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1. Introduction

In the framework of a pure single particle model no electromagnetic transitions with $\Delta j > L$ should occur (j -selection rule). In doubly odd nuclei only a few cases of j -forbidden gamma transitions are known, for example $^{114,116}In$, $^{204,206,208}Bi$. We searched for further j -forbidden isomers in neutron-deficient Bi nuclei, which are far off the closed shell configuration. In beam measurements with heavy ion induced compound nucleus reactions offer an excellent tool for the investigation of neutron deficient Bi nuclei with $A \leq 204$.

2. Experimental Results

^{200}Bi i s o m e r s

At the heavy ion cyclotron U-300 targets of ^{193}Ir (enriched to 98%) were irradiated by a ^{12}C beam of 81 MeV energy. The beam dimension at the target position amounted to about 5x10 mm^2. The targets were produced by sedimentation of metallic iridium on an aluminium backing of $\approx$ 1 mg/cm^2. The target thickness amounted to 7.7mg/cm^2.

Figure 1 shows the prompt and delayed gamma ray spectra obtained with a *Ge(Li)* planar detector (1.8 cm^2 x 11 mm) of 2.5 keV energy resolution at 200 keV. The prompt spectrum was measured during the 1 ms beam pulse. The delayed spectrum was measured during 1 ms, beginning with 1 ms after the end of the beam pulse. As far as the assignment of the gamma lines is known, it is given in the picture. From the not assigned transitions the 272.1 and 498 keV lines belong to isomers with a half-life between 200 ns and 1 ms. In table 1 the gamma intensities are listed as they were calculated from the prompt spectrum by means of the computer program "GAMMA"[1]. The energy calibration was based on the energy values given by Hanser[2] for the ^{200}Bi decay lines and the energy of the Coulomb excitation line at 139.0 keV, also known from the ^{193}Os decay[3].

In order to obtain exact measurements of the isomeric life-times delayed time spectra were measured. For measurements in the ms range the dee-voltage of the cyclotron was externally gated. After a 550 ms activation period 8 delayed spectra were measured during the following 800 ms beam-off time, from which the lifetime of the 428.2 keV transition was obtained (fig. 2) to be $T_{1/2}$ = = 0.40 ± 0.05 s.

The gamma transitions 253.0, 286.1, 630.3 and 644.2 keV, shown in fig. 1, belong to a second isomeric state in ^{200}Bi. By making use of the natural beam bunching[4] two-dimensional time-energy spectra were measured, from which the mean value of the lifetime of the second isomeric state was obtained as $T_{1/2}$ =46 ± 4 ns. The properties of the second isomeric state will be discussed in a forthcoming paper.

The identification of the reaction products was performed by measuring the excitation functions shown in figs. 3 and 4. The energy of the incoming particles was degrated by calibrated aluminium foils, the intensity values of the gamma-rays were normalized by the total charge measured behind the target foil. The excitation function of the 428.2 keV line follows the trend of the gamma transitions excited in the ground state decay of ^{200}Bi (fig. 3), which is produced by the reaction ^{193}Ir (^{12}C , $5n$) ^{200}Bi . The excitation function of the 629.1 keV line from the ground state decay of ^{201}Bi is drawn for comparison. The 427.8 keV transition in ^{201}Bi , known from the ^{201}Po decay /5/ is, therefore, out of question of being identical with the found isomeric transition. As is shown in fig. 4 the nanosecond delayed lines follow the trend of the 428.2 keV line and belong, therefore, also to the ^{200}Bi nucleus. The 428.2 keV line has also been obtained by a cross bombardment of a target of natural platinum with ^{11}B ions, whereas the much weaker nanosecond delayed lines covered by the background caused from other reactions.The (HI , $px\,n$) reaction was excluded by irradiation of ^{193}Ir with ^{11}B ions, in which case the 428.2 keV line was not observed.

