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# THE NUCLEAR SPINS OF $I^{126}$, $I^{132}$, $I^{133}$, AND $I^{135}$*

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## INTRODUCTION

This paper reports some recent results of a continuing program to determine the nuclear spins, magnetic moments, and electric quadrupole moments of the radioactive halogen isotopes by the method of atomic beams. The determination of the ground-state spins of radioactive isotopes is particularly important for the interpretation of radioactive decay patterns, and the measurements of nuclear spins and moments provide experimental evidence for the formulation and evaluation of nuclear-structure theories. This work completes the measurement of the nuclear spins of the series of iodine isotopes $I^{123}$ through $I^{135}$ with the exception of the 52-minute $I^{134}$ isotope.

## METHOD

The atomic-beam apparatus used for these measurements was especially designed for use with radioactive volatile materials. Although similar in principle to the standard Atomic-Beam "flop-in" apparatus,[1] it differs from it in many constructional details, which have been described in a previous report.[2] The method of determination of spin of radioactive isotopes in atomic-beam experiments has also been discussed in detail in

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several recent publications,[2,3,4] and only a brief summary is presented here.

The electronic ground state of all halogen atoms is $^2P_{3/2}$, and thus, with normal ordering of the hyperfine levels, there are in general two observable flop-in transitions for which the resonance frequencies are unique functions of the value of nuclear spin and magnetic field. For $I > 0$ these transitions, designated $\alpha$ and $\beta$, are

$$\alpha: \ (\underline{F} = \underline{I} + 3/2, \ \underline{M}_{\underline{F}} = -\underline{I} + 1/2) <-> (\underline{F} = \underline{I} + 3/2, \ \underline{M}_{\underline{F}} = -\underline{I} - 1/2)$$

and

$$\beta: \ (\underline{F} = \underline{I} + 1/2, \ \underline{M}_{\underline{F}} = -I + 3/2) <-> (\underline{F} = \underline{I} + 1/2, \ \underline{M}_{\underline{F}} = -\underline{I} + 1/2),$$

where $\underline{F}$ is the total angular-momentum quantum number of the atom, $\underline{I}$ the nuclear-spin quantum number, and $\underline{M}_{\underline{F}}$ the projection of the total angular momentum along the direction of quantization. In order to determine the spin of an isotope unequivocally, these resonances are observed at several different values of the magnetic field. The resonances are detected by allowing the beam to fall upon silver-coated collection buttons which are subsequently counted in continuous-flow proportional counters. The magnitude of the resonance signal is indicated by the counting rates of the buttons. The isotope contributing to the signal is identified by its radioactive decay properties.

The beam of iodine atoms is formed by attaching a vial containing a mixture of radioactive and natural iodine to a heated platinum dissociation tube heated by electron bombardment to about 700°C to dissociate the iodine molecules to atoms.[5] The vapor pressure of iodine at room temperature is adequate for the maintenance of the beam. On some occasions a radio-frequency discharge tube has been employed.[2]

## SAMPLE PREPARATION

Owing to the wide range of masses embraced by the isotopes studied here, several different methods are required for the production and separation of the radioactive samples.

Iodine-126. The bombardment of a foil of natural tellurium metal by 12-Mev protons produces 28-min $I^{128}$, 12.6-hr $I^{130}$, 4-day $I^{124}$, and 13-day $I^{126}$ by the (p, n) reaction. Following a bombardment in the Berkeley 60-inch cyclotron, the tellurium target is dissolved in $HNO_3$ with some iodine carrier (NaI) and the solution made basic with NaOH. Formic acid is added to precipitate the tellurium as $TeO_2$, leaving the active iodine in solution. The solution is made slightly acidic with $H_2SO_4$, and $NaNO_2$ solution is added to oxidize the iodine to its elemental state so that it can be readily extracted into $CS_2$. Natural iodine carrier is dissolved in the $CS_2$. The solution is mixed thoroughly and the $CS_2$ is evaporated off, leaving the crystalline mixture of active and natural iodine in a glass vial which is attached directly to the atomic-beam apparatus.

