gamma/c)(2kT/M)^{1/2}$, D is the Doppler width, T the effective temperature of absorber or scatterer, λ the wavelength of the γ ray of energy E_γ, M the mass of the resonantly excited nucleus, g the statistical factor, n the number of resonant nuclei per cm^3, d_a the average absorber thickness (in cm), k the Boltzmann constant, c the speed of light, and δ is taken to be 0.66 from Ref. 8.

For the determination of n, a value of 3.3 g/cc was used for the density of the solid xenon. The density was measured by weighing a known volume of solid xenon at liquid-nitrogen temperature, and it agrees well with the value given in the work of Pollack[15]. With this value for the density, $n = 3.20 \times 10^{21}$ atoms/cm^3. Other numerical values are as follows: $\lambda^2 = 3.80 \times 10^{20}$ cm^2 and (by use of a Debye temperature of 54.3 K[14] and the Lamb correction for crystalline binding[7]) $D = 0.213$ eV.

Only the results of the self-absorption measurements with the elemental iodine source were used to determine the lifetime. Since the resonant scattering peak was much weaker for the CH_3I source, it was not possible to unambiguously select the channels bracketting the peak position. The apparent self-absorption obtained depended on the energy interval selected. For the more clearly defined peaks obtained with the elemental iodine sources, the self-absorption was not significantly changed by such nonphysical manipulations. Consequently, the results with the CH_3I source were judged to be considerably less reliable than those obtained by using the elemental iodine sources.

Table I shows the results of the resonant self-absorption runs and corresponding values of $g\Gamma$ and τ/g for the 637-keV level obtained with the elemental iodine sources. These results include a correction for the effect of the self-absorption in the $\frac{5}{8}$-in.-thick scatterer.[7,8] However, compared with the uncertainty in T_{ab}, the correction produces a negligible difference from the result obtained using the approximate expression for T_{ab}.