The remarkable increase of the isomeric ratio with rising projectile energy,which is shown in fig. 5, leads to the conclusion, that the found 428.2 keV isomer is of high spin character. In fig. 6 the difference spectrum is shown, which we got from 4 x 400 ms delayed spectra by subtraction of the forth spectrum from the first one. Besides the 428.2 keV line and the *Bi* *KX*-ray lines no further gamma ray lines could be detected within the limit, set by the statistical fluctuations.From this fact we deduced,that the first isomeric state deexcites by only one gamma transition. From the intensity ratio to the *KX* - rays we derived a conversion coefficient of

$$\alpha_K \text{ (428.2 keV)} = 0.09 \pm 0.05,$$

which is the nearest to the theoretical value $\alpha_K(E3)$ =0.08 of an *E3* transition .

^{198}Bi i s o m e r

An 8.3 mg/cm^2 target of ^{191}Ir (enriched to 94.3 %) was irradiated with ^{12}C ions of 81 MeV energy. After a 10 s irradiation period and a 3 s break two delayed spectra were measured each of 15 s duration. In fig. 7 the earlier measured spectrum (upper curve) and the difference of both delayed spectra (lower curve) are drawn. The difference spectrum shows a strong delayed gamma ray line of E_γ =248.5 ± 0.5 keV, which we ascribe to an isomeric transition in ^{198}Bi . In order to determine its half-time, the decay was followed over 8 x 3 s (fig. 8), resulting in the value $T_{1/2}$ = 7.7 ± 0.5 s.

The intensity of the 248.5 keV transition depends on the heavy ion energy (fig. 9) in the same manner as the gamma transitions 197.7 and 318.0 keV from the ground state decay of ^{198}Bi, so that we take it for an isomeric transition in the same nucleus. It is to be noticed, that a weak 247.8 ± 0.2 keV line was listed by Hanser /2/ among the decay lines of a mass separated ^{198}Bi source. This line may be caused by a rest activity of the same ^{198}Bi isomer. The 248.5 keV transition we also found by irradiation of a 19 mg/cm^2 tantalum target with 120 MeV ^{22}Ne ions, which energy corresponds to the peak cross section of the reaction $^{181}Ta(^{22}Ne, 5n)^{198}Bi$.

From the intensity ratio of the 248.5 keV transition to the Bi-KX ray lines (fig. 7) the conversion coefficient

$$\alpha_K \; (248.5 \text{ keV}) = 0.24 \pm 0.05$$

was obtained, which agrees well with the theoretical value $\alpha_K(E3) = 0.27$ of an $E3$ transition.

The difference spectrum in fig. 7 shows further delayed gamma lines which may be ascribed to known isomers, namely ^{191m}Ir ($T_{1/2}$ = 4.9 s, E_γ = 129 keV) and ^{193m}Au ($T_{1/2}$ = 3.9 s, E_γ = 220 and 258 keV). The intensity ratios to the respective KX-ray lines correspond approximately to the known conversion coefficients of these transitions. The ^{191}Ir isomer seems to be excited by inelastic scattering processes, but the formation of the ^{193}Au isomer suggests to assume a fairly big cross section of the two-proton transfer reaction.

S e a r c h f o r ^{202}Bi i s o m e r s

A target of ^{196}Pt (enriched to 86%) was irradiated by ^{11}B ions of 71 MeV energy. The target consists of pieces of ≈ 50 mg/cm^2 thick metallic foil sticked to an 1.3 mg/cm^2 *Al* backing. In the energy range up to 1 MeV delayed gamma ray spectra were measured in different time ranges, beginning with ≈ 30μs after the end of the beam pulse. No delayed gamma transitions with lifetimes bet - ween some 10 μs and some 100 ms were found, which could be ascribed to isomeric states in ^{202}Bi, although strong ^{202}Pb transitions from the ^{202}Bi ground state decay were observed. On the other hand the known isomers/6/ ^{198m}Tl ($T_{1/2}$ = 27 ms) and ^{200m}Tl ($T_{1/2}$ = 37 ms) were obtained by the competing reactions $^{196}Pt(^{11}B, \alpha 4n)^{199}Tl$ and $^{196}Pt(^{11}B, \alpha 3n)^{200}Tl$ with cross section values comparable to that of the reaction $^{196}Pt(^{11}B, 5n)^{202}Bi$.