Iodine-132. The 2.3-hr $I^{132}$ is conveniently obtained by a "milking process" from the 77-hr $Te^{132}$ parent in an iodine generator provided by the Brookhaven National Laboratory.[6] The tellurium is adsorbed in an alumina mesh within the generator, and the iodine is removed by flushing with 25 ml of 0.01 M $NH_4OH$ solution. The active iodine is oxidized and extracted from the solution as described above. The generator regains its secular equilibrium in approximately 12 hours, and fresh samples of $I^{132}$ may be removed at 12-hour intervals if desired. One iodine generator originally charged with 108 mC of $I^{132}$ provided sufficient amounts of $I^{132}$ to measure the nuclear spin and to obtain preliminary values of the nuclear moments.

Iodine-133. The 21-hour $I^{133}$ isotope is obtainable as a reactor fission product from the Brookhaven National Laboratory. It is received as NaI in aqueous solution from which the $I^{133}$ is easily extracted. Some $I^{131}$ (8-day activity), whose spin is also 7/2, is present with the $I^{133}$ in the sample, and decay analysis was necessary to ensure correct identification of the observed resonance signals.

Iodine-135. The iodine isotopes $I^{131}$ through $I^{135}$ are obtained as fission products after the deuteron bombardment of $U^{238}$. The uranium targets used were in the form of thin uranium foils. As $I^{132}$ and $I^{133}$ are more easily and economically obtained in the ways already described, the method of uranium bombardment was used only for the production of 6.7-hr $I^{135}$ and 52-min $I^{134}$. The target foils of uranium are bombarded with 24-Mev deuterons in the Berkeley 60-inch cyclotron and then dissolved in HCl. The solution (to which carrier has been added) is diluted and $NaNO_2$ added to oxidize the iodine to elemental form. The final extraction proceeds as described earlier. This method of separation, though simple, yielded sufficient activity for successful measurements on $I^{135}$ but a more rapid method would be advantageous for measurements on the short-lived $I^{134}$.

## RESULTS

The results of spin measurements on $I^{126}$, $I^{132}$, $I^{133}$, and $I^{135}$ are summarized in Table I. The magnetic field values at which $\alpha$ and $\beta$ resonances were observed are indicated. Figure 1 shows the results of a spin search on a radioactive iodine sample produced by the (p, n) reaction on tellurium. The high-counting resonance buttons at spins 5($\alpha$) and 5($\beta$) were decayed and the signals found to be due to 12.6-hr $I^{130}$.[7] The signal at spin 2 is due to contributions from both a 2($\alpha$) and a 2($\beta$) transition, and its

## TABLE I

Results of spin measurements

| Isotope | Half life | Spin value | Magnetic field at which resonances (both α and β) were observed (gauss) |
|---|---|---|---|
| $I^{126}$ | 13 days | 2 | 0.71 1.42<br>6.92 |
| $I^{132}$ | 2.3 hours | 4 | 2.82 6.92<br>13.42 25.39<br>46.08 |
| $I^{133}$ | 21 hours | 7/2 | 2.82 6.92<br>13.42 |
| $I^{135}$ | 6.7 hours | 7/2 | 2.82 6.92<br>10.87 |

