

then ξ' is the Stokes parameter for the emitted photon beam. An alternative procedure for arriving at the same result consists in making w maximum subject to the condition

$$\xi_1^2 + \xi_2^2 + \xi_3^2 = (|a_1|^2 + |a_2|^2)^2 = 1,$$

which the parameter ξ satisfies from definition. The Stokes parameter ξ' of the photon beam is then related to this ξ of the detector by the simple equation $\xi' = \tau\xi$ where τ , the degree of polarization, is given by

$$\tau = (w_{\max} - w_{\min}) / (w_{\max} + w_{\min}).$$

Because of its relative importance in the study of the polarization of β rays which are known to be longitudinally polarized, we consider only the contribution ξ_{3L}' to the circular polarization of the bremsstrahlung from longitudinally polarized primary electron beam. We find from Eqs. (6), (8), and (12)

$$\begin{aligned} \xi_{3L}' &= -(\zeta_0 \cdot \mathbf{p}_0 / p_0) \{ \pi(\Phi_L + 8m^2\theta_0\Phi_L') / 8m\omega\Phi(0) \} \\ &= (\zeta_0 \cdot \mathbf{p}_0 / p_0) f_L(\omega, E_0, \theta_0). \end{aligned} \quad (13)$$

In Fig. 1, f_L has been plotted as a function of the photon energy ω . Since f_L is found to be positive, it is apparent from Eq. (13) that the sense of circular polarization (right or left) of the bremsstrahlung is the same as that of the polarization (parallel or antiparallel to the momentum) of the primary beam. The amount of circular polarization rapidly increases with the photon energy and near the upper end of the bremsstrahlung spectrum it is $\sim 90\%$ for completely polarized primary beam. These results are in perfect agreement with the experimental findings of Goldhaber et al.⁵

ACKNOWLEDGMENT

The author is thankful to Professor S. Gupta for his keen interest in this work and many helpful discussions.

⁵ Goldhaber, Grodzins, and Sunyar, Phys. Rev. **106**, 826 (1957).

Spins of Some Radioactive Iodine Isotopes*

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(Received March 26, 1958)

The spins of I^{123} , I^{124} , and I^{131} have been measured by the method of atomic beams; the spins are $\frac{5}{2}$, 2, and $\frac{7}{2}$, respectively. The result $I = \frac{7}{2}$ for I^{131} confirms an earlier measurement by a different method.

INTRODUCTION

THIS paper reports the first results of a program to determine the nuclear spins, magnetic moments, and quadrupole moments of some of the available radioactive halogens by the method of atomic beams. These quantities are of interest because an extension of measurements in a region of the periodic table where collective effects are not expected to dominate will serve to broaden the experimental basis of the single-particle shell model and lead to further tests of the model itself. In addition to the results of spin determinations of three iodine nuclei, this paper contains a description of an atomic-beam apparatus that appears particularly suited to the study of radioactive substances.

METHOD

The method used, an atomic-beam "flop-in" type of experiment, was first proposed by Zacharias *et al.*^{1,2} In recent years there has been considerable application

of this technique to the measurement of the spins and moments of radioactive nuclides,^{3,4} and only a brief description of the method is given here.

The ground state of all halogen atoms is $P_{\frac{3}{2}}$. Thus (with normal ordering of the F levels) there are two observable flop-in transitions at low frequency. For $I > 0$ these are

$$(F = I + \frac{3}{2}, M_F = -I + \frac{1}{2}) \rightarrow (F = I + \frac{3}{2}, M_F = -I - \frac{1}{2})$$

and

$$(F = I + \frac{1}{2}, M_F = -I + \frac{3}{2}) \rightarrow (F = I + \frac{1}{2}, M_F = -I - \frac{1}{2}),$$

where F is the total angular-momentum quantum number of the atom, I the nuclear-spin quantum number, and M_F the projection of the total angular momentum along the direction of quantization. Figure 1 shows the relevant energy-level diagram for a halogen atom with $I = \frac{5}{2}$. The two transitions are indicated by arrows; they will be referred to as (+) and (-) transitions, respectively. A measurement of the frequencies of either or both of these transitions in the linear

* This work was performed under the auspices of the U. S. Atomic Energy Commission.