3. Discussion

Figure 10 shows the decay schemes of the $I^{\pi}=10^-$ isomeric states in doubly odd *Bi* nuclei. The ground state spins have been obtained by measurements of atomic beam resonances/7/ down to the ^{200}Bi nucleus. The value I = 7 of the ^{200}Bi ground state may be explained by the configuration/8/ of the neighbouring odd *A* isotope ^{199}Pb . The ground state spin of ^{198}Bi has not yet been measured. In the neighbouring isotope ^{197}Pb the level sequence 3/2$^-$ (g. st), 5/2$^-$ (85 keV) and 13/2$^+$ (319 keV) was found/15/. The configurations $[\pi(h_{9/2})^1 \nu(p_{3/2})^1]\ 6^+$ as well as $[\pi(h_{9/2})^1 \nu(f_{5/2})^1]\ 7^+$ can be taken into consideration for the ^{198}Bi ground state. As is shown in table 2 the decay branchings and the $\lg ft$ values for the feeding of the 7^- and 5^- levels of the lead daughter nuclei are quite similar for the ^{198}Bi and ^{200}Bi decay. This favours a 7^+ assignment of the ^{198}Bi ground state and may explain the direct deexcitation of the isomeric state to the ground state.

From the comparison with the isomeric $\nu(i_{13/2})^{-1}$ states of the neighbouring Pb isotones (fig. 11) the configuration $\pi(h_{9/2})^1 \nu(i_{13/2})^{-1}$ may be deduced. From the theoretically predicted multiplet splitting /10/ follows, that in case of a particle-hole configuration the lowest state has the spin value $I = I_{max} - 1$. For ^{208}Bi Alford et al. /11/ showed that the 10^- level is in fact the lowest state of the $\pi(h_{9/2})^1 \nu(i_{13/2})^{-1}$ multiplet.

The 10^- levels deexcite to the 7^+ states of the $\pi(h_{9/2})^1 \nu(f_{5/2})^{-1}$ configuration through j-forbidden $E3$ transitions. In table 3 the hindrance factors of the isomers in ^{208}Bi /12/, ^{206}Bi and ^{204}Bi /13/ are compared with our results. It may be concluded that in this cases the j selection rule is fairly strong, in contrary to the j-forbidden $E3$ transitions in the doubly odd nuclei ^{114}In and ^{116}In /16/, for which hindrance factors between 10 and 20 are valid. By contrast with the behaviour of the j-forbidden transitions in odd nuclei, where a big hindrance factor was only found near the shell closure the hindrance factors of the doubly odd Bi nuclei are nearly independent of the number of neutrons outside the closed shell. In spite of their low excitation energies the 10^- levels have a nearly pure shell model configuration also in case of ^{200}Bi and ^{198}Bi . An extension of the systematics on the more neutron deficient nuclei ^{196}Bi and ^{194}Bi is prevented by the β^+ decay of the 10^- state to the 10^+ state of the lead daughter nucleus/17/, which competes with the gamma deexcitation due to the low excitation energy of the 10^- state.

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Table 1. Relative gamma intensities of the ^{200}Bi isomers calculated from the spectrum measured during the 1 ms beam pulse (fig. 1).

E_γ(keV)	I_γ	$T_{1/2}$(s)
253.0±0.1	50+ 2	$(5.0\pm0.4)10^{-8}$
286.1±0.1	44+ 2	$(4.4\pm0.4)10^{-8}$
428.2±0.1	100+2	(o.4±0.05)
630.3±0.2	56+ 2	$(4.5\pm0.4)10^{-8}$
644.2±0.2	37+ 4	$(4.4\pm0.4)10^{-8}$

Table 2. Main branches of the $Bi \rightarrow Pb$ decay

a) Q_{β^+} -value taken from *P. A.* Seegers mass table/14/.
b) total intensities taken from Hanser/2/.

