TABLE VI. Comparison of experimental and theoretical values of U_j^2.

	Te^{131}		Te^{129}		Te^{127}		Te^{125}	
	Theory	Expt	Theory	Expt	Theory	Expt	Theory	Expt
$d_{3/2}$	0.25	0.26	0.37	0.21	0.47	0.22	0.57	0.24
$s_{1/2}$	0.03	0.10	0.06	0.09	0.09	0.18	0.18	0.20
$h_{11/2}$	0.16	0.22	0.26	0.32	0.37	0.50	0.47	0.66

TABLE VII. Results (see text).

Target isotope	Analog pair	Q_{dp}(MeV)	E_p(MeV)	ΔE_c(MeV) (Measured)	ΔE_c(MeV) (Long *et al.*)
^{124}Te	^{125}Te–^{125}I	4.33	7.497	14.052	14.027
^{126}Te	^{127}Te–^{127}I	4.00	7.704	13.928	13.946
^{128}Te	^{129}Te–^{129}I	3.79	7.846	13.862	13.870
^{130}Te	^{131}Te–^{131}I	3.61	7.962	13.801	13.795

V. SUMMARY

The correspondence between the proton analog states in the tellurium isotopes and the parent states in (d,p) measurements from the same targets is in agreement with the existence of a proton analog state in the nucleus $(N,Z+1)$ for every level in the $(N+1,Z)$ nucleus. The analysis of the elastic scattering data has been shown to supplement the (d,p) analysis, and in some cases has yielded new spectroscopic information. The ground state of ^{131}Te, with three holes in a closed shell of 82 neutrons, has the simplest level structure of the odd-A tellurium isotopes investigated. The complexity of the level scheme increases as one moves further from the closed neutron shell. The high density of states and the smaller cross sections for individual transitions makes the analysis of the high excitation ^{124}Te(p,p) data nearly impossible.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Dr. B. B. Kinsey for his interest in and support of the experiment. Thanks are also due to C. G. Shugart and G. A. Lock for assistance in taking the data, and to E. Riley for the preparation of the drawings.

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Decay Studies of Iodine-118 and -120*

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The radioactive decay of iodine-118 ground and isomeric state and iodine-120 ground and isomeric state from irradiations of silver with carbon-12 ions, palladium with nitrogen-14 ions, and cadmium with boron-11 ions has been studied with a germanium lithium-drifted detector, a NaI crystal, an anthracene crystal, and several 400-channel analyzers. The electron and γ spectra, and singles and coincidence spectra, have been interpreted. Tentative decay schemes for the iodine-118 ground state and isomeric state as well as the iodine-120 ground state and isomeric state are given. The half-life of I^{118g} was found to be 13.0±0.3 min (γ-ray energies: 542, 605, and 1147 keV, β^+ endpoint energy: 6.05 MeV). The half-life of the isomeric state was found to be 8.5±0.5 min (γ-ray energies: 600 and 612 keV). The half-life of I^{120g} was found to be 83±4 min (γ-ray energies: 560, 640, 1520, and 1540 keV, β^+ endpoint energies: 3.45 and 2.9 MeV). The half-life of the isomeric state was found to be 53±4 min (γ-ray energies: 600 and 612 keV, β^+ endpoint energy: 3.85 MeV). A comparison of the levels of $Te^{118,120,122,124,126}$ is given.

1. INTRODUCTION

THE neutron-deficient isotopes of iodine were first investigated in connection with the spallation reaction of lanthanum and the fission reaction of uranium with 19-GeV protons by Andersson *et al.*[1] After an electromagnetic isotope separation iodine-118 was found to have a half-life of (13.9±0.5) min and γ rays of 511, 555, 605 and 1150 keV. The half-life of iodine-120 was determined to be 1.35±0.01 h and the corresponding γ rays measured with a NaI(Tl) detector system were found to have the following energies: 511, 560, 620, (1190), and 1520 keV.

When this work was initiated, no high-resolution experiments had been performed on these neutron-deficient isotopes. Furthermore, the decay characteristics of these isotopes were not known. The present study with the high-resolution Ge(Li) detectors was undertaken to obtain more information on these isotopes with better energy determination of the close-lying γ rays. Also the availability of heavy-ion beams from the Yale Heavy-Ion Accelerator made it possible to produce these isotopes in relatively clean form. The decay properties of I^{118} and I^{120} will be discussed in this paper.

* Work supported by the U. S. Atomic Energy Commission.
[1] G. Andersson, G. Rudstam, and G. Sorensen, Arkiv Fysik 28, 37 (1965).