¹ J. R. Zacharias, Phys. Rev. **61**, 270 (1942).

² Davis, Nagle, and Zacharias, Phys. Rev. **76**, 1068 (1949).

³ William A. Nierenberg, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1957), Vol. 7, p. 349.

⁴ Kenneth F. Smith, Progr. Nuclear Phys. **6**, 52 (1957).

Zeeman region is sufficient to determine the spin. If g_F is the g factor of the particular F level in which a transition is observed at frequency ν_X (where X is the isotope) in a magnetic field H , we have

$$\nu_X \cong g_F(\mu_0 H/h), \quad (1)$$

where μ_0 is the Bohr magneton and h is Planck's constant. For a $P_{3/2}$ electronic state the g factors are

$$g_F \cong \frac{4}{2I+3}, \quad (F=I+\frac{3}{2}), \quad (2)$$

$$g_F \cong \frac{4}{3} \frac{2I+9}{(2I+1)(2I+3)}, \quad (F=I+\frac{1}{2}).$$

Equations (1) and (2) are derived under the assumptions of pure Russell-Saunders coupling and of vanishing nuclear magnetic moment. The magnetic field H is measured by observation of a transition in an isotope of known spin; in this experiment a beam of Cs^{133} is employed. For Cs^{133} , I is $\frac{7}{2}$, and (at moderate fields) for the transition $(F=4, M_F=-3) \rightarrow (F=4, M_F=-4)$, we have

$$\nu_{\text{Cs}} \cong \frac{1}{4}(\mu_0 H/h). \quad (3)$$

Hence at a given field H , the ratio of ν_X to ν_{Cs} is

$$\nu_X/\nu_{\text{Cs}} \cong 4g_F, \quad (4)$$

and it is necessary only to search for a signal due to the isotope of unknown spin at the discrete frequencies determined by Eq. (4). Once a signal has been observed, a resonance is traced out for both transitions at a number of different fields to establish the spin unequivocally. The particular isotope involved is identified by its decay half-life. Measurements of the two transition frequencies at high field where electronic and nuclear moments are partially decoupled are necessary to determine the magnetic and quadrupole interaction constants; the exact procedure adopted will be more fully discussed in subsequent papers.

SAMPLE PREPARATIONS

Radioactive I^{123} and I^{124} were produced by the bombardment of powdered antimony metal with 48-Mev alpha particles in the Crocker 60-in. cyclotron. The 13-hr I^{123} is produced by the reaction $\text{Sb}^{121}(\alpha, 2n)\text{I}^{123}$ and the 4-day I^{124} by the reactions $\text{Sb}^{121}(\alpha, n)\text{I}^{124}$ and $\text{Sb}^{123}(\alpha, 3n)\text{I}^{124}$. The 8-day I^{131} was obtained in 30-mC lots from Oak Ridge National Laboratories in the form of NaI in sodium sulfite solution. Iodine is easily precipitated from NaI by mild oxidizing agents in acid solution. Carrier iodine (20 mg) in the form of NaI was added to the Oak Ridge sample and iodine was precipitated by the addition of NaNO_2 and dilute sulfuric acid. The iodine was extracted into carbon disulfide and added to a flask containing approximately 200 mg of elemental iodine. The mixture was well shaken and