Isotope	$T_{1/2}$(min)	Q_{β^+}(MeV) a)	Excitation of Pb levels I = 7^- E(MeV)	I_{β^+}(%) b)	lg ft	I = 5^- E(MeV)	I_{β^+}(%) b)	lg ft
^{198}Bi	12	6.43	2.142	46	6.1	1.824	35	6.3
^{200}Bi	35	5.73	2.154	56	6.0	1.909	36	6.4

Table 3. Properties of *l*-forbidden isomeric transitions in doubly odd *Bi* isotopes.

Isotope	10^- level E(keV)	isomeric transition E_γ(keV)	multipole order	half-life $T_{1/2}$(s)	hindrance factor F_W($\times10^3$)
^{208}Bi	1571	921	E 3	$2.5\ 10^{-3}$	3.3
^{206}Bi	1043	904	E 3	$8.9\ 10^{-4}$	1.1
^{204}Bi	808	752	E 3	$1.3\ 10^{-2}$	3.5
^{202}Bi	–	–	–	–	–
^{200}Bi	428	428	E 3	$4.0\ 10^{-1}$	2.4
^{198}Bi	248	248	(E 3)	7.7	2.2

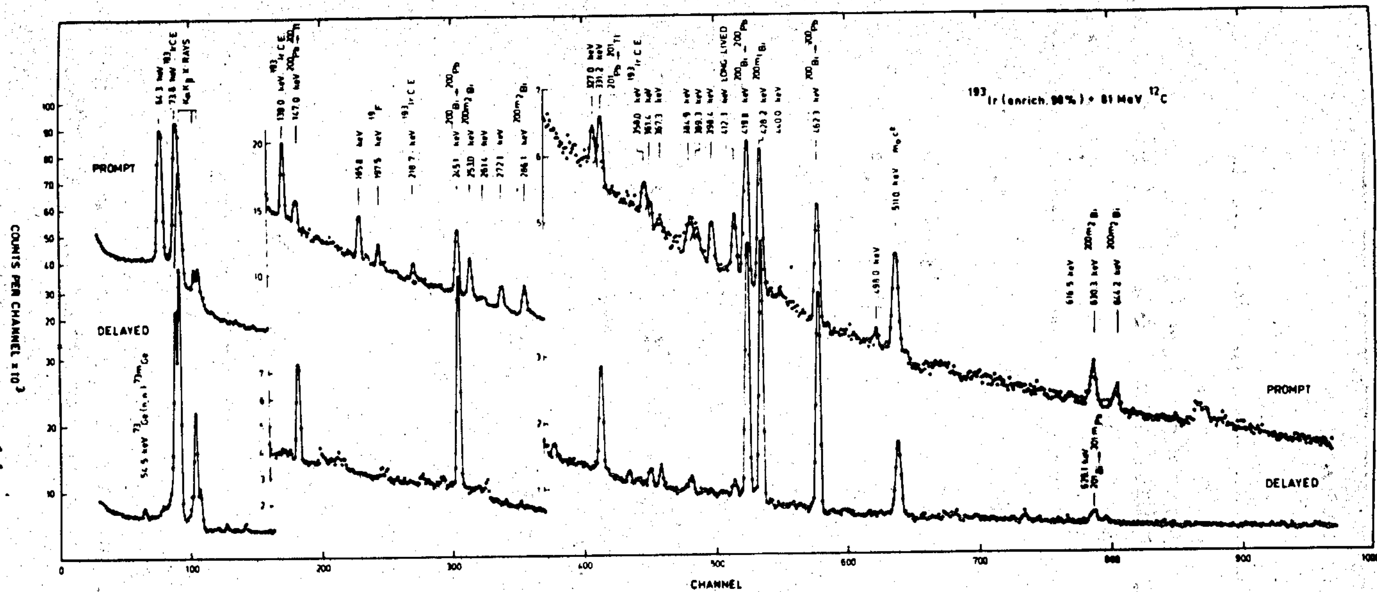

Fig. 1. Gamma-ray spectra of the reaction $^{193}Ir + ^{12}C$, each measured for 1 ms during (upper curve) and between (lower curve) the beam pulses.