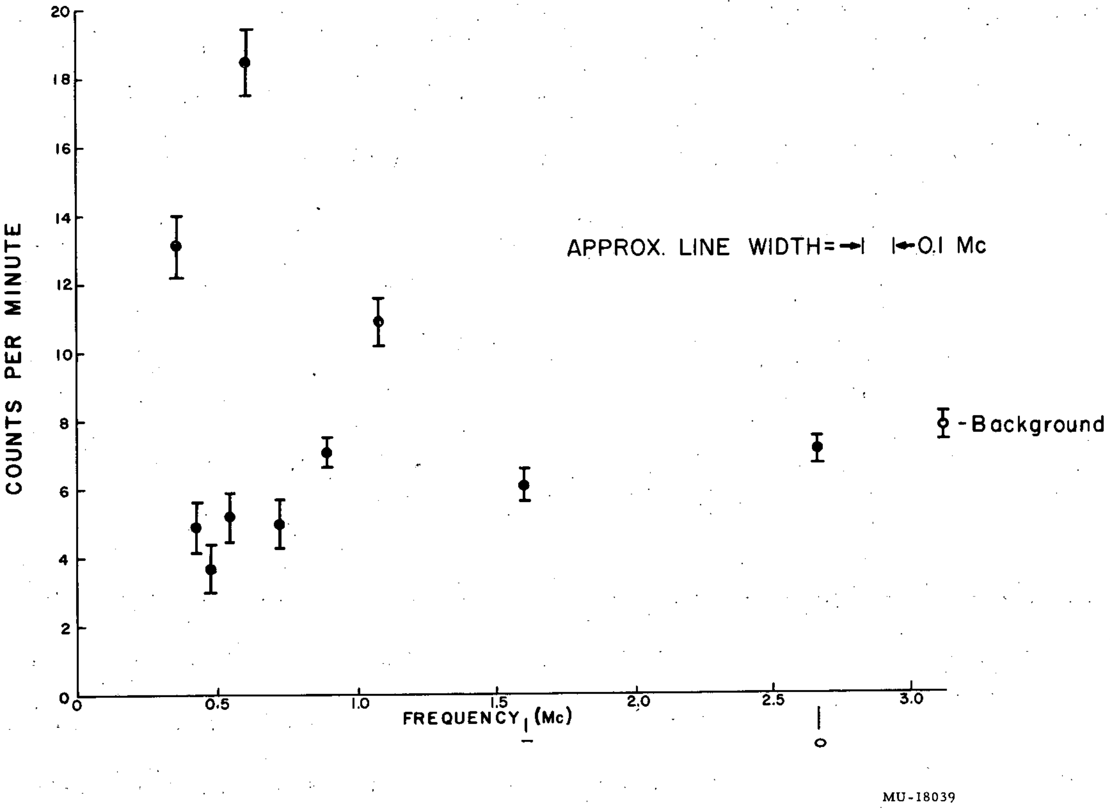


Fig. 1. Spin search on iodine sample produced by proton bombardment of tellurium metal. The high-counting buttons at spins 2(αβ) and 5(α), 5(β) are due to $I^{126}$ and $I^{130}$ respectively. ( $\nu_{Cs}$ = 0.5 Mc, H = 1.43 gauss)

decay was consistent with published half-life values for $I^{126}$. Complete radio-frequency resonances were traced at magnetic fields where the $2(\alpha)$ and $2(\beta)$ resonances were resolved (see Fig. 2).

Figures 3, 4, and 5 show radio-frequency resonances observed in $I^{132}$, $I^{133}$, and $I^{135}$. The fission-produced samples contain some $I^{131}$, $I^{133}$, and $I^{135}$ and each has spin 7/2 therefore, as mentioned earlier, the decays of the spin-7/2 resonances are complex because of the several components present.

## DISCUSSION

With the exception of $I^{134}$, the nuclear spins of the iodine isotopes $I^{123}$ through $I^{135}$ are now known. The results are summarized in Table II together with odd-proton and odd-neutron level assignments that lead at least to the correct spin values of the ground states if not in all cases to the correct parity where it is known. In those instances in which the neutron number, N, is even the unpaired 53rd proton in iodine is reasonably assigned to the $4d_{5/2}$ level for $N < 76$, while for $N > 76$ the most reasonable assignment is to the level $5g_{7/2}$.

The nuclear spins of the odd-A odd-N nuclei are consistently 1/2 for N = 65 to N = 75, but from N = 76 to N = 82 the observed spins are 3/2. It is not unreasonable to suppose that these spin values arise from the $3s_{1/2}$ and $4d_{3/2}$ levels respectively. The spin value 2 of $I^{124}$ and $I^{126}$ can be explained by assuming that the odd neutrons (71, 73) are in the $3s_{1/2}$ level and that they couple with the $d_{5/2}$ proton in accordance with Norheim's "weak" rule. However, the parities of the ground states in these two cases are thought to be negative;[9, 10] the present assignment would class them as positive. At $I^{128}$ (N = 75) the observed spin of 1 can be explained only by assuming that the odd neutron lies in the $4d_{3/2}$ level, though this is not the