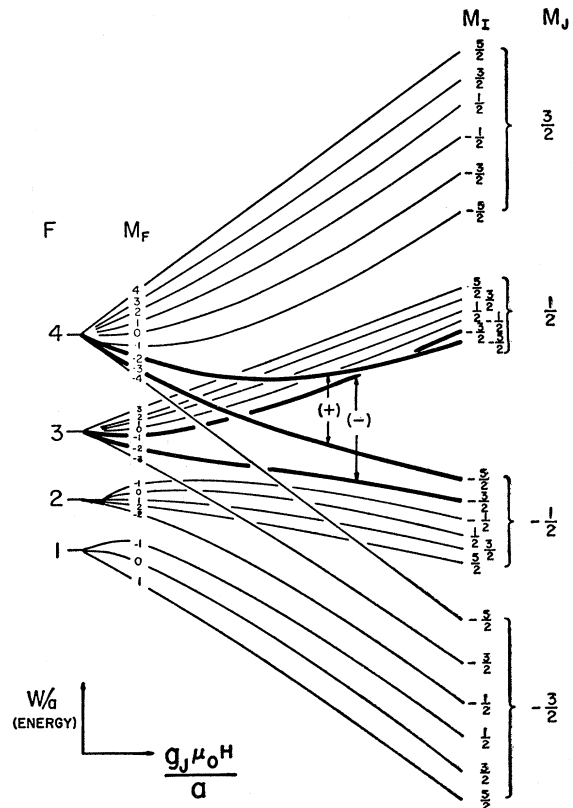


FIG. 1. Energy-level diagram of $^2P_{1/2}$ state with $I = \frac{5}{2}$. The two permissible "flop-in" transitions are indicated by arrows.

the carbon disulfide was evaporated off under vacuum. The dry flask was attached directly to a discharge tube, which is necessary to dissociate the iodine molecules into iodine atoms. The vapor pressure of iodine at room temperature is adequate for the maintenance of the discharge.

Several attempts were made to separate the iodine from the antimony metal by distillation under vacuum and condensation of the iodine on a cold surface, but yields were only moderate (approximately 50%) and difficulties arose because the antimony tended to volatilize with the iodine. A simple and efficient chemical separation procedure was devised which produces yields of 80 to 90%. The antimony powder is dissolved in concentrated HCl by the addition of a few drops of hydrogen peroxide and then a few milligrams of NaI carrier is added. When the solution is adjusted just past the neutral point with NaOH, the antimony precipitates as SbOCl which can be filtered off. The precipitate is washed with a few milliliters of NaOH containing NaI, and the iodine precipitated from the filtrate and extracted by use of the procedure already outlined.

For the production of I^{123} the antimony targets were bombarded for 3 hours with 48-Mev alpha particles at a beam current of 15 to 20 μa . Though some information

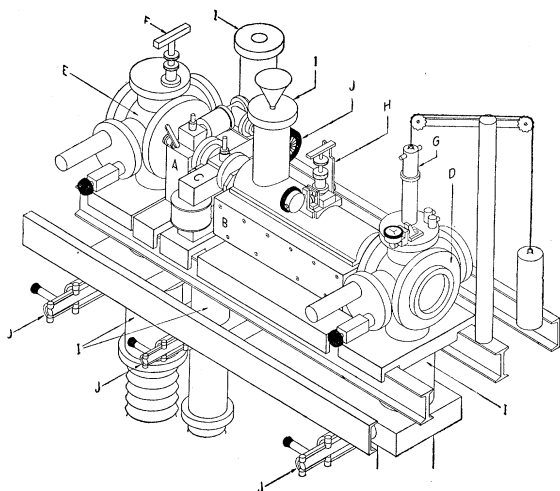


FIG. 2. Schematic view of atomic-beam apparatus. A, B, C—magnets; D—detector can; E—oven can; F—calibrating oven; G—button loader; H—stopwire assembly; I—liquid-nitrogen traps; J—valves.

was obtained on I^{124} from these bombardments, for the specific study of I^{124} the bombarding time was increased to 9 hours and the I^{123} allowed to decay away for several half-lives.