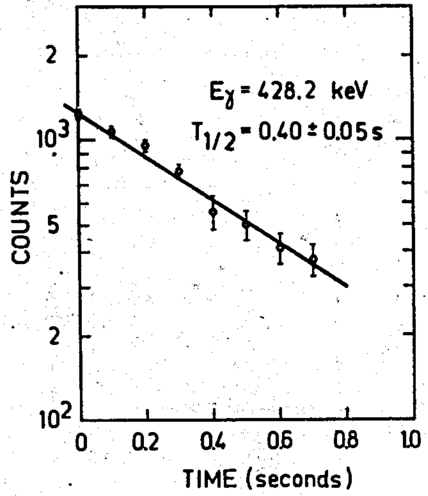

Fig. 2. Decay curve of the isomeric 428.2 keV transition in ^{200}Bi .

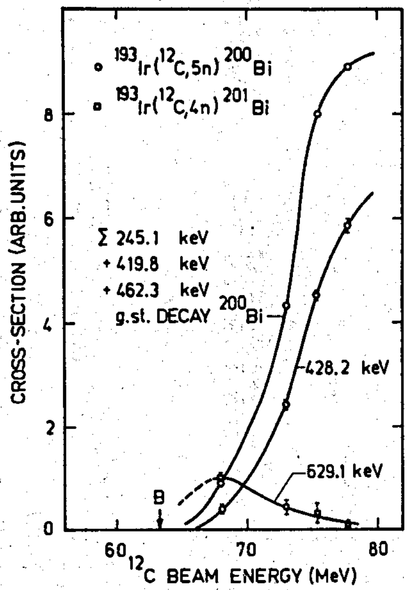

Fig. 3. Excitation functions of the reaction ^{193}Ir + ^{12}C, obtained from the spectra measured between the beam pulses. B denotes the energy of the Coulomb barrier.

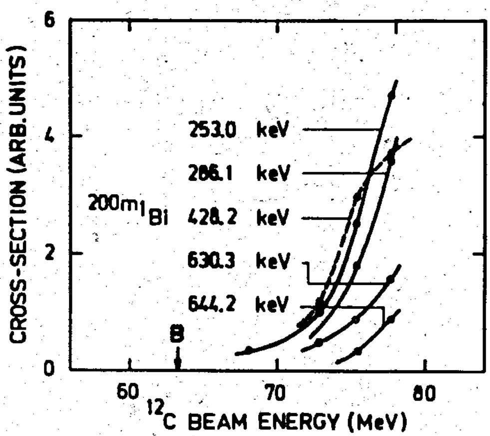

Fig. 4. Excitation functions of the reaction ^{193}Ir + ^{12}C, obtained from the spectra measured during the 1 ms beam pulse. B denotes the energy of the Coulomb barrier.

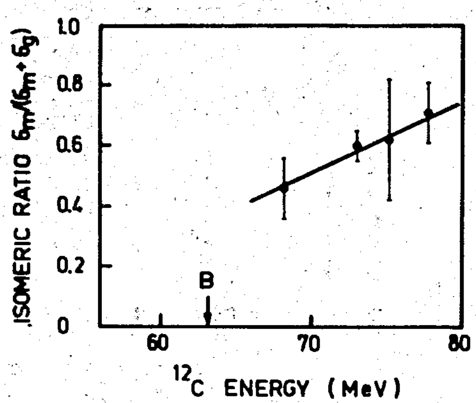

Fig. 5. Energy dependence of the isomeric ratio for $^{200m_1}Bi$. σ_m denotes the cross section for the population of the isomeric state and σ_g the cross section for the direct population of the ^{200}Bi ground state.

