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High spin states in ^{194}Tl

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High spin states in ^{194}Tl, excited through the ^{181}Ta(^{18}O,5n) reaction in the energy range $E = 80$–100 MeV, were studied using in-beam γ-ray spectroscopic techniques. Excitation functions, activity spectra, γ-ray angular distributions, and γ-γ coincidences were measured. The strongly Coriolis distorted $\tilde{\pi} h_{9/2} \otimes \tilde{\nu} i_{13/2}$ two-quasiparticle band already known in ^{196,198}Tl has also been found in this case. It is based on an $I^{\pi} = 8^-$ isomeric state located 292.8 keV above ^{194}Tl^m, $I^{\pi} = 7^+$.

[NUCLEAR REACTIONS ^{181}Ta(^{18}O, 5$n\gamma$), $E = 80$–100 MeV, measured E_γ, I_γ, $\sigma(E, E_\gamma, \theta_\gamma)$, γ-γ coin. ^{194}Tl deduced levels, J, π. Natural target. Ge(Li) detectors.]

I. INTRODUCTION

Up to now no in-beam study of the prompt γ rays following the production of ^{194}Tl has been made. Previous knowledge about this nucleus stems from the early work of Jung and Andersson,[1] who performed β-spectrometer measurements on mass separated sources from synchrocyclotron bombardments of Hg and Tl with protons. This investigation yielded information about the ground state (^{194}Tl^g, $I^{\pi} = 2^-$), a long lived isomer (^{194}Tl^m, $I^{\pi} = 7^+$), and their subsequent $EC + \beta^+$ decay into ^{194}Hg.

On the contrary, the two next heavier doubly odd isotopes ^{196,198}Tl have been recently studied in beam using the (HI, xn) reaction[2,3] and very interesting phenomena characteristics of this transitional region have been found.[2-4] A collective two-quasiparticle band of $\tilde{\pi} h_{9/2} \otimes \tilde{\nu} i_{13/2}$ parentage has been established there, and it is the aim of the present work to enlarge the systematics about this structure and to follow its eventual variation with neutron number.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The ^{18}O beam delivered by the Munich MP tandem was utilized to populate high spin states in ^{194}Tl by means of the ^{181}Ta (^{18}O, 5n) reaction. In order to select the most appropriate bombarding energy to reach ^{194}Tl, an excitation function for the (^{18}O, xn) reaction was measured, using ^{18}O$^{7^+,8^+}$ ions at terminal voltages ranging between 10 and 11 MV thus covering the interval E(^{18}O) $= 80$–100 MeV. An 870 μg/cm^2 thick self-supporting ^{181}Ta foil with an approximate energy loss of 1.5 MeV for the ^{18}O beam was used for this measurement. The beam was stopped in a Faraday cup located several meters downstream from the target to minimize the background. γ-ray spectra were measured with a large volume (140 cm^3) Ge(Li) detector and for the lower energy part with a planar intrinsic (10 cm^3) Ge diode. Figure 1 displays excitation functions of some strong γ lines for all the observed reaction channels. Only compound reactions involving neutrons in the exit channel were observed leading to the final nuclei

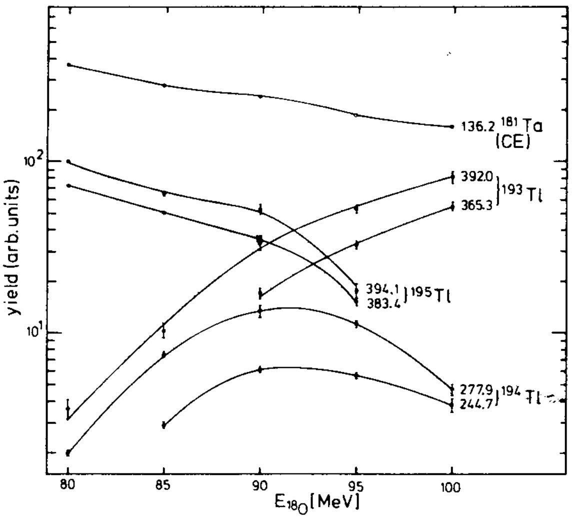

FIG. 1. Excitation functions for some of the strongest γ rays produced by the ^{181}Ta (^{18}O, xn) ($x = 4, 5, 6$) reactions. Also, the Coulomb excitation (CE) yield of the $\frac{9}{2}^+ \rightarrow \frac{7}{2}^+$ ground state transition in the target is shown (Ref. 7).