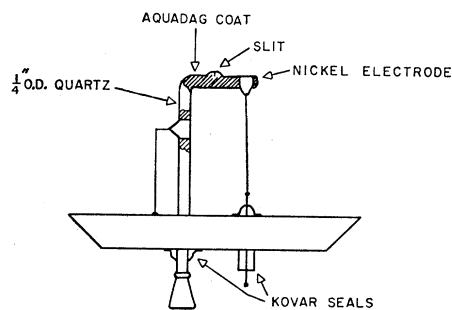
APPARATUS

The atomic-beam machine used for these experiments is, in principle, of the standard "flop-in" type, but differs in many constructional details from those previously described in the literature. A sketch of the machine is shown in Fig. 2. The three magnets are mounted externally to the vacuum system. The *A* and *B* magnet gaps are surrounded by manifolds, with the *A* manifold being pumped by its own diffusion pump (MCF 300),⁵ and the *B* manifold via a connection to the detector can *D*. The *C*-field can is pumped separately with another MCF 300 pump. With the exception of the *A*-magnet pump, all pumps are hung from the cans, and valves are included in all the pumping paths above the liquid nitrogen traps.⁵ The valves allow the main system to be brought up to atmospheric pressure without cooling the pumps and warming the traps. The system can be pumped from atmospheric pressure to 3×10^{-6} mm Hg in about 5 minutes. The oven and detector pumps are MCF 700 oil-diffusion pumps. The oven, detector, and *C*-field cans together with the magnets are mounted upon heavy plates which sit astride Dural runners. Provision is made for independent horizontal and vertical motion of each plate. The magnet-energizing coils are external to the vacuum system and a single turn of water-cooled copper tubing on the coil formers of the *A* and *B* magnets keeps the temperature at a reasonable value.

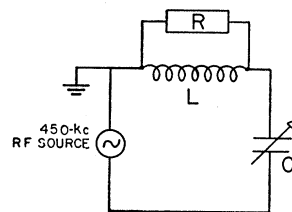
⁵ The MCF series of pumps is manufactured by Consolidated Vacuum Corporation, Rochester, New York. The valves employed are Temescal valves produced by the same company.

The present mode of construction has certain mechanical advantages: (1) apparatus line-up is easily performed, (2) a change from a "flop-out" to a "flop-in" system can be simply achieved by reversing the *B* magnet, (3) the length of the *C* field can be readily changed, and different rf loops incorporated, (4) the system of valves allows easy and rapid access to the cans, and rapid attainment of a working vacuum; (5) component parts can readily be decontaminated or, if necessary, replaced (this is a major advantage, particularly for work with long-lived radioactive isotopes).

During the early stages of construction, attempts were made to pass a potassium beam down thin-walled stainless steel tubes supported between the magnet gaps. The diameters of the *A* and *B* magnet tubes were 0.080 in. and 0.375 in., respectively. With this arrangement, only extremely weak beams were recorded at the detector. When the *A* tube was replaced by a 0.375-in. diameter tube of the same length, a beam of approximately half the expected intensity was recorded. Attempts to improve the transmission by prolonged outgassing of the tubes *in situ* at 300 to 400°C gave no improvement, but subsequent cooling of the tubes with liquid nitrogen led to some improvement in transmission. After the tubes had been outgassed for 3 hours and a beam observed, the beam reduced to zero 10 seconds after application of power to the heating coils and reappeared as the tubes cooled. At this point the *A*- and *B*-magnet vacuum manifolds were incorporated.



RF DISCHARGE TUBE



DISCHARGE STABILIZER

FIG. 3. Discharge tube and discharge-stabilizing circuit.

The electronics associated with the apparatus is to a large extent conventional with the exception of the AB -magnet power supply. The magnets were wound to operate at 300 v at 5 amp and are energized by an electronically regulated supply that is stable to one part in 30 000; consequently changes in the C field due to time-dependent fringing effects are largely eliminated.

The calibrating oven F is loaded with cesium metal in a dry nitrogen atmosphere and is raised and lowered by a motor. The radioactive beam is collected upon buttons coated with evaporated silver which are introduced and removed from the machine via a vacuum lock. The button loader is shown at G . Buttons are stored in a vacuum bottle to prevent poisoning of the silver surface. Exposure of the buttons to air for one or two days reduces the collection efficiency markedly, presumably by the formation of a surface coating of silver sulfide. The collection efficiency of freshly silvered surfaces for iodine (both atomic and molecular) is high and reproducible.

