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1. Introduction

The odd-mass bismuth nuclei with one $h_{9/2}$ proton outside the closed Z=82 proton shell are of importance from the point of view of the shell model. Excited levels of neutron deficient odd- A bismuth nuclei have been studied in the ground state decay of tho neighbouring polonium nucleides /1/ down to ^{201}Bi, and in the decay of the isomers ^{201m}Po and ^{199m}Po /2/. These investigations have shown the existence of core excited proton hole states $s^{-1}_{1/2}$, $d^{-1}_{3/2}$ and $d^{-1}_{5/2}$. Compound nucleus reactions offer the possibility of exciting high-spin states. In ^{207}Bi a $21/2^+$ isomeric state ($T_{1/2} = 182 \pm 6\,\mu s$) was produced by the ($\alpha$,2n) reaction, the decay scheme of which was interpreted by three-particle configurations /3/. Heavy ion reactions offer the possibility of producing such states also in the more neutron-deficient Bi nuclei, which allows systematic comparisons.

2. Experiments

2.1. Gamma-Ray Spectra

At the external beam of the U-300 heavy-ion cyclotron in-beam measurements of the isomeric γ-decay were performed. The experimental arrangement has been described previously /4/. Enriched targets of ^{191}Ir (98.1%) and ^{193}Ir (88.5% and 94.3%) were irradiated by ^{12}C ions. The targets were produced by sedimentation of metallic powder on aluminium foils of ~ 1 mg/cm^2. With a 25 cm^3 coaxial and a 2 cm^3 planar Ge(Li) detector prompt γ-ray single spectra and delayed γ-ray spectra in the ns-, μs-and ms-range were measured in the energy range 50 keV - 2 MeV. The energy resolution was about 2.5 keV in the lower parts of the spectra. For the ns-time measurements the natural beam bunching of 238 ns period was used /4/.

The μs-time measurements were started after the slowing down time of the 1 ms pulse, which amounts /4/ to about 50 μs. Delayed spectra of 4 x 200 μs were selected by a timing device. The beam pulsing of 1 ms beam-on time and 3 ms beam-off time offered the possibility also to look for ms-delayed lines.

Figure 1 shows a summed prompt spectrum obtained by bombardment of ^{191}Ir with ^{12}C ions of 73 and 78 MeV. The corresponding prompt and delayed spectra obtained with ^{193}Ir are shown in fig. 2. Energies and intensities of the newly found γ-ray transitions have been determined using the computer program GAMMA /5/ and are summarized in table 1 together with the Po-decay data /2/. For the ^{191}Ir bombardment the energy calibration was performed with the γ-ray lines of 511.006 ± 0.002; 129.4 ± 0.1 (C.E., ref. 6); 562.4 ± 0.1 and 1063.49 ± 0.24 keV (^{198}Pb, ref. 7) and for the ^{193}Ir bombardment with the γ-ray lines 511.006 ± 0.002; 138.89 ± 0.01, 218.8 ± 0.2 (C.E., ref. 8); 245.15 ± 0.13; 419.77 ± 0.13; 462.34 ± 0.13 and 1026.49 ± 0.17 keV (^{198}Pb, ref. 7). In order to determine the half-life of the γ-ray transitions, summarized in table 1, two-dimensional energy-time measurements were performed. Figure 3 shows the results of the ns-time measurement of the long-lived γ-ray transitions of ^{201m}Bi. Within the period of the ^{12}C beam bunching no remarkable decay was observed, i.e., the half-life may be estimated as $T_{1/2} > 2\mu s$. On the other hand, for the 617.1 keV transition a half-life of $T_{1/2} \sim 70$ ns was obtained (fig. 4). Similar results were obtained for the long-lived γ-ray transitions of ^{199m}Bi, namely $T_{1/2} > 2\mu s$. The doublet lines of 494.2 and 499.8 keV show quite different decay characteristics, as can be seen in fig. 5. From the decomposition of both lines the decay curve of the 494.2 keV γ-ray transition, shown in fig. 4, was obtained, from which a half-life value of $T_{1/2} \sim 25$ ns follows. The μs-time measurements showed that the long-lived γ-ray transitions were absent already in the second $200\mu s$-time window. From the minimum detectable intensities of the strongest γ-ray lines an upper half-life limit of $T_{1/2} \leq 50 \mu s$ could be estimated for both isomers.