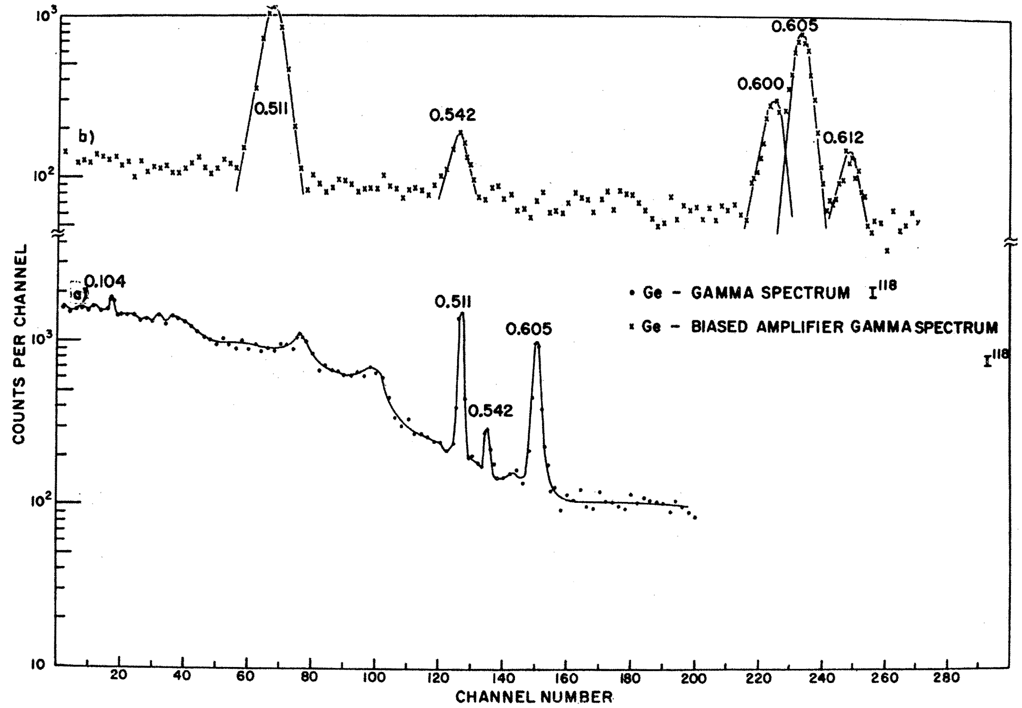

FIG. 1. The Ge(Li) detector measured γ-ray spectrum (a) of I^{118} as well as (b) the biased amplifier γ-spectrum of I^{118}, between 450–650 keV.

2. SOURCE PREPARATION AND CHEMICAL SEPARATION

In order to produce samples of iodine-118 and -120, several different reactions with various heavy-ion beams, energies, and target materials were investigated. Following is a brief discussion of the three reactions which were subsequently used in the experiments discussed in this paper.

Sample I

Natural Ag targets (1.5 mg/cm^2), evaporated on Al, were bombarded for 10 min with 67-MeV carbon-12 ions. The incident beam energy, based on excitation functions determined in preliminary experiments, was achieved by degrading the beam with Al foils.[2] The recoiling iodine isotopes were collected in a 4.5-mg/cm^2 Al catcher foil. After a cooling period of 10 min (to allow the iodine-117, $T_{1/2}\sim3$ min, to decay out), the chemical separation of iodine was performed. The bombarded Al catcher foil was dissolved in HCl and 10 mg/ml of iodide carrier was added to the above solution. The iodine was extracted with carbon tetrachloride, reextracted into water and precipitated as AgI.[3] The sources so obtained were used for the study of the iodine-118 ground state and isomeric state.

[2] L. C. Northcliffe, Natl. Acad. Sci.—Natl. Res. Council Publ. 1133 (1964).

[3] W. W. Meinke, Atomic Energy Commission Report No. AEC D-2738, 164, 1949 (unpublished).

Sample II

$CdSO_4$, pressed into pills, was bombarded with 115-MeV B^{11} ions for 1 h. The B^{11} beam was totally stopped in the Al-wrapped $CdSO_4$ pills. The target was permitted to cool for 1.5 h and after this the chemical separation of iodine was performed. The sources produced in this way contained the activities of I^{120} ($T_{1/2}=1.3$ h) and I^{121} ($T_{1/2}=2.1$ h). Both isotopes were studied using these sources.

Sample III

Dry $PdCl_2$ was pressed into pills and bombarded with 10.5-MeV/nucleon N^{14} ions for 1 h. After a cooling period of 1.5 h, the chemical separation of iodine was performed. Also, short bombardments of 10-min periods on $PdCl_2$ were performed and the chemical separation of iodine was done immediately after the end of bombardment. These sources were used as a reference and to confirm the results obtained from samples I and II.

3. EXPERIMENTAL ARRANGEMENTS

The half-lives were established by following the decay of (a) the integral β spectrum in a large plastic phosphor; (b) the gross activity in a β proportional counter, and (c) specific γ-ray transitions with both NaI(Tl) or Ge(Li) detector systems.

For γ-ray measurements, singles as well as coincidence measurements, a 6-mm-thick×6-cm^2-area Ge(Li) detector (having a resolution of 4 keV for the 1.33-MeV Co^{60} photopeak) was used. In addition to this several

3×3-in. NaI(Tl) crystals (having a resolution of 8.5% for the 661-keV photopeak of Cs^{137}) were employed in recording the singles, doubles, and triples coincidence spectra. The pulse height was analyzed with several RIDL 400-channel analyzers. The coincidence circuit had a resolving time of approximately $\tau_{1/2}=40$ nsec. Since as many as 12 individual samples were required for recording one coincidence measurement, four multichannel analyzers and coincidence systems were used, simultaneously recording the coincidence spectra gated on specific photopeaks or energy segments of the β spectrum. For the measurement of the β spectra, a 1-in.-thick×2-in.-diam anthracene crystal coupled to a Dumont 6292 photomultiplier was employed. In all coincidence measurements the counters were shielded with sufficient lead from each other to avoid Compton scattering. In the measurements performed, the C/R ratio was always kept greater than 50.

4. EXPERIMENTAL RESULTS: I^{118}

A. Half-Life and Single γ-Ray Measurements

The half-life of the 511-keV annihilation radiation was followed by selecting this peak in a single-channel analyzer. Two half-lives were observed, namely, 13 and 8.5 min. These are the mean values obtained from several runs.

TABLE I. γ-ray energies and observed half-lives of I^{118}.