The discharge tube is driven by an rf oscillator at 450 kc/sec and is mounted on a movable plate as part of the oven can E ; it is shown in Fig. 3 together with a regulating circuit that has been found particularly useful. The tube is quartz, and good capacitive coupling between the electrodes and discharge is achieved by painting the surface under the electrodes and in the neighborhood of the slit with Aquadag. The latter step was found to be essential to obtain an efficient discharge. The dissociation efficiency of this discharge is high for iodine and bromine (80 to 100%). The slit width and height are approximately 0.005 and 0.040 inch, respectively. The discharge regulator was

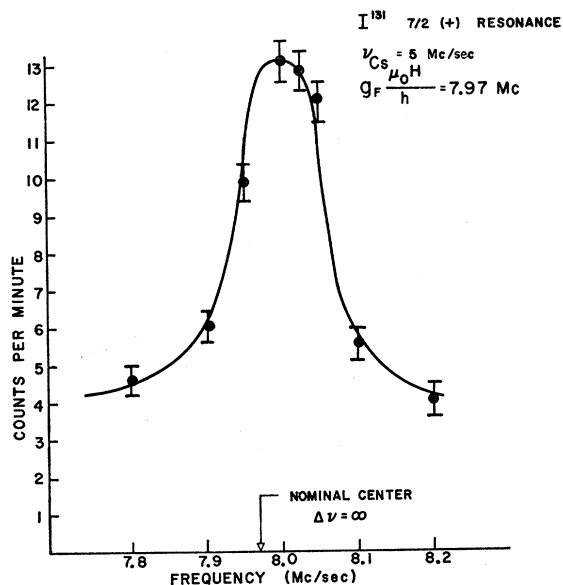


FIG. 4. $\frac{7}{2}(+)$ resonance in I^{131} . The arrow indicates the expected position of the resonance peak in the absence of quadratic and higher-order shifts.

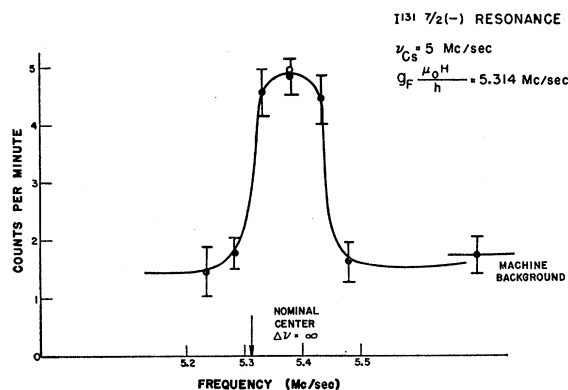


FIG. 5. $\frac{7}{2}(-)$ resonance in I^{131} .

devised originally by Steinmetz in 1890,⁶ and has the interesting property that at resonance the current through R is independent of R . An extremely stable discharge results if the circuit is tuned to operate slightly off-resonance.

A General Radio type 805-C oscillator is employed to power the rf loop, which consists of a single U-shaped turn of $\frac{1}{16}$ -in. diam copper wire whose plane is oriented parallel to the C field. With this arrangement cesium resonance half-widths are about 130 kc/sec. The oscillator frequency is measured with a Hewlett-Packard type 524 B frequency meter. During exposure of a button to the iodine beam, normally for 5 to 10 min, the frequency remains constant within a few hundred cycles. Little or no trouble has been experienced with C -field drift during the exposure time.

The I^{123} and I^{124} are detected by counting the K x-rays (~ 30 kev)⁷ emitted after electron capture. Thin-crystal scintillation counters with a background counting rate of approximately 0.5 counts/min are employed for this purpose; these counters have been described previously.⁸

The I^{131} is detected by counting the decay beta particles in small-volume gas-flow proportional counters. The buttons are inserted directly into the counters which, because of their small surface area, have the unusually low background of 2 to 3 counts/min. These counters will be described elsewhere.

RESULTS

Iodine-131.—The two resonances shown in Figs. 4 and 5 were each obtained with approximately 20 mC of I^{131} in the oven vial mixed with 200 mg of natural iodine carrier. The cesium resonance frequency was

⁶ See Albert C. Candler, *Modern Interferometers* (Hilger and Watts, Ltd., London, 1951), p. 32, for a description of this circuit and some early references.