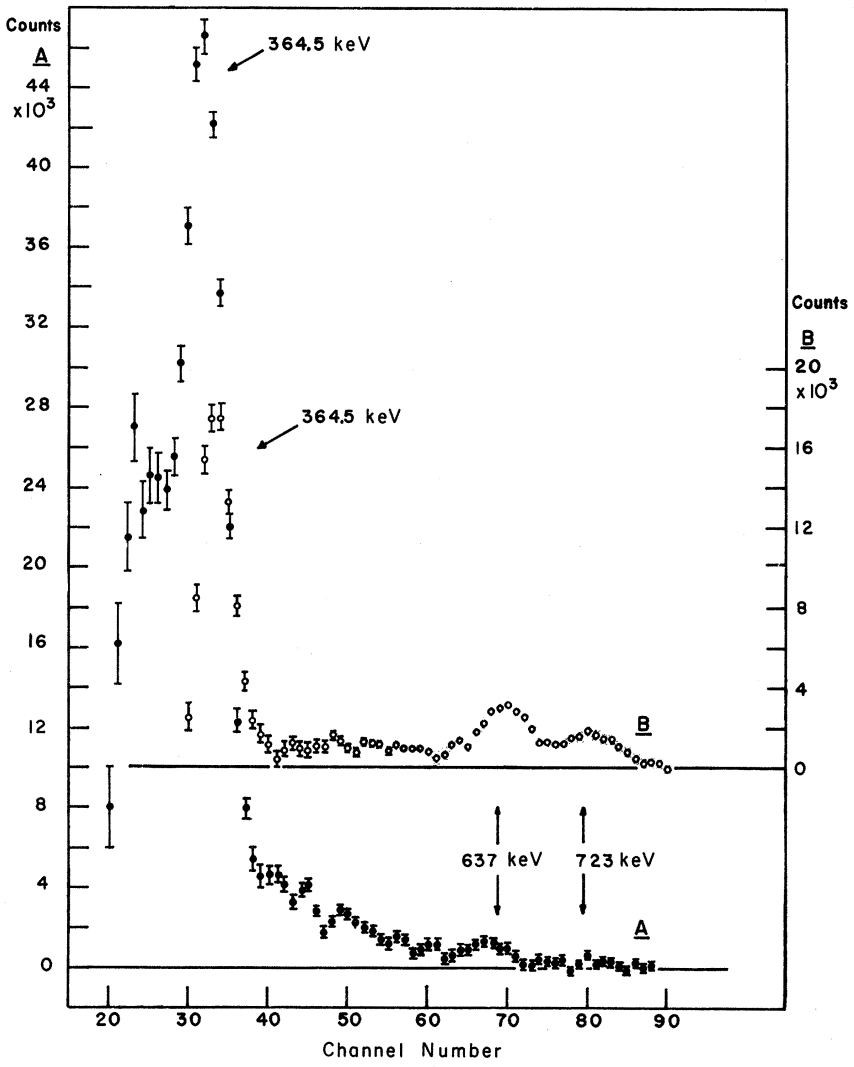

FIG. 3. Pulse-height spectrum of the scattered radiation; scatterer and $\frac{7}{16}$-in.-thick xenon absorber in position. A: gaseous source of CH_3I^{131} and B: gaseous source of II^{131}. The nonresonant background has been subtracted in each case. The statistical error for the higher-channel data points in B are about the size of the circles.

Assuming a spin of $\frac{7}{2}$ for this level ($g=2$), a weighted average of the two results yields a $\Gamma = (3.7 \pm 1.6) \times 10^{-4}$ eV and the mean life $\tau = 1.8 \pm 0.8$ psec.[16]

2. Lifetime of 723-keV Level

No net self-absorption was observed for the 723-keV γ rays with either absorber. For the $\frac{7}{16}$-in. absorber T_{ab} was $= 1.023 \pm 0.047$, and for the $1\frac{1}{2}$-in. absorber $T_{ab} = 1.014 \pm 0.137$. Although the 723-keV level decay to the ground state has a partial width $\Gamma_0 \approx 0.85\Gamma$, the same expression for T_{ab} as for the 637-keV decay was used. This approximation was assumed small compared with the experimental error.

By using this expression with a weighted average of the experimental values for T_{ab} and assuming a spin of $\frac{5}{2}$, one obtains for the 723-keV level $\Gamma < 4.4 \times 10^{-4}$ eV and $\tau > 1.5$ psec.

3. Angular Distributions

a. 637-keV Level

Angular-distribution measurements were carried

TABLE I. Results of self-absorption measurements for the 637-keV level.

Source	Absorber thickness (in.)	T_{ab}	$g\Gamma$ (eV)	τ/g (sec)
II^{131}	$\frac{7}{16}$	0.953 ± 0.030	$(8.0 \pm 5.1) \times 10^{-4}$	$(8.2 \pm 5.3) \times 10^{-13}$
II^{131}	1.5	0.876 ± 0.072	$(6.5 \pm 4.1) \times 10^{-4}$	$(9.8 \pm 6.2) \times 10^{-13}$

out at average scattering angles between 90 and 145°. A total of six separate angular-distribution runs were made, two with the disk-shaped scatterer and four with the smaller rectangular scatterer. The data collected for each scatterer at given values of the scattering angle φ, scatterer orientation angle θ, and scatterer-detector distance were grouped together, corrected for source decay, and analyzed in the following manner.

A computer program was written which divided the scatterer into small sections and then calculated the relative contribution to the resonant scattering from each section for a given pair of angular-correlation coefficients, A_2^2 and A_4^2; i.e., each scatterer element's contribution to the total scattering was proportional to $W(\cos\varphi_i) = 1 + Q_2 A_2^2 P_2 \times(\cos\varphi_i) + Q_4 A_4^2 P_4(\cos\varphi_i)$ and to the actual solid angle subtended by the detector at element i.[17] Q_2 and Q_4 contain the corrections for finite angular resolution, and P_2 and P_4 are Legendre polynomials. The effect of the graded absorber in front of the detector and the lead shielding was determined by moving a point source on the scatterer surface and recording the counting rates. At a given mean scattering angle φ_0 the computer-calculated resonance scattering for 900 elements was

$$Y_j = \sum_{i=1}^{900} Y_{ji} .$$

These results were then normalized to the observed data points Y_j^D by minimizing the quantity

$$\sum_{j=1}^{NA} (\alpha Y_j - Y_j^D)^2 ,$$

where NA = the number of angles (or data points) and

$$\alpha = \left(\sum_{j=1}^{NA} Y_j^D Y_j\right) \Big/ \left(\sum_{j=1}^{NA} Y_j^2\right) ,$$

the normalizing constant.