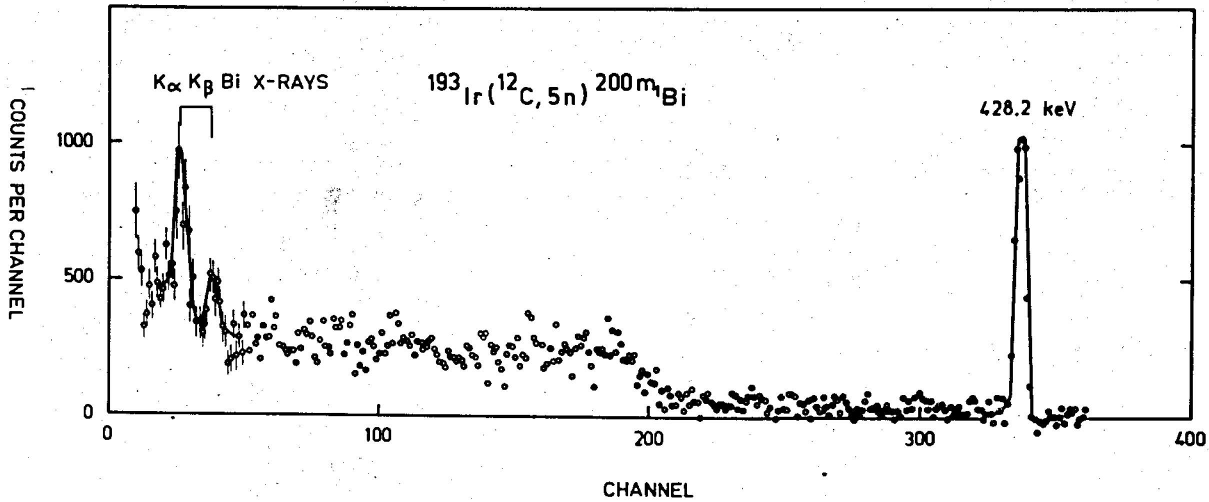

Fig. 6. Difference spectrum of the $^{200m_1}Bi$ deexcitation, obtained by subtraction of two delayed spectra with 1.2 s relative delay, each measured for 400 ms after a 570 ms activation period.