γ-ray energy (keV)	Mean half-life from various experiments (min)
511	12.4±0.5
542	13.2±0.1
605	11.7±0.6
600	8.5±0
612	8.2±0.2
600, 605, 612	12±1

The problem of identifying the γ rays from iodine-118 is illustrated in Fig. 1. Figure 1(b) is a singles spectrum of γ rays from sample I, as seen in a Ge(Li) detector and a 400-channel analyzer. Photopeaks of the following energies were observed: 104±2, 511, 542±2, and 605±7 keV. Andersson *et al.*[1] had reported γ rays of 511, 555, and 605 keV. However, in this case, the 605-

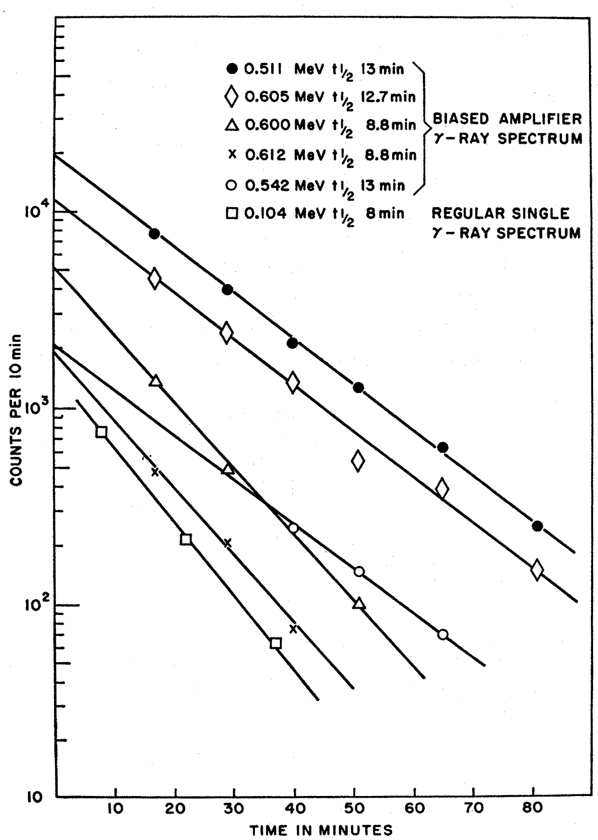

FIG. 2. Half-life measurements of the various γ rays of I^{118} followed with the Ge(Li) detector (6cc) and a biased amplifier. The half-life of the 104-keV line was determined from the regular single γ-ray spectrum of I^{118}.

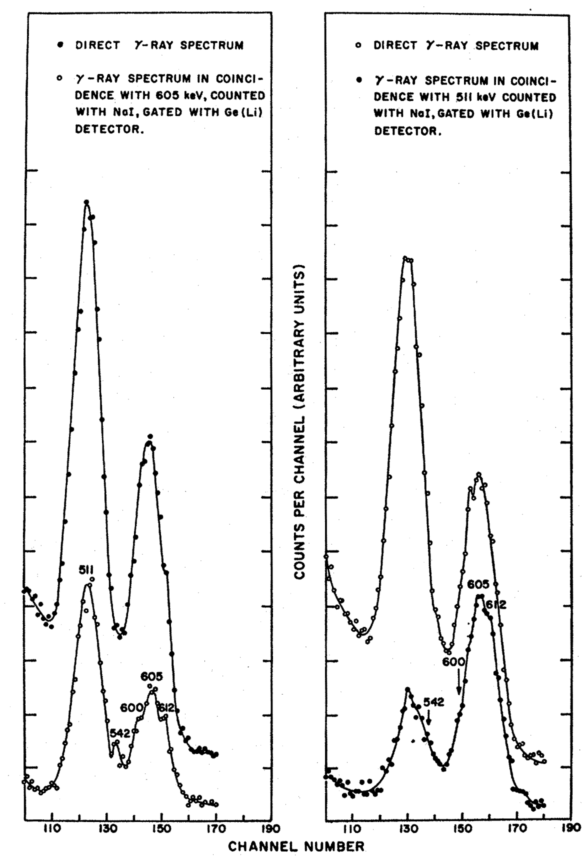

FIG. 3. Coincidence measurements of I^{118}, gated with the Ge(Li) detector and counted with a NaI(Tl) crystal. The open circles in the left-hand diagram are the counts in coincidence with 605 keV (511, 542, 600, and 612 keV). The solid circles in the right-hand diagram show the counts in coincidence with 511 keV (542, 600, 605, and 612 keV).

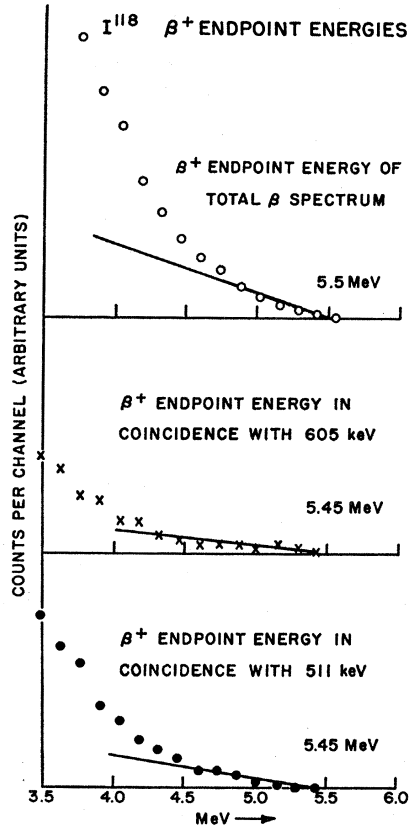

FIG. 4. β^+ endpoint energies of I^{118} measured from the total β spectrum, as well as in coincidence with 605 and 511 keV.

keV photopeak (see Fig. 1) was seen as an unusually broad peak. The half-life measurement of this 605-keV photopeak in a single-channel analyzer gave a half-life shorter than that of the 542-keV line. This suggested the use of an ORTEC Model 408 biased amplifier for the measurement of the singles spectra. Figure 1(a) shows the spectrum taken with the biased amplifier. Only the portion between 500 and 700 keV was amplified. The broad 605 γ line was resolved into the following lines: 600 ± 2, 605 ± 2, and 612 ± 2 keV. Figure 2 shows the half-life of the above photopeaks using the biased amplifier. The half-life of the 542- and 605-keV lines was observed to be 13 ± 0.3 min and the half-life of the 600- and 612-keV lines was found to be 8.5 ± 0.5 min. The two half-lives as seen above indicated an isomeric state in I^{118}. This result was confirmed by the various β and γ coincidence experiments performed later. Table I gives the half-lives assigned to various γ rays of I^{118}. The half-life of the 104-keV line was observed to be approximately 8 min.