⁷ A. H. Compton and S. K. Allison, *X-Rays in Theory and Experiment* (D. Van Nostrand and Company, Inc., Princeton, New Jersey, 1935), Chapter VIII.

⁸ J. C. Hubbs and W. A. Nierenberg, University of California Radiation Laboratory Report UCRL-3434, June, 1956 (unpublished).

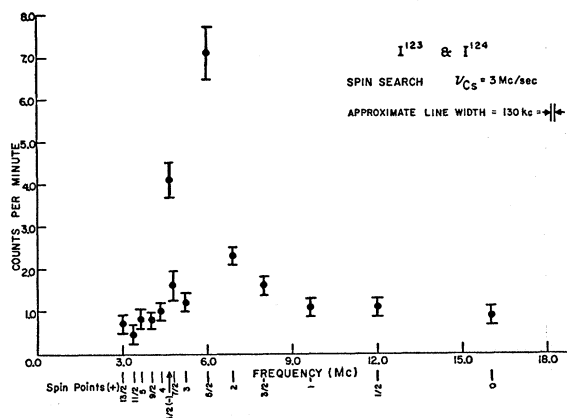


FIG. 6. Spin search on cyclotron-produced I^{123} and I^{124} .

5 Mc/sec corresponding to a C -field setting of 19.93 gauss. Similar resonances have been obtained at 7.99 gauss (cesium resonance frequency = 2 Mc/sec). The $\frac{7}{2}$ (+) resonance buttons were each exposed for 10-min periods, but the exposure time was reduced to 5 min for the $\frac{7}{2}$ (-) resonance. The direct-beam counting rate was approximately 250 counts/min for a 5-min exposure with the AB magnets turned off. When the magnets were turned on, the counting rate dropped to 40 counts/min. With 200 mg iodine carrier, the discharge running time was approximately 3 hr. In Figs. 4 and 5, the small difference between the frequency of the resonance peaks and the corresponding values of $g_F(\mu_0 H/h)$ is due to partial decoupling of the nuclear and electronic magnetic moments by the C field.

It will be noted that the background signal level in the absence of rf power is appreciable. This large apparatus background has been encountered in work with bromine as well as iodine isotopes and is due to the high volatility of these substances. Attempts to reduce it by surrounding the buttons with a liquid-nitrogen-

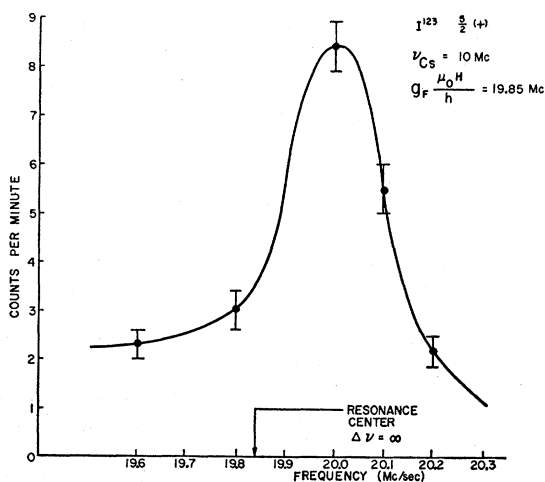


FIG. 7. $\frac{7}{2}$ (+) resonance in cyclotron-produced I^{123} .

cooled shield have not produced much improvement; possibly what is required is a silver coating on the inner walls of the magnets and vacuum systems.

The observed resonances allow an unambiguous assignment of $\frac{7}{2}$ for the nuclear spin of I^{131} , a result which verifies an earlier measurement by a different method.⁹