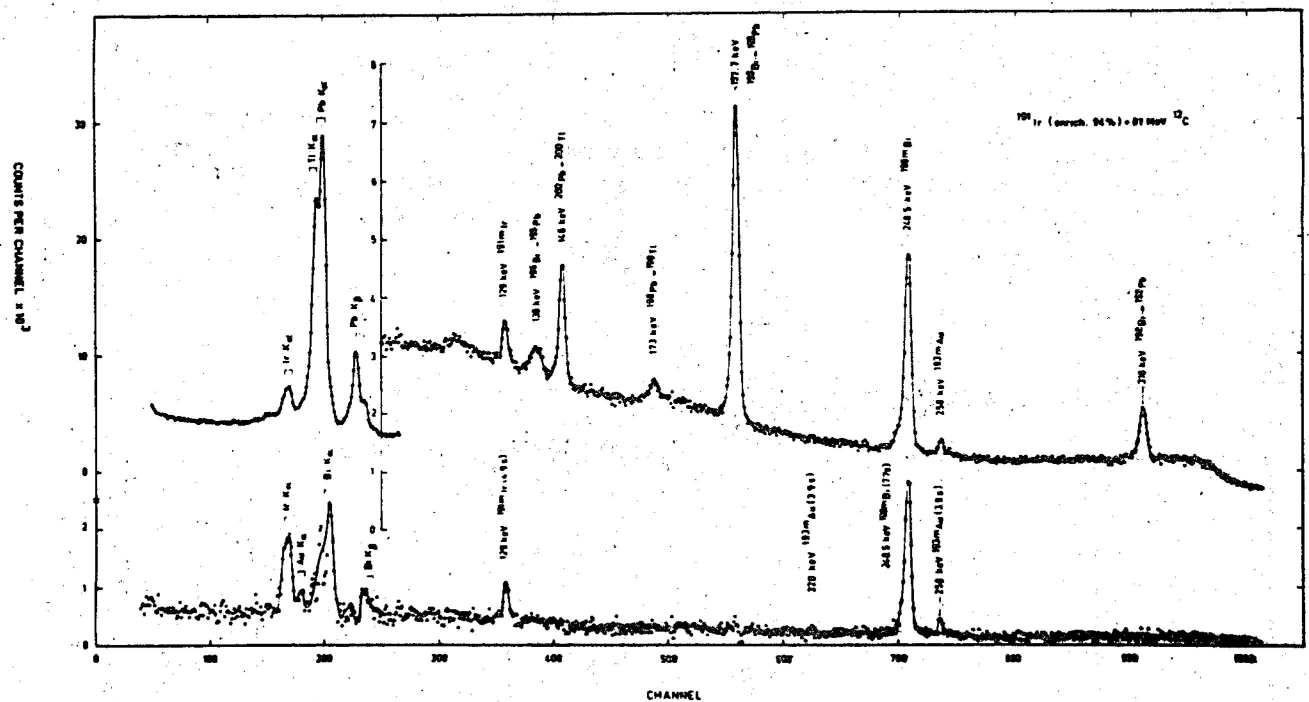

Fig. 7. Single and difference spectra of the reaction ^{193}Ir + ^{12}C . The difference spectrum was obtained from two successive spectra, each measured for 15 s. Besides of dead time losses the earlier measured spectrum was affected by a slight deterioration of the energy resolution causing in the difference spectrum the apparent $Bi\,K_{\alpha}$ line splitting.

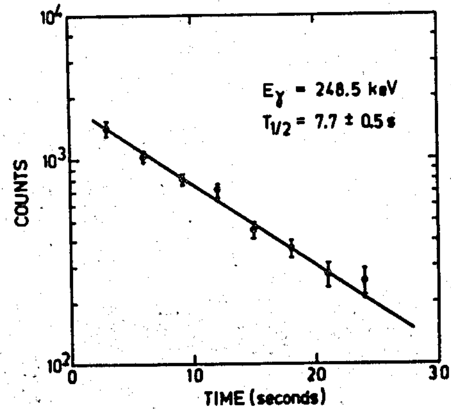

Fig. 8. Decay curve of the isomeric 248.5 keV transition in ^{198}Bi .

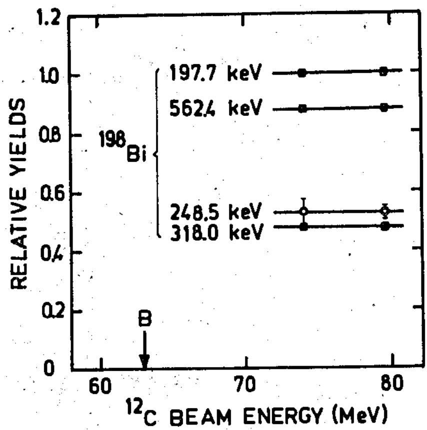

Fig. 9. Relative excitation functions of the reaction ^{191}Ir (^{12}C , $5n$) ^{198}Bi . The target consists of 3.1 mg/cm^2 ^{198}Ir (enriched to 88.5%) on 0.8 mg/cm^2 Al backing.