B. Coincidence Studies

For γ-γ coincidence measurements, two 3×3-in. NaI(Tl) or a 3×3-in. NaI(Tl) and a Ge(Li) detector were used 90° to each other. In each case the NaI crystal was covered with a lucite plate to cut off β particles. Figure 3 shows the coincidence spectrum in gate with the 511-keV γ line. The spectrum was recorded with a 3×3-in. NaI(Tl) crystal. The 511-keV gate was selected with a Ge(Li) detector. The spectrum shows γ rays of 542, 600, 605, and 612 keV. The coincidence with the weaker γ rays (542, 600, and 612 keV) was concluded from the asymmetric shoulders of the 605-keV photopeak. (See Fig. 3.) The spectrum in coincidence with the 605-keV line showed strong photopeaks at 511, 542, 600, and 612 keV. It would have been appropriate to perform the coincidence measurements with the gates of 542, 600, and 612 keV. However, the low intensities of these γ rays and the short half-life did not permit these measurements.

The first conclusion to be drawn from these measurements is that the 542-, 600-, 605-, and 612-keV transitions are in coincidence with the 511-keV annihilation peak and that the 600-, 605-, and 612-keV γ rays are in coincidence with each other. The 605-keV γ ray is the most intense line and first excited state of Te^{118}. The strong coincidence of the 605-keV peak with the 542-keV line and the 600-keV line indicates levels of 1147 and 1205 keV in Te^{118}. In the singles NaI(Tl) spectrum the presence of a very weak 1147-keV photopeak suggests this level also. This very weak photopeak is not observed in the Ge(Li) detector because of the very low efficiency of the Ge(Li) detector for high-energy (above 1 MeV) γ rays. The level at 1817 keV is proposed because of the coincidence of the 612-keV γ ray with the 600-keV γ line which is in coincidence with the 605-keV. The two half-lives of 8.5 and 13 min associated with the various γ lines suggest an isomeric level in I^{118}. The 104-keV line is not in coincidence with any of the above γ rays.

β-γ coincidence studies were performed in order to obtain more information on the decay of I^{118}. The β spectrum in coincidence with the 511-keV annihilation peak showed a $\beta+$ endpoint energy of 5.45 ± 0.15 MeV.

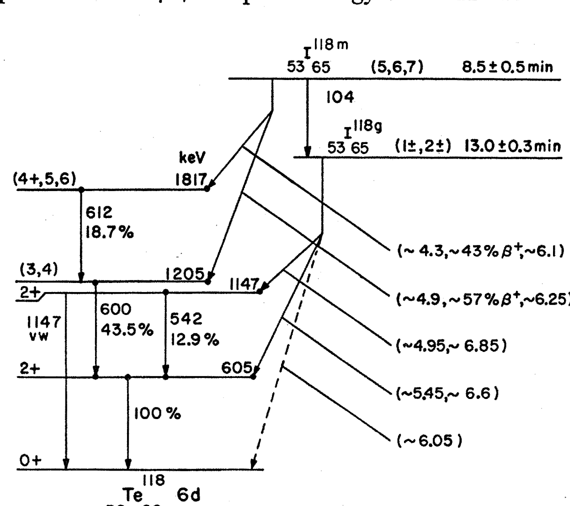

FIG. 5. Proposed decay scheme for I^{118} ground state and isomeric state.