To help determine a goodness of fit between the calculated and measured results a parameter σ was defined by

$$\sigma = \left[\frac{1}{NA}\sum_{j=1}^{NA}(\alpha Y_j - Y_j^D)^2\right]^{1/2} .$$

The values of σ corresponding to pairs of A_2^2 and A_4^2 are plotted in Fig. 4. The allowed values for these coefficients are, however, not freely variable. They are determined by the mixing ratio δ where $\delta^2 = E2/M1$. The values of A_2^2 and A_4^2 corresponding to the various δ's, assuming a spin sequence $\frac{3}{2}^+ - \frac{5}{2}^+ - \frac{3}{2}^+$, are also plotted in Fig. 4 together with the point at $A_2^2 = 0.219$, $A_4^2 = 0.128$ which corresponds to a pure $E2$ transition to the ground state ($\frac{3}{2}^+ - \frac{7}{2}^+ - \frac{3}{2}^+$). The minimum σ for this run (rectangular scatterer, four angles) occurred at $A_2^2 \approx 0.15$, $A_4^2 \approx 0.02$. The smallest σ physically allowable occurred for $\delta = 0.42$, corresponding to $A_2^2 = 0.15$ and $A_4^2 = 0.01$. Taking our measurements as $Y_j^D \pm E_j$, where E_j is the error on each datum point, then

$$\tfrac{1}{4}\left(\sum_{j=1}^{4} E_j^2\right)^{1/2} = 1.7 .$$

Equating this "mean deviation" with σ, one sees that values of A_2^2 lying between approximately 0.05 and 0.2 and A_4^2 between 0 and 0.13 would fit the data. In Fig. 5 this is demonstrated graphically by plotting the computer-generated distributions for the four possibilities under consideration here plus the best-fit value of $\delta = 0.42$. Distributions based on $\delta = 0.42$, a pure $M1$ ($\frac{5}{2}^+ - \frac{3}{2}^+$), or a pure $E2$ ($\frac{7}{2}^+ - \frac{3}{2}^+$) transition, fit the data within the error bars, while distributions either for $\delta = 7.4$ (Ref. 4) or a pure $E2$ ($\frac{5}{2}^+ - \frac{3}{2}^+$) transition (Ref. 3) are in marked disagreement with the data.

The results of all the angular distributions runs were consistent with the foregoing results and agreed with the following conclusion, namely that the 637-keV level is $\frac{7}{2}^+$ decaying by a pure $E2$ transition to the ground state, or that the level is $\frac{5}{2}^+$ and decays predominantly by an $M1$ transition.

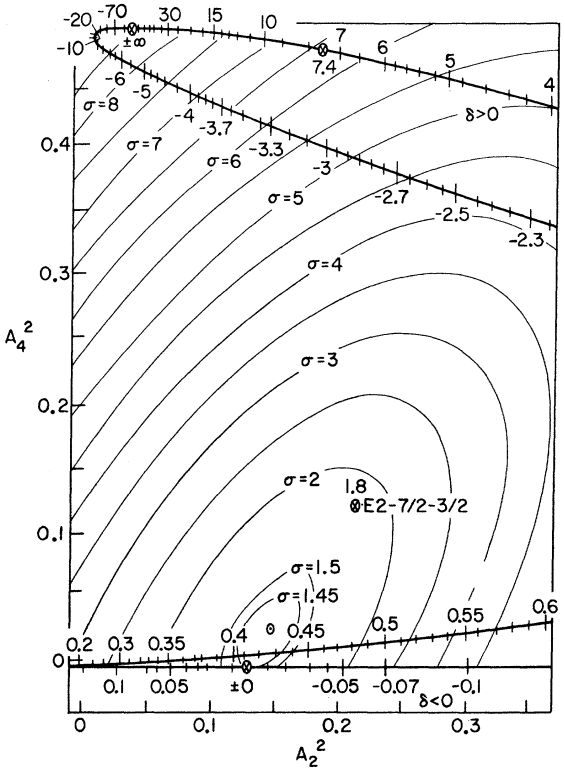

FIG. 4. Angular-correlation contour plot corresponding to the data shown in Fig. 5 for $E_\gamma = 637$ keV. The interpretation of this plot is given in the text.