Iodine-123 and Iodine-124.—Figure 6 shows the results of a spin search on cyclotron-produced iodine at a field of 11.97 gauss. Strong peaks will be noted at frequencies corresponding to (+) and (-) transitions in a spin- $\frac{5}{2}$ isotope, and a smaller (+) peak indicating the presence of an isotope with spin 2. The decay of a direct-beam button shows the presence of two components with half-lives of 15 hr and 5 days, respectively, and on the basis of the published half-lives¹⁰⁻¹⁴ these have been identified as I^{123} and I^{124} . Figures 7 and 8 show examples of $\frac{5}{2}$ (+) and $\frac{5}{2}$ (-) resonances at a field of 39.70 gauss. Similar resonances have been obtained at fields of 11.97 and 23.89 gauss. The decay curves of the $\frac{5}{2}$ (+) resonance-peak buttons show the presence of both I^{123} and I^{124} . The long 4.2-day I^{124} tail is due to resonance overlap; at the fields employed, the I^{124} (2-) resonance occurs at approximately the same frequency as the $\frac{5}{2}$ (+) resonance. The $\frac{5}{2}$ (-) resonance-peak button decay is uncontaminated by overlap. Because of this overlap, the antimony targets were allowed to stand for several half-lives of I^{123} prior to processing and searching for I^{124} resonances. Figures 9 and 10 show 2 (+) and 2 (-) resonances obtained at a field of 39.70 gauss. The two peak buttons of Fig. 9 and the three of Fig. 10 were decayed and showed only the presence of the 5-day I^{124} isotope.

On the basis of these results the spin of I^{123} is $\frac{5}{2}$ and that of I^{124} is 2.

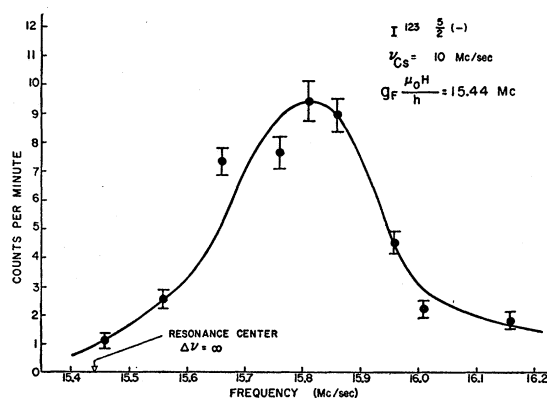


FIG. 8. $\frac{5}{2}$ (-) resonance in cyclotron-produced I^{123} .

⁹ Livingston, Benjamin, Cox, and Gordy, Phys. Rev. **92**, 1271 (1953).

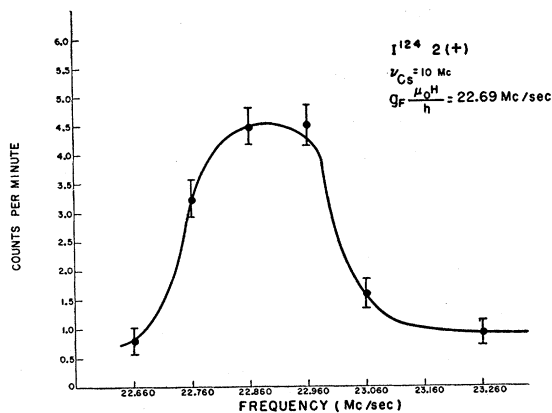
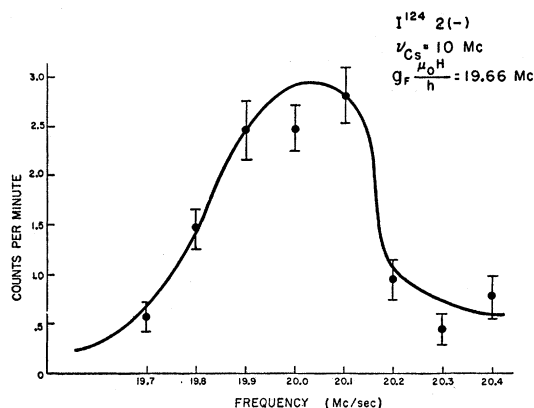
¹⁰ Mitchell, Mei, Maunchien, and Peacock, Phys. Rev. **76**, 1450 (1949).

¹¹ L. Marquez and I. Perlman, Phys. Rev. **78**, 189 (1950).

¹² H. B. Mathur and E. K. Hyde, Phys. Rev. **96**, 126 (1954).

¹³ J. L. Meem and F. Maenschien, Phys. Rev. **76**, 328 (1949).