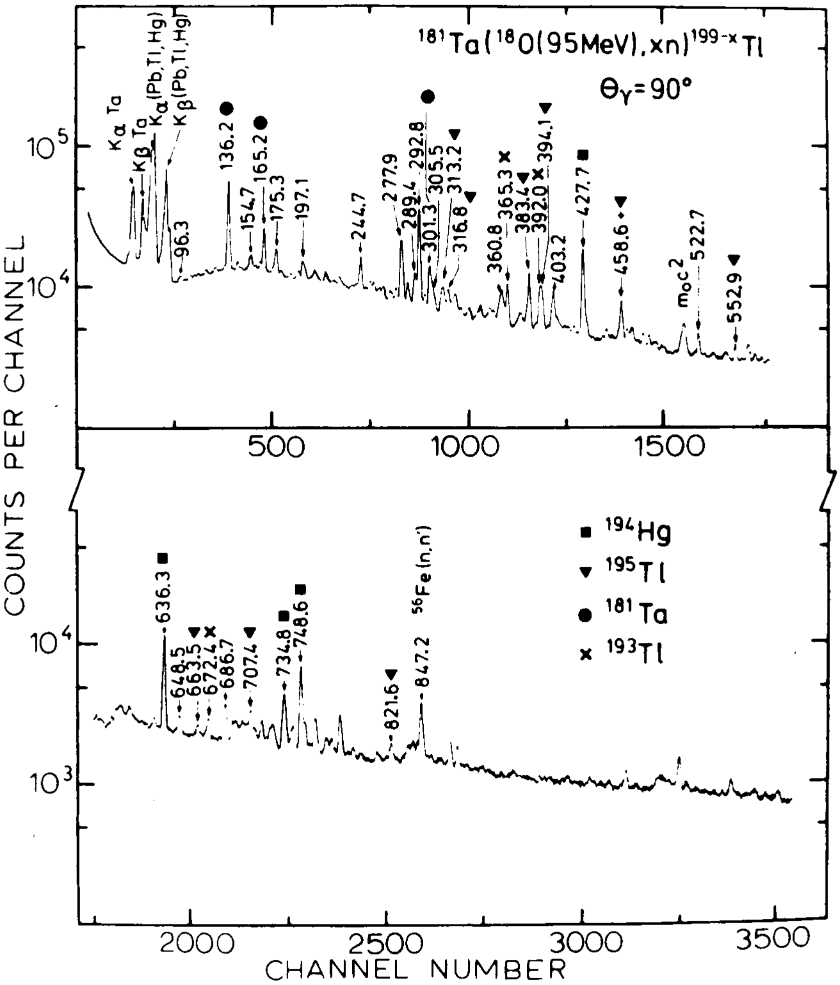

FIG. 2. Singles γ-ray spectrum for the ^{181}Ta(^{18}O, xn) reaction at 95 MeV bombarding energy and 90° to the beam direction. Transitions in ^{194}Tl are labeled only with their energies.

^{195,194,193}Tl. The corresponding cross sections are well separated, thus allowing an unambiguous isotopic assignment for almost all γ rays. In addition fairly strong Coulomb excitation (CE) of the target takes place. Previous knowledge of the two neighboring odd mass isotopes ^{193,195}Tl (Refs. 5 and 6) was of great help in the identification of several γ rays appearing in the spectra.