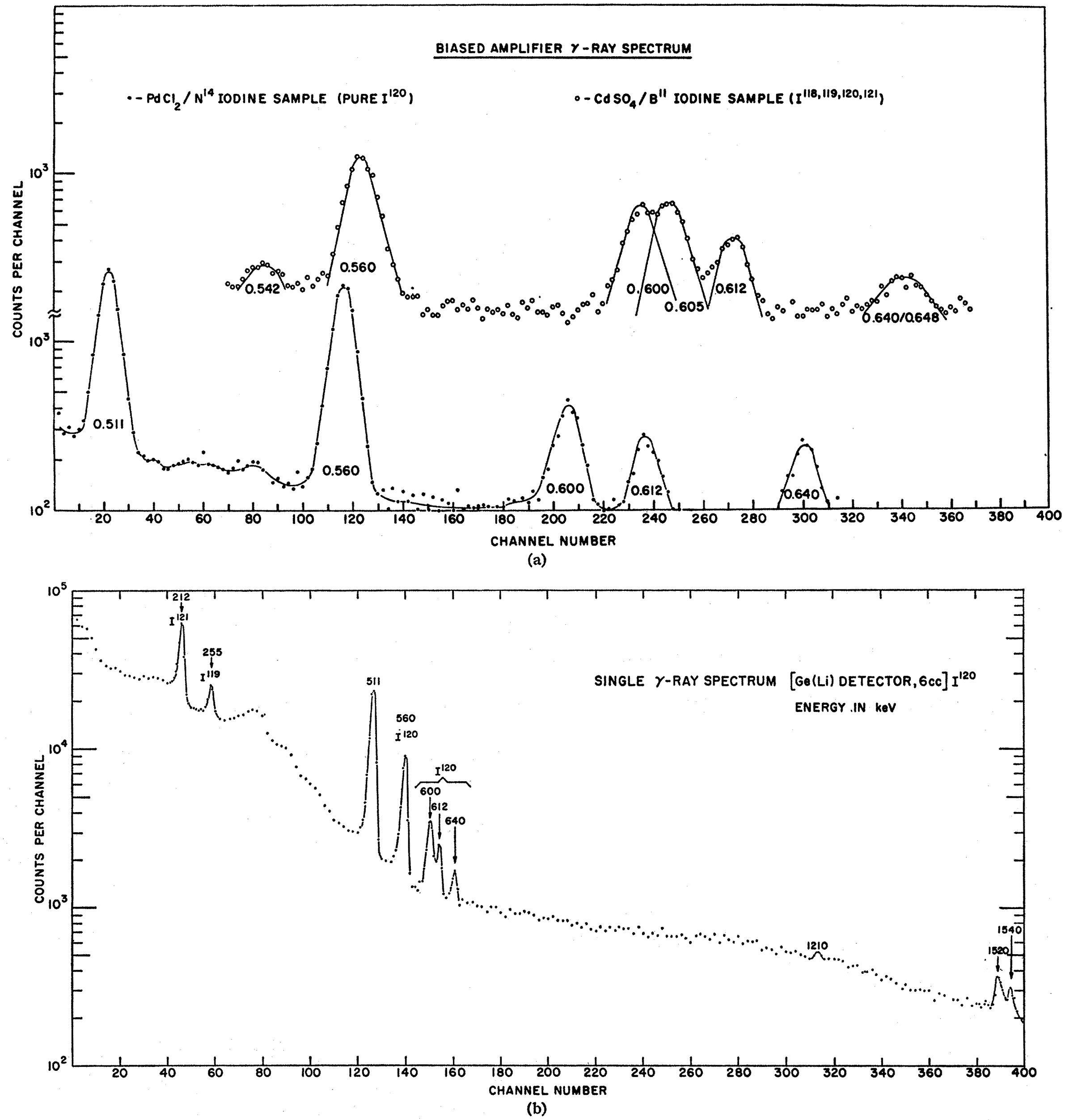

FIG. 6. (a) Biased amplifier γ-ray spectrum of I^{120} produced from $PdCl_2+N^{14}$ and $CdSO_4+B^{11}$. (b) Shows the singles γ-ray spectrum of I^{120} in a 6-cc Ge(Li) detector and a 400-channel analyzer.

The β spectrum in coincidence with the 605-keV line showed a value of 5.45 ± 0.15 MeV for the $\beta+$ endpoint energy. Figure 4 shows the $\beta+$ endpoint energies measured in coincidence with 511 and 605 keV, gated with a Ge(Li) detector. The value of 5.45 MeV agrees well with value of 5.5 MeV observed by Butement *et al.*[4] This indicates that there is no β transition from the ground state of I^{118} to the ground state of Te^{118}. Therefore the mass difference between I^{118} and Te^{118} is 7.07 MeV. The β spectrum in coincidence with the 600-keV γ ray gave a $\beta+$ endpoint energy of about 4.9 MeV. This suggests that this β branch is feeding the 1205-keV level in Te^{118}. Similarly the coincidence of the 612-keV line with the 4.3-MeV β group suggests that this β branch is feeding the 1817-keV level. These measurements were performed in gating with NaI on either the low-energy or the high-energy side of the broad hump of 600, 605, and 612 keV.

The errors in the measurement of the β-ray energies are high and therefore only a tentative decay scheme is shown in Fig. 5.

[4] F. D. S. Butement and S. M. Qaim, J. Inorg. Nucl. Chem. **27**, 1729 (1965).

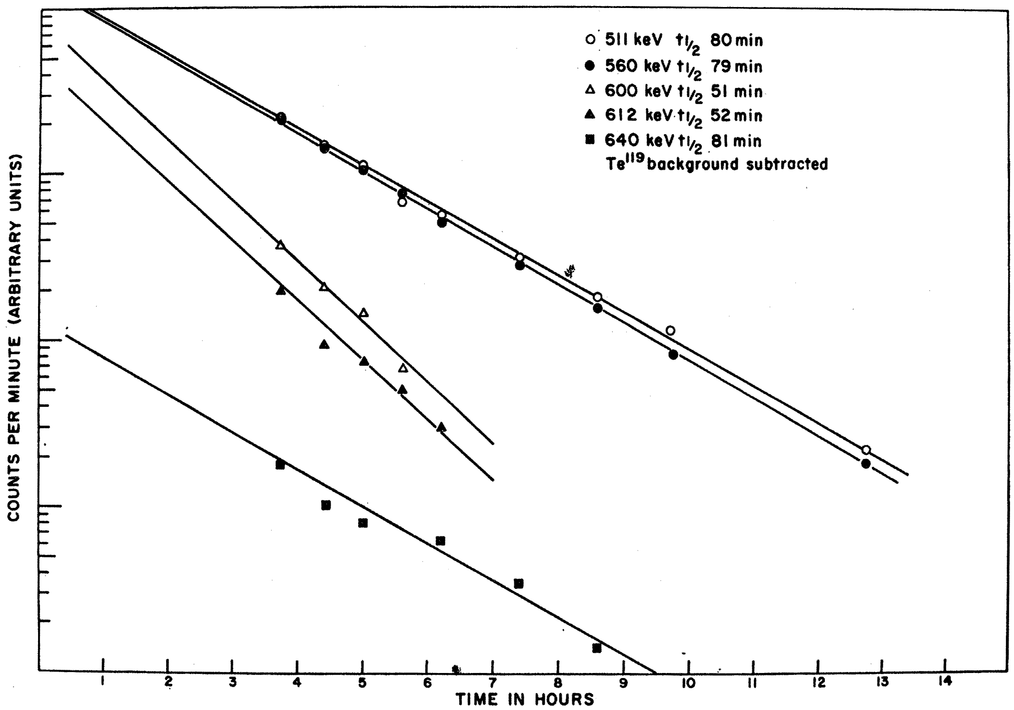

FIG. 7. Example of the half-life measurements of the various γ-rays of I^{120} with the biased amplifier Ge(Li) system.