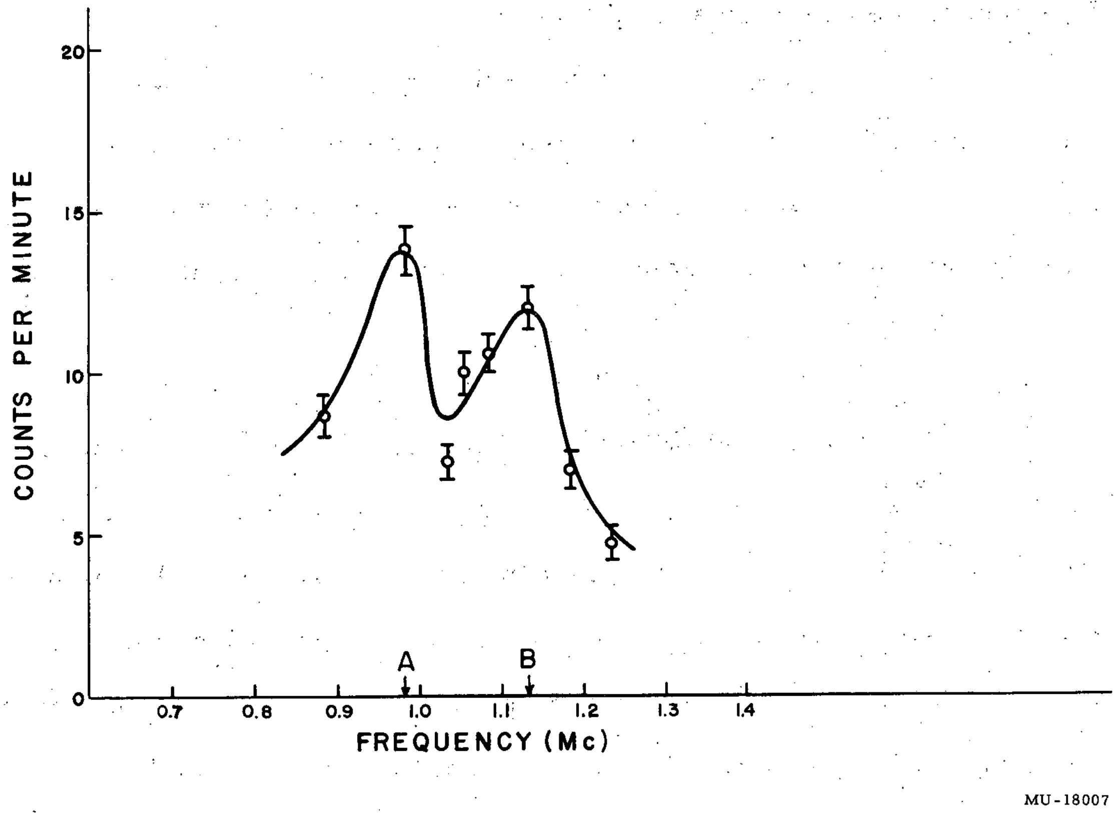
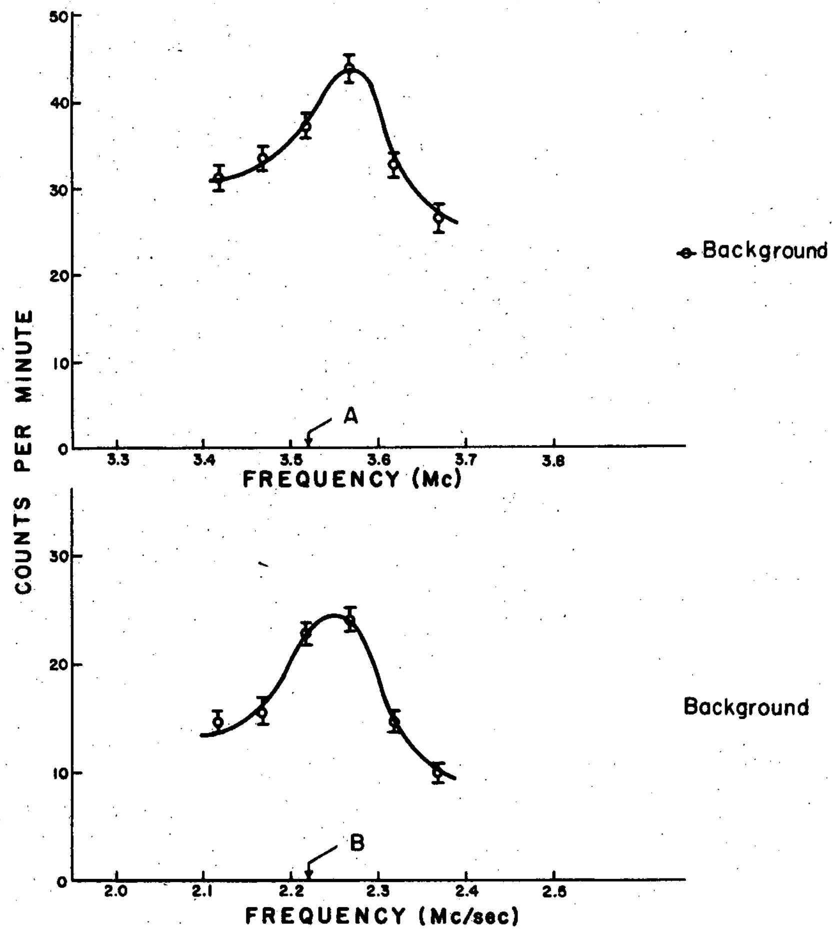