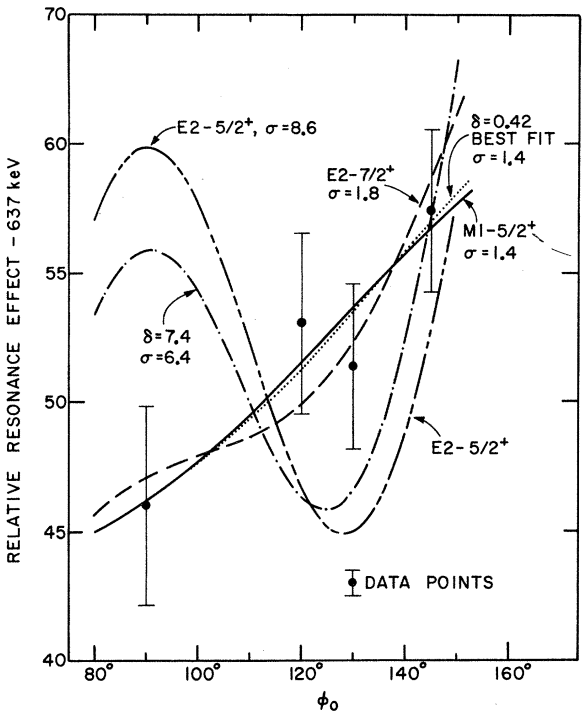

FIG. 5. Angular-correlation data obtained in a typical run with the rectangular scatterer and an II^{131} source for $E_\gamma = 637$ keV. The distribution to be expected for various kinds of transitions are indicated. The definition of σ is given in the text.

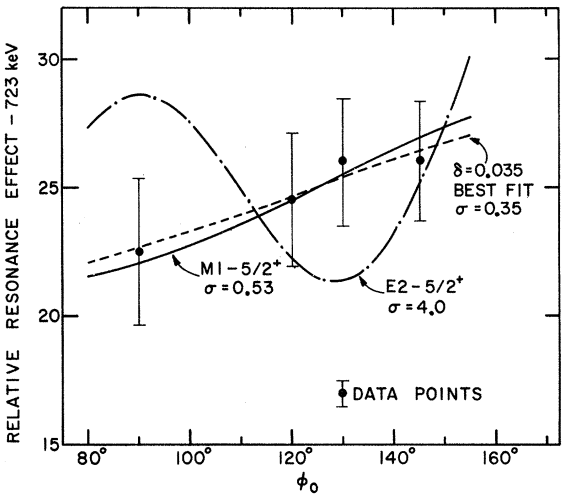

FIG. 6. Angular-correlation data for 723-keV γ ray (cf. Fig. 5).

The choice of a $\frac{7}{2}^+$ assignment to the 637-keV state is preferred, since it is consistent with the results of most of the previous investigations.[4-6]

b. 723-keV Level

A similar analysis was carried out for the angular distribution of the 723-keV resonantly scattered γ rays using the I_2 source and the rectangular scatterer. The least-squares fit, based on the

TABLE II. Summary of γ-ray transition properties for levels in Xe^{129} and Xe^{131} based on information from Refs. 2 and 17 and the present investigation. The total-internal-conversion coefficient α_T is indicated for those levels where experimental information is available. The retardation and enhancement factors are given with respect to the Weisskopf estimates (see Ref. a). The factor given for a transition type shown in parentheses is the limiting value which would be obtained if the transition goes 100% this way.

	Level energy (keV)	Transition energy (keV)	Transition type	α_T	Retardation factor	Enhancement factor
Xe^{131}	80	80	$M1$	1.5	20	
	164	164	$M4$	44		3.2
	364	284	$E2$	0.05		48
		364	$E2$(98%)	0,02		204
			$M1$(2%)		1.2×10^3	
	637	272	($E2$)		1.3	
			($M1$)		116	
		637	$E2$			108
	723	318	($E2$)			≤140
			($M1$)		≥45	
		358.5	($E2$)			≤14
			($M1$)		≥350	
		643	$E2$			≤7
		723	$M1$	4×10^{-3}	≥24	
Xe^{129}		39.6	$M1$	13.4	42	
		196.6	$M4$	15.7		2.6

[a] D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by Ajzenberg-Selove (Academic Press Inc., New York, 1960), p. 858.