Figure 2 shows a singles spectrum measured at $E(^{18}O)=95$ MeV with a thicker target (5.1 mg/cm^2) backed by a ^{208}Pb ($\simeq$100 mg/cm^2) stopper. This beam energy was chosen for all further experiments in order to enhance the population of highest spin states.

The present reaction leads to no appreciable population of the $I^\pi=2^-$ ground state of ^{194}Tl. The only hitherto known transition[1] feeding ^{194}Tl^g (a 204 keV γ ray de-exciting a state at 204 keV) is, at most, 2% of the strongest 292.8 keV line belonging to the prompt decay of ^{194}Tl and, in addition, no isomeric transition leading from the 7$^+$ state (^{194}Tl^m) to the ground state was observed, in agreement with Ref. 1. A study of the $EC+\beta^+$ decay of ^{194}Tl to ^{194}Hg lends further support to the above conclusion; within the experimental accuracy the transition intensity of the $4^+\to2^+$ 636.3 keV line equals that of the $2^+\to0^+$ 427.7 keV γ ray.[7] Furthermore, there is a good intensity balance between this last line and the above mentioned 292.8 keV ^{194}Tl transition. At least 98% of the cross section for the (^{18}O, 5n) reaction leads to the long lived 7$^+$ state which represents an effective ground state.

As mentioned in the Introduction we know about the existence of collective structures in these nuclei from studies concerning ^{198,196}Tl (Refs. 2 and 3). These bands are built on $I^\pi=8^-$ isomeric states ($T_{1/2}=12.3$ and 21.3 nsec respectively) which de-excite through hindered $E1$ transitions into the corresponding 7$^+$ states. Since a similar band was expected here and the velocity of the recoiling residual nuclei is about 1% of the light velocity (which means that they come out of the thin, 870 μg/cm^2

TABLE I. ^{194}Tl γ-ray energies, relative angle integrated γ intensities, and angular distribution coefficients in the ^{181}Ta (^{18}O, 5n) reaction at 95 MeV.

E_γ (keV)[a]	I_γ[b]	a_2	a_4
96.3[c]	7 ± 3	−0.25 ± 0.12	−0.10 ± 0.10
154.7	23	−0.50 ± 0.15	0.06 ± 0.06
175.3	37	−0.50 ± 0.30	0.01 ± 0.03
197.1	26	−0.04 ± 0.06	0.00 ± 0.03
227.3	3	−0.56 ± 0.40	0.15 ± 0.20
244.7	35	−0.50 ± 0.06	0.04 ± 0.04
277.9	72	−0.50 ± 0.03	0.02 ± 0.02
279.2	17	−0.43 ± 0.07	0.05 ± 0.05
283.3	18	−0.44 ± 0.10	0.01 ± 0.01
289.4	28	−0.44 ± 0.10	0.01 ± 0.02
292.8	184	−0.19 ± 0.05	0.01 ± 0.02
373.5	6 ± 3[d]		
403.2	30	−0.58 ± 0.06	0.03 ± 0.03
458.6	28	−0.80 ± 0.20	0.10 ± 0.10
522.7	19	0.26 ± 0.04	−0.06 ± 0.06
648.5	13	0.25 ± 0.03	−0.07 ± 0.09
686.7	30	0.20 ± 0.08	−0.03 ± 0.03
741.9	13	0.24 ± 0.05	−0.08 ± 0.10

[a] Gamma energies accurate to ±0.2 keV.

[b] Errors range from 5% to 15% (for the weaker lines) unless otherwise stated.

[c] Contaminated by 97.0 keV, 7$^-$ → 5$^-$ transition in ^{194}Hg (Ref. 7).