5. EXPERIMENTAL RESULTS: I^{120}

A. Singles γ-Ray Spectrum Studies

The singles γ-ray spectrum and the half-lives were determined in the previously described manner, using sources described as sample II and sample III. Figure 6(a) shows the γ spectrum of sample II using a Ge(Li) detector and a biased amplifier. The following γ rays were found: 511, 560±2, 612±2, 640±2, 1520±8, and 1540±8 keV. These γ-ray energies agree well with the reported values of Andersson *et al.*[1] However, using the biased amplifier the 620-keV γ line reported by Andersson *et al.* was resolved into a (600±2)- and (612±2)-keV line and the 1520-keV line was resolved into a (1520±8)- and a (1540±8)-keV line [Fig. 6(b)]. The half-life of the various γ rays, each followed with a single-channel analyzer, showed distinctly two half-lives, namely 83±4 and 53±4 min. (Figs. 7 and 8). The half-life of the 600- and 612-keV γ rays was found to be 53±4 min. The photopeak at 648 keV was found to grow and afterwards decayed with a half-life of 16 h (Te^{119}). Table II gives the half-lives of various γ rays in different runs. The decay of the positrons greater than 1.2 MeV was followed and the half-life obtained was 78 min as shown in Fig. 9.

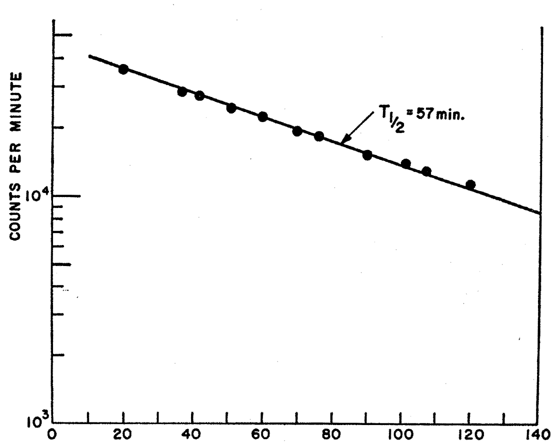

FIG. 8. Half-life measurements of 600 and 612 keV together; no background subtracted. Total peak counts.

B. Coincidence Studies

For coincidence studies the experimental arrangements were the same as described in Sec. 4 B. The

TABLE II. γ-ray energies and half-lives for I^{120}. Average from these experiments: $T_{1/2}$ for ground state of I^{120}: 83±4 min; $T_{1/2}$ for isomeric state of I^{120}: 53±4 min.

γ-ray energy (keV)	Sample II Half-life (min)		Sample III Half-life (min)	
	Expt. I	Expt. II		
511	85 (cont.~10% I^{121})	80	87 ($I^{120,121}$);	50
560	85		80	
600	53		50	
612	49		55	
640	83		85	
1520, 1540	85			

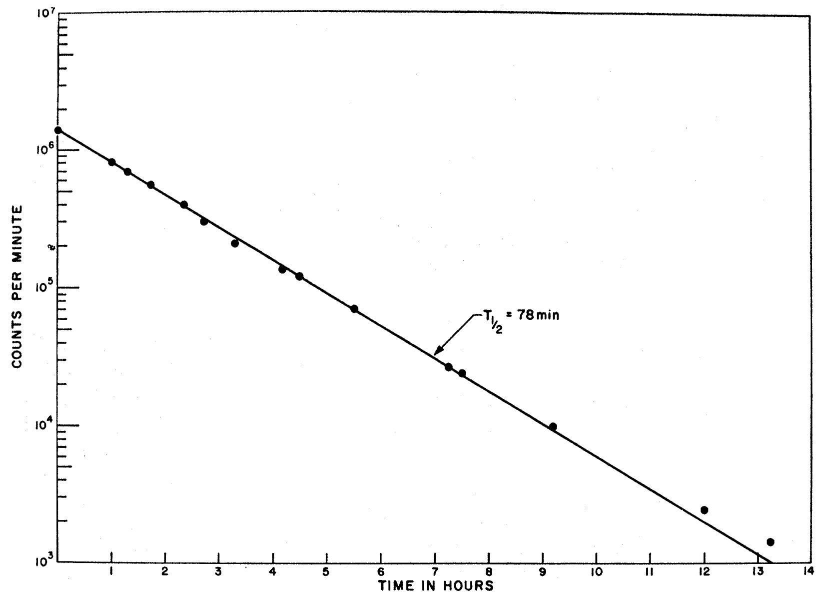

FIG. 9. Decay of positrons greater than 1.2 MeV. Since in our samples I^{121} was produced, we followed the half-life of the positrons greater than 1.2 MeV. The positron energy for I^{121} is 1.13 MeV.