previous discussion, yielded $\sigma = 0.35$ corresponding to $\delta = 0.035$ and $A_2^2 = 0.094$, $A_4^2 = 0$. The value of δ corresponding to a pure $M1$ ($\frac{5}{2}^+ - \frac{3}{2}^+$) transition was 0.53. Referring to Fig. 6, one sees that these two distributions fit the data quite well and are practically indistinguishable. The calculated distribution corresponding to a pure $E2$ ($\frac{5}{2}^+ - \frac{3}{2}^+$) transition is also shown in Fig. 6 and disagrees with the data. The "mean deviation" in the measurements was 1.3, which would permit A_2^2 to vary from 0 to ≈ 0.25 and A_4^2 from 0 to 0.08.

IV. DISCUSSION

The similarity between the low-lying level structure of Xe^{129} and Xe^{131} has been discussed most recently in work by Graeffe and Walters,[2] wherein they compare the experimentally determined level structure for these isotopes with theoretical predictions of Kisslinger and Sorensen.[18] A further test of this similarity would be to compare the electromagnetic transitions from corresponding levels. As Table II shows, there is good agreement between transitions from the two lowest levels in each nucleus. Unfortunately, transition rates from other levels in Xe^{129} are unknown and so cannot be compared with those given in Table II for Xe^{131}. It would be particularly interesting to have more complete information about the decay of the 322-keV level in Xe^{129}. If this level has a spin and parity of $\frac{5}{2}^+$, then its decays to the $\frac{3}{2}^+$ and $\frac{1}{2}^+$ levels should be similar to those of the 364.5-keV $\frac{5}{2}^+$ level in Xe^{131}. In particular, one would expect the 282.6-keV mixed $M1$-$E2$ transition in Xe^{129} to be essentially pure $E2$, similar to the 364.5-keV transition in Xe^{131}, where the $M1$ component appears to be highly forbidden.

From the lower limit set on the lifetime of the 723-keV state, together with the observed resonant scattering and relative abundances of the I^{131} γ rays, one finds that $N(E_{res})/N$ for the 723-keV transition appears to be at least three times greater than that for the 637-keV transition. This point has been discussed previously,[11] and can be explained under the assumption that a longer lifetime for the 723-keV transition allows a greater relative number of nuclei, recoiling following Coulomb fragmentation, to achieve the necessary initial momentum (if resonant scattering is to occur) before emission of the γ ray. However, it should also be pointed out that the lower limit set on the lifetime of the 723-keV transition is quite sensitive to the uncertainty in the self-absorption measurements. A 50% increase in this error would lower the lifetime limit sufficiently to explain the magnitude of the observed resonance scattering for the 723-keV γ rays as compared with that for the 637-keV γ rays.

Although resonant fluorescent scattering of the 364-keV γ rays was observed, the results were not useful, because of difficulties in quantitatively evaluating the resonant effect. Tests showed that the matched scatterer used in this experiment gave a good fit only above 500 keV, and the amount of mismatch at lower energies varied appreciably with angle. The mismatch made it difficult to evaluate the considerable background contributions from Rayleigh and Compton scattering.

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[1]R. E. Bell, in *Beta- and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 698.

[2]G. Graeffe and W. B. Walters, Phys. Rev. 153, 1321 (1967).

[3]E. Johnson, J. F. Schooley, and D. A. Shirley, Phys. Rev. 120, 1777 (1960).

[4]H. Daniel, O. Mehling, P. Schmidlin, D. Schotte, and E. Thummernicht, Z. Physik 179, 62 (1964).

[5]W. D. Hamilton, Proc. Phys. Soc. (London) 78, 1071 (1961).

[6]H. Jungclaussen, J. Schintlmeiter, and H. Sodan, Nucl. Phys. 43, 650 (1963).

[7]F. R. Metzger, in *Progress in Nuclear Physics*, edited by O. R. Frisch (Pergamon Press, London, England, 1959), Vol. 7.

[8]S. Ofer and A. Schwarzchild, Phys. Rev. 166, 725 (1959).

[9]F. R. Metzger, Phys. Rev. Letters 18, 434 (1967).

[10]F. R. Metzger, Phys. Rev. 171, 1257 (1968).

[11]M. Berman and G. B. Beard, Phys. Rev. Letters 22, 753 (1969).