¹⁴ Aagaard, Andersson, Burgman, and Pappas, J. Inorg. Nuclear Chem. **5**, 105 (1957).

FIG. 9. 2(+) resonance in cyclotron-produced I^{124} .FIG. 10. 2(-) resonance in cyclotron-produced I^{124} .

DISCUSSION

The spins of the stable iodine isotopes I^{127} and I^{129} are known to be $\frac{5}{2}$ and $\frac{7}{2}$, respectively. They indicate that the $d_{5/2}$ and $g_{7/2}$ single-particle shell-model levels are both readily available to the odd proton. The spins of $\frac{5}{2}$ and $\frac{7}{2}$ for I^{123} and I^{131} fit nicely into this picture. I^{124} possesses an odd number (71) of neutrons. Odd- A nuclei with neutron numbers between 65 and 75 consistently exhibit spin $\frac{1}{2}$ because of the filling of the $h_{11/2}$ level in pairs. If it is assumed that the neutron part of I^{124} also possesses spin $\frac{1}{2}$, the consequences of Nordheim's rules can be investigated.¹⁵ If the odd proton is assumed

¹⁵ M. G. Mayer and J. H. J. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley and Sons, New York, 1955), pp. 194-196.

to be $g_{7/2}$, Nordheim's strong rule applies, and the expected spin is 3; if the proton is $d_{5/2}$, the weak rule applies, and a spin near but not necessarily equal to 3 is implied. As the observed spin is 2, it is likely that the odd proton of I^{124} is in a $d_{5/2}$ level.

ACKNOWLEDGMENTS

The authors wish to thank Professor William A. Nierenberg for support and advice, and to acknowledge the able assistance of Mr. Larry M. Cohen and Mr. Douglas MacDonald. Members of the Radiation Laboratory chemistry department and health chemistry group have made substantial contributions to the success of this work.

Directional Correlation of the Gamma Rays in $Gd^{154}\dagger$

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(Received December 26, 1957; revised manuscript received April 14, 1958)

Directional correlation measurements have been carried out on five cascades involving the gamma rays in Gd^{154} . The results of these measurements in conjunction with the work of Juliano and Stephens, and Cork *et al.*, show the existence of two rotational bands and possibly the start of two more such bands. The nature of these bands are explained in terms of the Bohr-Mottelson model for spheroidal nuclei. The levels are characterized by the quantum numbers (K, I, π) and are listed in order of increasing energy. The ground state rotational band consists of the ground state (0, 0, +) and the first and second excited states of (0, 2, +) and (0, 4, +), respectively. The 0.998-Mev and 1.130-Mev levels are

assigned to a second rotational band with $K=2$ and spin and parity values 2+, 3+, respectively. The assignment of quantum numbers to the 1.400-Mev level can be made as either (2, 2, ±) with the mixture of (99.5±0.25% D , 0.5±0.25% Q) for the 1.277-Mev gamma ray, or (3, 3, ±) with the mixture of (85±2% D , 15±2% Q) for the 1.277-Mev gamma ray. The state at 1.723 Mev is best characterized by the quantum numbers (2, 2, -) with the mixture of (99.7±0.3% $E1$, 0.3±0.3% $M2$) for the 0.725-Mev gamma ray, or (3, 3, -) with the mixture of (78.5±6% $E1$, 21.5±6% $M2$) for the 0.725-Mev gamma ray.

INTRODUCTION

UNTIL rather recently, the exact nature of the decay of Eu^{154} has been obscured by the activity of Eu^{152} . Since the half-life of Eu^{154} (16 ± 4 years) is of

the same magnitude as that of Eu^{152} (13 years), separation of the two isotopes on the basis of their half-lives is virtually impossible. An investigation of the mode of decay of both of these isotopes has been carried out by Cork *et al.*¹ using sources obtained by neutron bom-

† Supported in part by the Michigan Memorial Phoenix Project and Office of Naval Research.

* Eastman Kodak Fellow.

¹ Cork, Brice, Helmer, and Sarason, *Phys. Rev.* **107**, 1621 (1957).