Fig. 2. Radio-frequency resonance observed in $I^{126}$ at a field of 1.42 gauss. ($\nu_K = 1$ Mc)

Frequency A: Spin 2(β) nominal center.
Frequency B: Spin 2(α) nominal center. $\Delta\nu = \infty$ .



MU-18009

Fig. 3. Resonances observed in $I^{132}$ at a field of 6.92 gauss. ($\nu_K$ = 5 Mc)

Above: spin 4(α).
Below: spin 4(β).
Frequency A: nominal center $\Delta\nu = \infty$.
Frequency B: nominal center $\Delta\nu = \infty$.

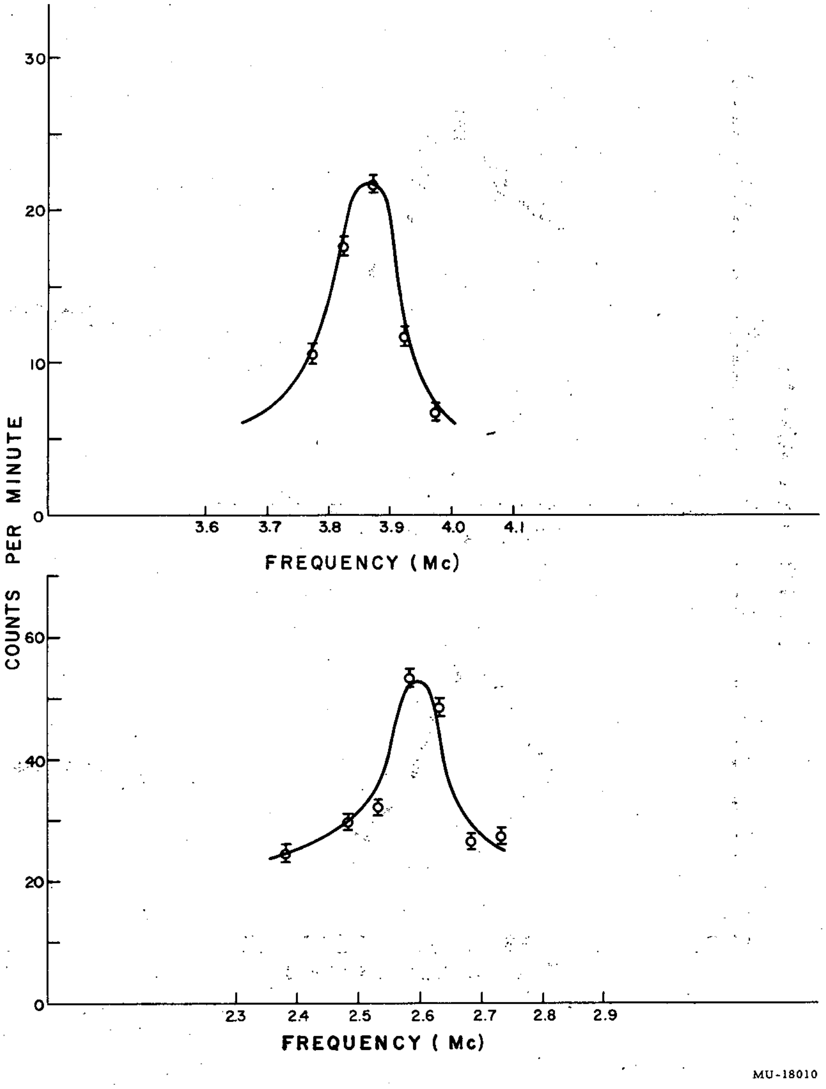