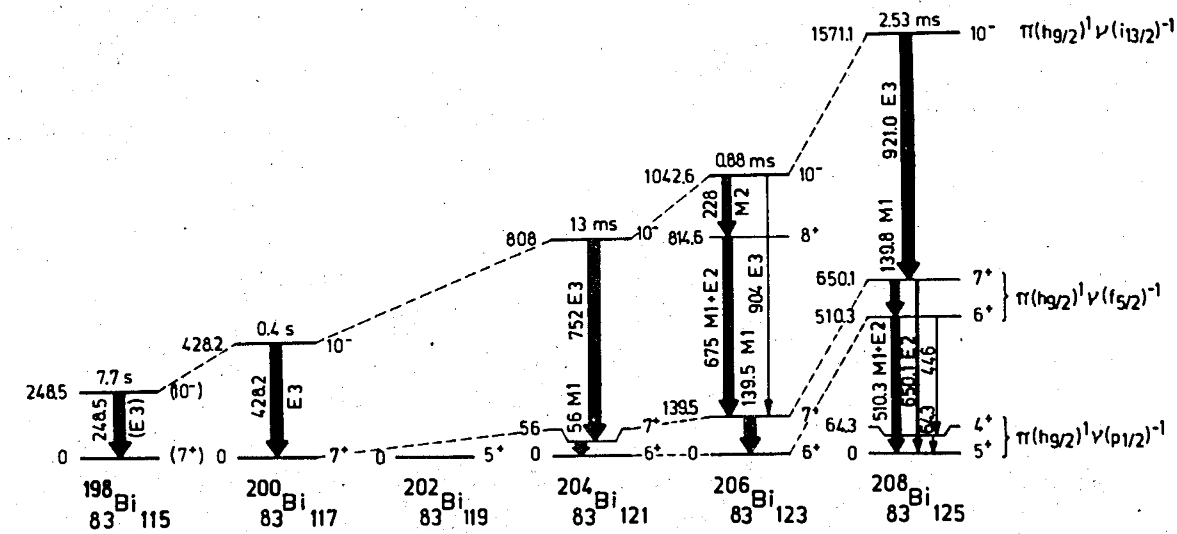

Fig. 10. Decay schemes of the 10^- isomeric states in doubly odd *Bi* nuclei.

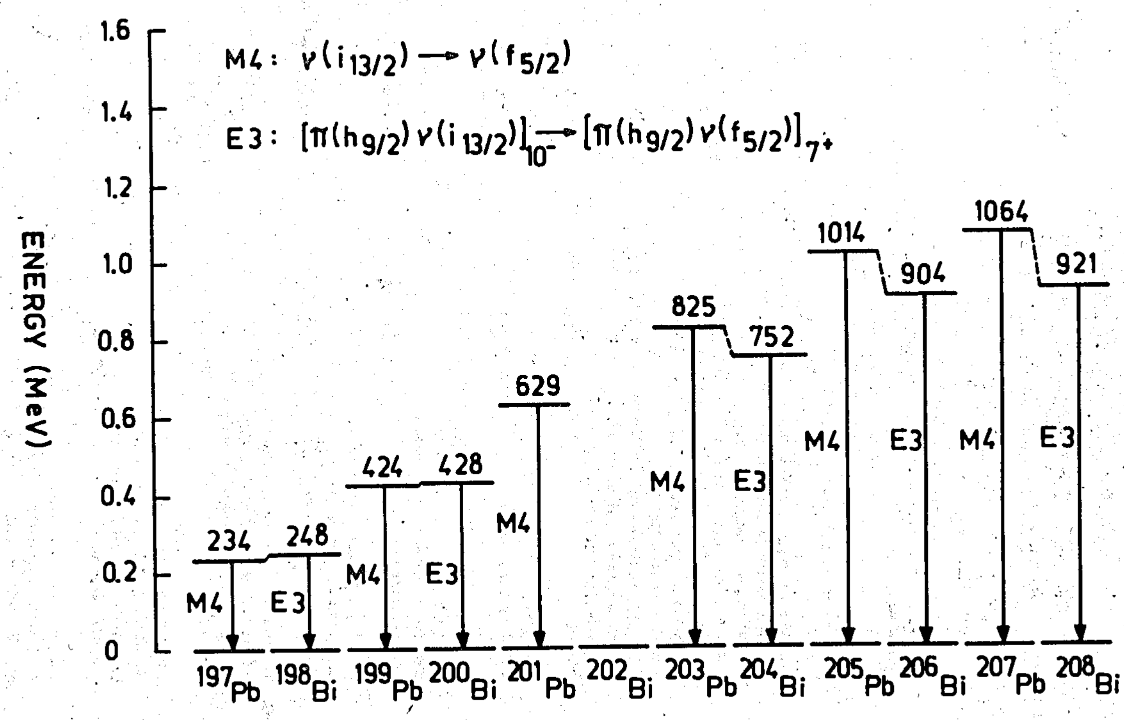

Fig. 11. Comparison of corresponding isomeric transitions in odd *Pb* and doubly odd *Bi* nuclei.