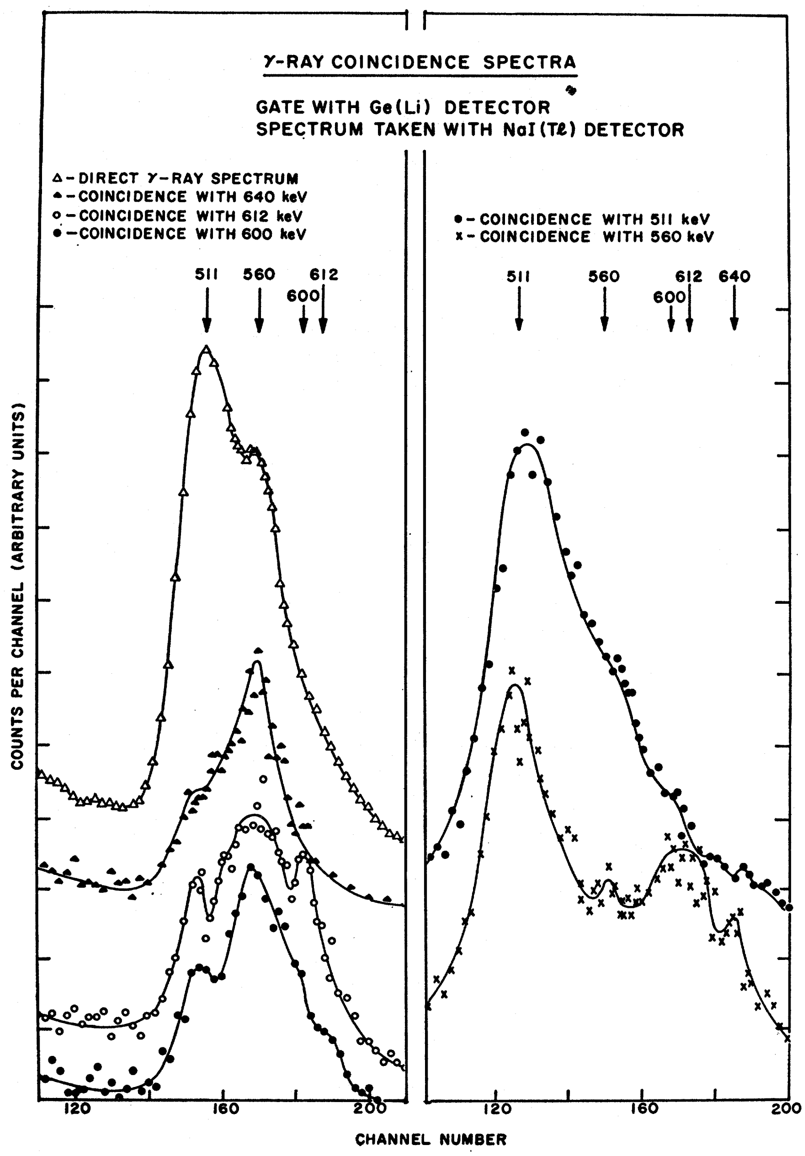

FIG. 10. The various coincidence measurements which were made with the various γ rays of the I^{120} ground state and isomeric state.

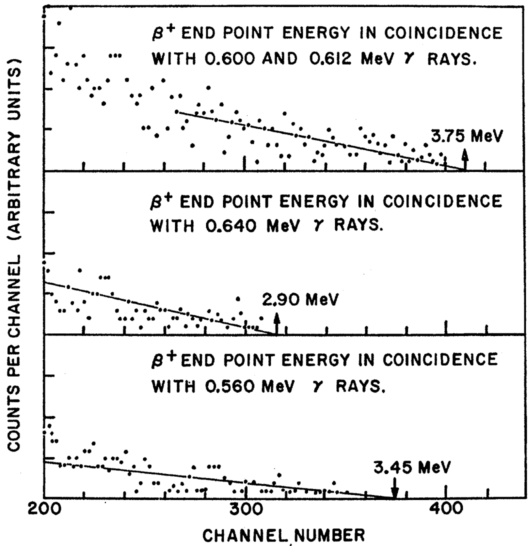

FIG. 11. Different β^+ endpoint energies are given in coincidence with 600 and 612 keV; 640 and 560 keV.

coincidence spectrum in gate with the 560-keV photopeak gave strong γ rays of 511, 600, 612, and 640 keV, and weak γ rays of 1520 and 1540 keV. The gate with the 511-keV photopeak showed lines at 560, 600, 612, and 640 keV; the gate with the 640-keV line gave γ rays of 511 and 560 keV. Also, the 612-keV γ ray is in coincidence with 511, 560, and 600 keV and the 600-keV line is in coincidence with 511-, 560-, and 612-keV γ rays (see Fig. 10).

The intensity measurements of the above γ rays and the coincidence results indicate that the 560 keV is the strongest and therefore first excited state in Te^{120}. The

TABLE III. Results of β-γ coincidences.

γ-ray energy in coincidence (keV)	Coincident β-ray energy (MeV)
511	4.0 $\pm$0.1
560	3.45$\pm$0.1
600	3.75$\pm$0.15
612	3.13$\pm$0.15
640	2.9 $\pm$0.2

coincidence of 600- and 640-keV γ rays gives levels of 1160 and 1200 keV in the Te^{120}. The coincidence of the 612-keV line with the 560- and 600-keV line and not with the 640-keV line shows that there is a level at 1772 keV. The coincidence of the 1520- and 1540-keV lines with the 560-keV line indicates levels of 2080 and 2100 keV. The presence of two half-lives in I^{120} suggests that some of these levels are being fed by the ground state and some by the isomeric state of I^{120}. The β-γ coincidence results (see below) also confirm the above results.

The $\beta+$ endpoint energy in coincidence with the 511-keV annihilation radiation gave a value of 4.0 $\pm$0.05 MeV. The β endpoint energies in coincidence with 560-, 600-, 612-, and 640-keV γ rays were measured. For this a Ge detector was used to gate each of the above γ rays. The β spectrum was taken with a large plastic phosphor. Since the efficiency of the Ge detector is very low at higher energies, use of a NaI(Tl) detector was also made in a second experiment to confirm the results obtained with the Ge(Li) detector. In the NaI(Tl) detector the above γ rays could not be resolved; therefore, the lower energy part of the broad 511-, 560-, and 600-keV photopeak was chosen as a