Fig. 4. Radio-frequency resonances observed in $I^{133}$. ($\nu_K$ = 5 Mc, H = 6.92 gauss)

Above: spin 7/2(α), $g_F \frac{\mu_o H}{h} = 3.87$ Mc.

Below: spin 7/2(β), $g_F \frac{\mu_o H}{h} = 2.58$ Mc.

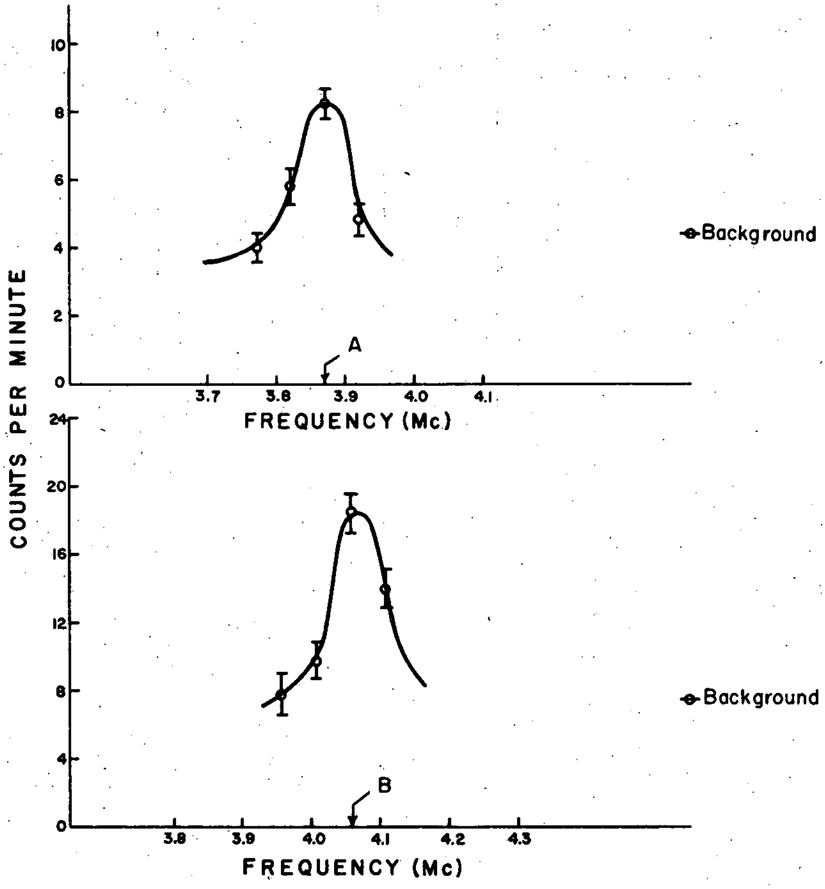


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Fig. 5. Radio-frequency resonances observed in $I^{135}$.
( $\nu_K$ = 5 Mc, H = 6.92 gauss)

Above: spin 7/2($\alpha$).
Below: spin 7/2($\beta$).
Frequency A: nominal center $\Delta\nu = \infty$.
Frequency B: nominal center $\Delta\nu = \infty$.