[d] Intensity at 90°.

target used in this case), we searched for nanosecond isomerism by measuring spectra, in otherwise equal experimental conditions, with and without the lead stopper. The 292.8 keV γ ray showed a marked decrease in its intensity relative to other lines known to belong to ^{194}Tl. From this information we were able to get an estimate of its half-life which lies in the 15–40 nsec interval. Such a figure coincides well with what is expected from the $B(E1)$ values of ^{198,196}Tl (i.e., $T_{1/2} \approx 30$ nsec) and also fits into the statistics of hindered $E1$ transitions.[8] γ-ray angular distributions were measured with the 5.1 mg/cm^2 thick Ta foil backed by the lead stopper. The stopper was utilized in order to collect the whole intensity of the isomeric transition and to avoid distortions of its angular distribution from decays away from the target. Bringing the beam energy close to the Coulomb barrier of lead, the thick target improved the peak to background ratio as compared to the 870 μg/cm^2 Ta foil. An angle dependent efficiency calibration was determined to correct for the absorption in the ^{208}Pb stopper. Table I gives results of singles measurements for those lines identified as transitions in ^{194}Tl. The especially large error for the 96.3 keV transition is due to the fact that this line is contaminated with the 7$^-$→5$^-$, 97.0 keV γ ray in ^{194}Hg (Ref. 7). The figure given in Table I corresponds to the remaining (prompt) intensity after subtraction of the Hg component as obtained from a study of the activity spectrum.

In addition a γ-γ coincidence experiment using two large Ge(Li) detectors was performed. Table II gives results of a quantitative evaluation of coincidence intensities for some of the largest gates. These total transition intensities were obtained under the multipolarity assumptions discussed below. The new level scheme shown in Fig. 3 was constructed on the basis of the data presented so far. The supplementary assumption that the intraband $\Delta I = 1$ cascade transitions are predominantly of M1 character is necessary to achieve consistency for the proposed scheme. This is especially true for the 96.3 keV transition which, if M1, should have a total conversion coefficient of about 9.5. The above assumption, which determines the parity of the cascade, is reasonable not only because of the collective character of the band but also considering its similarity to the structures found in the heavier doubly odd Tl isotopes.[3] The evidence for the 373.5 keV crossover transition comes only from singles measurements and therefore is indicated with a dashed line in Fig. 3. However, its intensity coincides well with what is obtained from the $I\gamma(373.5)/I\gamma(277.9)$ branching if the value for the $B(E2)/B(M1)$ ratio from the next higher lying level is

TABLE II. Total transition coincidence intensities.[a]

Gate \ E_γ	96.3	244.7	277.9	283.3	289.4	292.8	403.2	458.6	522.7	648.5	686.7	741.9
96.3		0.7	1.5			1.5						
244.7	3.5		5.0	1.0	1.1	3.0	1.3	0.8			1.1	0.2
277.9	3.0	1.7		0.9	1.4	4.0	1.4	0.9		0.5	0.7	
292.8	6.7	3.7	7.1	1.5	2.0		2.8	1.7	0.7	0.5	0.8	W[b]
403.2	2.5	2.2	3.0	1.0	0.8	2.0		1.3	1.4			0.4

[a] The values given in the table have uncertainties ranging from 30% to about 50% for weak lines. Energies are in keV. Intensities for different gates are not normalized among each other.

[b] Weak line.