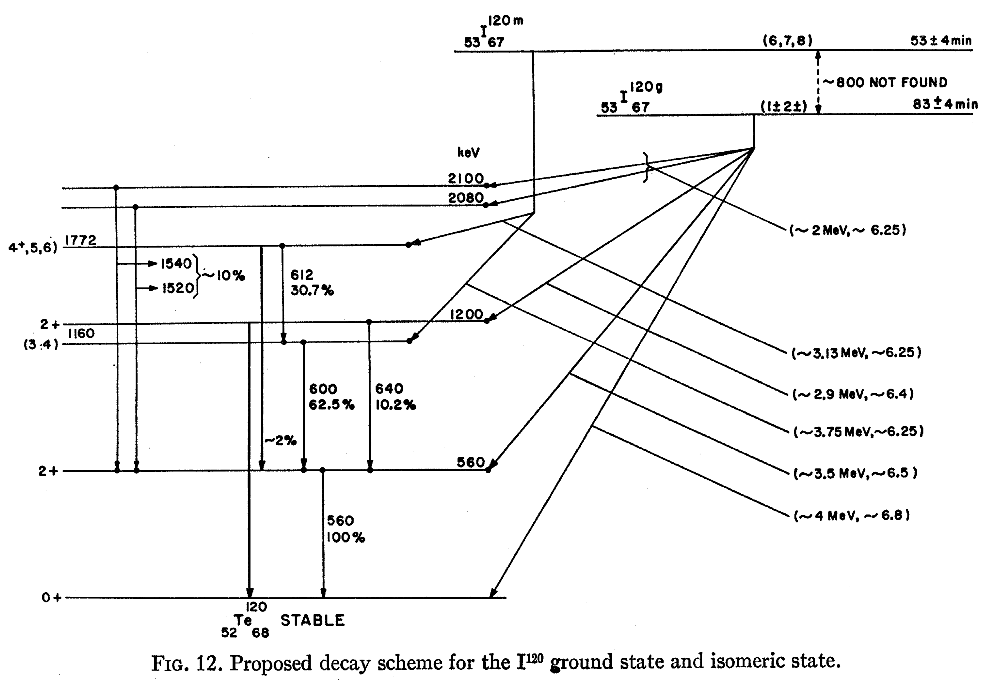

FIG. 12. Proposed decay scheme for the I^{120} ground state and isomeric state.

511-keV gate. Similarly for the 560-keV coincidence, the middle part of the broad peak was taken as a gate, and for the 600-, 612-, and 640-keV gate, the higher-energy side of the above peak was used as a gate. The β spectrum in coincidence with the 560-keV γ ray gave a $\beta+$ endpoint energy of 3.5 ± 0.100 MeV. Figure 11 shows the β spectra in coincidence with the gates chosen in the Ge(Li) detector. The β-γ coincidence results are summarized in Table III.

The presence of two half-lives in the β- and γ-ray studies suggest an isomeric state in I^{120}. From the $\beta+$ endpoint energies, and the levels observed in Te^{120}, the mass difference between the ground state of I^{120} and Te^{120} is found to be 5.1 MeV. The isomeric state is found to be about 800 keV above the ground state. The above results suggested that we should look for an isomeric transition of 800 keV or lower energy. The results show no indication of any such γ rays. Based on the above results a tentative decay scheme is proposed (as shown in Fig. 12). The β-γ coincidence results suggest a β^+ transition of 4 MeV from the ground state of I^{120} to the ground state of Te^{120}.

6. RESULTS AND CONCLUSIONS

The final results of the investigation of I^{118} and I^{120} are shown in the proposed decay schemes (Figs. 5 and 12). The logft values for the various $\beta+$ transitions vary from 6.1 to 6.8. The logft values for the electron capture branches are calculated on the basis that the Q values of I^{118}-Te^{118} and I^{120}-Te^{120} are probably very close to the values predicted from the energy-systematics curve of Way *et al.*[5] The logft values are rather near the upper limit permitted for allowed transitions in that region. The spin and parity of the ground states of the even-even nuclei Te^{118} and Te^{120} must be 0^+. A first forbidden transition would require that I^{118g} and I^{120g} have odd parity and spin 1. The shell model predicts even parity for all levels for N and Z between 50 and 82, with the single exception of the $h_{11/2}$ level. If one assigns $h_{11/2}$ to the odd neutron to give the required odd parity, one still cannot obtain a spin value $J=1$ with the two plausible assignments $d_{5/2}$ or $g_{7/2}$ for the 53 proton. However, if one assumes the transition as an allowed one, then the parity and spin of I^{118g} and I^{120g} could be 1^+. It could be due to the configuration of $(d_{5/2},d_{3/2})$. Also the $h_{11/2}$ level in combination with $d_{5/2}$ or $g_{7/2}$ proton states would give $2-$ $(g_{7/2},h_{11/2})$ and $8-$ $(d_{5/2},h_{11/2})$. The spin and parity of I^{124} and I^{126} is $2-$, whereas I^{122} and I^{128} have 1^+ as ground-state configurations. The spin of I^{130} is known to be greater than five and odd parity is assigned to it. From these considerations the spin and parity of the ground states of I^{118} and I^{120} are probably 1^+ or 2^- and the isomers high-spin angular momentum states. It is well known that the spin and parity of the ground, first, and second excited states of even-even nuclei are in general 0^+, 2^+, 2^+ or 0^+, 2^+, 4^+. Figure 13 shows the energy systematics curves for the first and second excited states of the even-even Te isotopes. The levels found and also reported by Lederer *et al.*[6] and Sakai *et al.*[7] by conversion electron measurement from $(p,2n)$ reactions on Sb^{121} agree very well. It is interesting to note that the energy curve of the first and second excited states of Te has a minimum at Te^{120}, and the second 2^+ level in Te^{118} is lower than the 4^+ level.

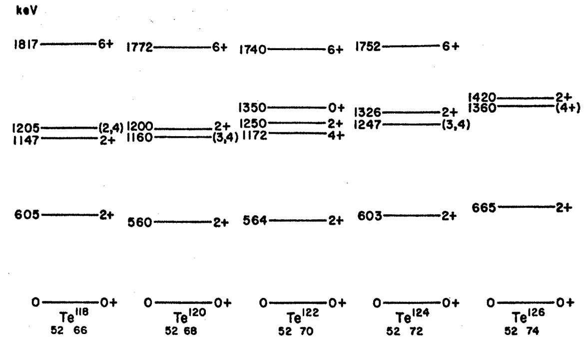

FIG. 13. Comparison of the levels of the even-even tellurium isotopes. Values from these experiments as well as from Refs. 6 and 7 are taken.

The isomeric states of I^{118} and I^{120} have a probable spin of 6, 7 or 8. These high-spin isomeric states of iodine-118 and -120 have not been observed previously. However, the high angular momentum transfer of heavy ions is very well known and therefore the explanation for the production of these high-spin isomeric states.

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

[6] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), pp. 261, 263.

[7] M. Sakai, T. Yamazaki, and H. Ejiri (private communication).