## TABLE II

Known spins of iodine isotopes $I^{123}$ through $I^{135}$. The single-particle shell-model configurations for $I^{124}$ and $I^{126}$ do not give rise to the ground-state parity believed correct (see text, but are included because of the simple spin classification that results.

| Proton Assignment | Neutron Assignment | Shell-model or Nordheim-rule spin prediction | OBSERVED SPINS (and references) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $I^{123}$ (a) | $I^{124}$ (a) | $I^{125}$ (b) | $I^{126}$ (c) | $I^{127}$ (d) | $I^{128}$ (e) | $I^{129}$ (f) | $I^{130}$ (g) | $I^{131}$ (h) | $I^{132}$ (c) | $I^{133}$ (c) | $I^{134}$ | $I^{135}$ (c) |
| $(5g_{7/2})^2(4d_{5/2})$ | EVEN | $I = 5/2$ | 5/2 | | 5/2 | | 5/2 | | | | | | | | |
| $(5g_{7/2})^3$ | EVEN | $I = 7/2$ | | | | | | | 7/2 | | 7/2 | | 7/2 | | 7/2 |
| $(5g_{7/2})^2(4d_{5/2})$ | $(3s_{1/2})$ | $2<I\leq 3$ WEAK | | 2 | | 2 | | | | | | | | | |
| | $(4d_{3/2})$ | $I = I$ STRONG | | | | | | 1 | | | | | | | |
| $(5g_{7/2})^3$ | $(3s_{1/2})$ | $I = 3$ STRONG | | | | | | | | | | | | | |
| | $(4d_{3/2})$ | $2<I\leq 3$ WEAK | | | | | | | | 5 | | 4 | | (?) | |

(a) Garvin, Green, and Lipworth, Phys. Rev. 111, 534 (1958).
(b) P. C. Fletcher and E. Amble, Phys. Rev. 110, 536 (1957).
(c) This paper.
(d) K. Murakawa, Sci. Papers Inst. Phys. Chem. Research (Tokyo) 20, 285 (1933); and Z. Physik 109, 162 (1938).
(e) J. W. Sherwood and S. J. Ovenshine, Phys. Rev. 114, 858 (1959).
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(g) Garvin, Green, and Lipworth, Phys. Rev. Letters 1, 292 (1958); J. E. Sherwood and S. J. Ovenshine, Phys. Rev. 114, 858 (1959).
(h) Livingston, Benjamin, Cox, and Gordy, Phys. Rev. 92, 1271 (1953); Garvin, Green, and Lipworth, Phys. Rev. 111, 534 (1958).

case in $Xe^{120}$, which also has 75 neutrons and exhibits a spin of 1/2.

It is of interest to note that if this assumption is made, the resultant spin of 1 is in agreement with the "strong" rule of Nordheim.[8] The spins of $I^{130}$ and $I^{132}$ are consistent with a weak rule coupling between an odd proton in the $5g_{7/2}$ level and an odd neutron in the $4d_{3/2}$ level. The spin of $I^{126}$ has been the subject of some discussion in the literature. Stevenson and Deutsch, on the basis of a($\beta\gamma$) angular correlation experiment, concluded that I = 2 (negative parity),[11] but Marty et al., who studied the shape of the $\beta$ spectrum made the assignment 1+.[12] Perlman and Welker, after a more exact determination of the comparative half lives of the $\beta$ transitions, concluded that $I = 2^-$ was the more reasonable assignment[13] a result strongly supported by the later and more detailed work of Koerts et al.[10] The work reported here definitely establishes the correctness of the spin value I = 2.

The decay scheme of $I^{132}$ has been investigated by Funston and Bernstein.[14] Though Funston and Bernstein do not make a spin and parity assignment to the ground state of $I^{132}$, Cheever et al., in a study of the decay of $Te^{132}$ suggest the assignment 4+;[15] this spin value is confirmed by the experiment reported here. The most recent work on $I^{133}$ is that of Holm and Ryde,[16] but the decay scheme is not completely analyzed. The result presented here should aid in this analysis. There appears to be little or no published work on the spectrum of $I^{135}$.

The disagreement between the experimental parity assignments to $I^{124}$ and $I^{126}$ and those resulting from the classification scheme of Table II is probably more apparent than real. It is certainly possible to pick single-particle-model neutron and proton states which give rise in all cases to the correct spins and parities, as it is also possible to reconcile the discrepancy by a suitable choice of states resulting from a deformed-core nuclear model such as the Nilsson model. However, in the absence of a measurement of the nuclear magnetic moment and nuclear electric quadrupole moment of the isotopes involved it is hardly more than speculative to list the alternative orbitals.

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