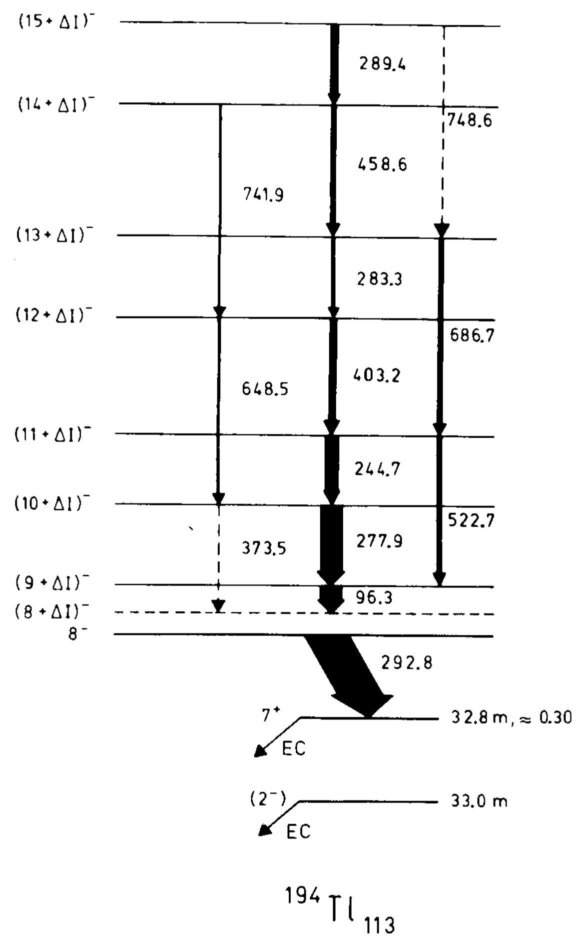

FIG. 3. Level scheme for ^{194}Tl proposed in the present work. $\Delta I = 0$, 1, or 2 (see text). The excitation energy of the 7^+ state (≈ 0.30 MeV) can be estimated from systematics.

used. There is also some evidence from coincidence spectra for the existence of the 748.6 keV crossover transition which in singles, if present, is hidden by the large 748.6 keV $5^- \rightarrow 4^+$ ^{194}Hg activity line.

III. DISCUSSION AND CONCLUSIONS

The reason why the cascade drawn in Fig. 3 is not ending directly on the 8^- isomeric state is primarily connected with the existence of a further low energy (61.5 keV) γ ray in ^{196}Tl where a very similar band is known.[3] In these heavy nuclei the large internal conversion may easily prevent the observation of such low energy lines. Also the huge x-ray intensities and the low energy background present in-beam obscure the portion of the spectrum below ≈85 keV. Furthermore, there are theoretical reasons[3,4] connected with the phase of the staggering of the intraband transition energies which indicate an additional low energy γ ray even in ^{196}Tl. In this treatment, where the two (noninteracting) odd valence particles are coupled to a rotor, the Coriolis force provides a natural explanation for the staggering, especially considering the existence of a similar phenomenon in related bands of neighboring odd Tl isotopes.[4] It was also indicated, however, that a residual proton-neutron (p-n) interaction gives a contribution to the staggering of opposite phase to that mentioned above.[4] Calculations including such a p-n force[9] seem to be able to reproduce qualitatively the band in ^{196}Tl without assuming an unobserved transition. Thus, the value of ΔI (see Fig. 3) remains open to some extent until its definitive experimental elucidation. At present possible values are $\Delta I = 0, 1, 2$.

A structure, very similar to those encountered in ^{196,198}Tl, has also been found in the present case. This band has been successfully analyzed in terms of a Coriolis distorted band where the configuration space used to describe the intrinsic motion is the $\pi h_{9/2} \otimes \nu i_{13/2}$ product space.[2-4] Since this structure is now known in three different nuclei, it is pertinent to discuss briefly its systematic features.

Looking at the available data,[3] one notes that the excitation energy of the 8^- bandhead above the long lived 7^+ isomer is decreasing as the neutron number decreases [$\Delta E(8^- \rightarrow 7^+) = 390.6$, 343.9, and 292.8 keV in ^{198,196,194}Tl respectively]. This fact, as we shall see, lends further support to the present interpretation. The structure of the 7^+ states has been interpreted as being mainly the spherical $(\pi s_{1/2} \otimes \nu i_{13/2})_{7^+}$ configuration.[10] The difference between this state and the 8^- one (if the present picture applies) is the orbit change for the proton which is associated with the development of a stable oblate deformation.[5] Hence, the $8^- \rightarrow 7^+$ energy difference should display a similar variation with neutron number as the excitation energy of the $\pi h_{9/2}$ bandheads above the $\pi s_{1/2}$ ground states in odd mass Tl isotopes,[5] which indeed turns out to be the case.

Other trends, specifically connected with the behavior of the band itself as a function of neutron number, have been recently discussed in Ref. 11.

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