[12]M. Berman, Ph.D. thesis, Wayne State University, 1968 (unpublished).

[13]C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York 1967), 6th ed.

[14]G. B. Beard, Phys. Rev. 145, 862 (1966).

[15]G. L. Pollack, Rev. Mod. Phys. 36, 748 (1964).

[16]Because of a computational error, the preliminary values for the lifetimes of the 637- and 723-keV levels given in work of M. Berman and G. B. Beard, Bull. Am.

Phys. Soc. 13, 1466 (1968) differ from those presented here.

[17]H. Frauenfelder and R. M. Steffen, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (North-Holland Publishing Company, Amsterdam, The Netherlands, 1965), Chap. XIXA.

[18]L. S. Kissingler and R. A. Sorenson, Rev. Mod. Phys. 35, 853 (1963).

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Level Structure of ^{148}Sm and ^{150}Sm from Average Resonance Neutron Capture*

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The average-resonance-neutron-capture spectra of ^{147}Sm$(n,\gamma)^{148}$Sm and ^{149}Sm$(n,\gamma)^{150}$Sm obtained with the Argonne in-pile (n,γ) facility are used to develop and extend the level schemes of ^{148}Sm and ^{150}Sm. In particular, the experiment gives information about the spin and parity assignments of 33 levels with excitation energies from 0 to 2.7 MeV in ^{148}Sm and 47 levels from 0 to 2.5 MeV in ^{150}Sm. Unique spin and parity assignments are given for almost all the states below 2.2 MeV in both isotopes. In many cases in which previous experiments gave conflicting indications, the new data led to definite spin assignments. The neutron binding energies in ^{148}Sm and ^{150}Sm were found to be 8140.6 ±1.8 and 7986.4 ±1.8 keV, respectively, after correction for the energy spectrum of the captured neutrons.

I. INTRODUCTION

Considerable experimental activity[1] has been directed toward the investigation of the level structures of samarium isotopes in recent years. Much of the interest in these nuclei has arisen from the fact that they span the transition region of the rare earths between the closed-shell "spherical" nuclei, with neutron number 82, and the deformed region beginning at neutron number 90. Besides radioactive-decay studies, numerous experiments employing a wide range of particle-nucleus interactions have been used to excite levels in these isotopes.

A reaction which has been used rather extensively to study the level structure of ^{150}Sm, for example, has been the thermal-neutron-capture γ-ray reaction. The large thermal-neutron cross section of ^{149}Sm and the spin-parities 3^- and 4^- of the s-wave capture states make the experiment attractive by presenting the opportunity to excite a large number of low-energy states. Recent (n,γ) experiments include the work of Smither,[2] in which precision γ-ray measurements were made with the Argonne bent-crystal spectrometer, along with γ-γ coincidence and directional-correlation measurements with an external neutron beam. Elze[3] recently measured the spectrum of internal-conversion electrons emitted by ^{150}Sm following thermal-neutron capture. The high-energy portions of the ^{149}Sm$(n,\gamma)^{150}$Sm and ^{149}Sm$(n,e^-)^{150}$Sm spectra have also been studied in detail with thermal neutrons. The combination of all this neutron work and the previously published β-decay and charged-particle experiments have established a solid base of low-lying levels with known J^π values on which one can build the rest of the level scheme.

II. AVERAGE RESONANCE NEUTRON CAPTURE

The experimental technique used in this paper has been described recently by Bollinger and Thomas.[4,5] It has proved very useful in determining the parities and possible spins of states fed by primary γ rays following neutron capture. The aim of this method is to measure the *average* intensity of the primary γ transitions to low-lying levels when the neutron-capture process takes place in a large number of neutron resonances. If the number of contributing resonances is sufficiently large, then this averaging process removes the large fluctuations in γ widths normally observed with neutron capture in a single resonance. This allows one to infer the multipolarity of the radiation, and thus the parity of the final state, and to limit the spin of the final state to within two choices – solely from knowledge of the relative γ intensity of the primary transition.

The relative intensities of the transitions observed in average-resonance-capture experiments presented in this paper can be interpreted in terms of the simple scheme indicated in Fig. 1. The $\frac{7}{2}^-$ ground states of ^{149}Sm and ^{147}Sm lead to 3^- and 4^- capture states for s-wave neutrons. If the region in which most of the capture occurs is broad