2.2. Excitation Functions

In order to ascribe the observed delayed γ-ray transitions to a certain product nucleus, the excitation functions, shown in figs. 6 and 7, have been measured. The energy variation was performed by degrading Al foils, whose stopping power was taken from the tables of Northcliffe and Schilling /10/. The absolute cross section values were obtained by normalization of γ-ray intensities to the Coulomb-excited transitions of 343.7 keV in ^{191}Ir and 357.8 keV in ^{193}Ir. The values $B(E2, 3/2^{+} \to 7/2^{+}) = 0{,}54 e^{2} fm^{4}$ (^{191}Ir) and $0.473\ e^{2} fm^{4}$ (^{193}Ir) as well as the branching ratios $(7/2^{+} \to 3/2^{+})/(7/2^{+} \to 5/2^{+})$, which were used for the calculation /11/ of the theoretical cross sections, were taken from ref. /12/. In comparison with the γ-ray transitions in ^{198}Bi and ^{200}Bi, excited by the (^{12}C,5n) reactions /9/, the excitation functions of the newly observed delayed transitions indicate the (^{12}C,4n) reaction. The excitation function maxima are shifted with respect to the locations, expected from the (HI, xn) reaction systematics /13/, and marked in figs. 6 and 7 by hatched fields. The calculations were based on the expression

$$(E_{exc}^{peak} - \sum_{i=1}^{x} B_{in})/x = (9.98 - 2.4A/100)\ \text{MeV},$$

where B_{in} is the neutron binding energy, A is the compound nucleus mass number, x is the number of evaporated neutrons. Apart from big fluctuations of the experimental points underlying the above interpolation formula, the uncertainty of the primary ion energy and the vicinity of the Coulomb barrier (marked by B in fig. 7) may cause the observed deviations. In order to illustrate the Coulomb barrier effect, the calculated curve of the cross section for compound nucleus formation /14/ is drawn in fig. 7. The unshifted excitation function of the 272 keV transition (dashed line) was obtained from this curve.

A further argument indicating the correct assignment follows from the observation [2] of a part of the delayed transitions in the EC–β^+ decay of the $13/2^+$ isomeric states in ^{199}Po and ^{201}Po. The excitation functions of the ns-delayed transitions of 494.2 and 617.1 keV coincide with those of the other delayed transitions. We, therefore, assume that they belong to the second isomeric states, ^{199m_2}Bi and ^{201m_2}Bi, respectively.

3. Decay Scheme

The nearly equal intensities of the four long-lived γ-ray transitions (table 1) and the fact, that no cross-over transitions have been observed, lead to the assumption of stretched cascade de-excitations of both isomers. Under the assumption of equal multipolarities, the rising intensities in the prompt spectra and the spectra of the Po-decay [2] suggest the level schemes shown in fig. 8. The relative excitation functions listed in fig. 9 suggest a rising spin sequence. From the decay of the ^{201m}Po isomer the 967.1, 412.0 and 272.0 keV transitions were found to be of M1 character [2]. With less reliability the ^{199m}Po decay data [2] suggest M1 multipolarity also for the 1002.5 and 499.8 keV transitions in ^{199}Bi. For both nuclei the ground state spin value 9/2 has been measured [15] in agreement with the shell model configuration $h_{9/2}$ of the last proton, which suggests negative parity. The above mentioned arguments lead to the spin and parity assignments given in fig. 8. A comparison of the measured intensity balance of the 185.5 keV and the 272.0 keV transitions of ^{201m}Bi with the theoretical conversion coefficient [16] indicates an M1 multipolarity (with a possible E2 admixture) also for the 185.5 keV transition and $I^\pi = 17/2^-$ for the 1836.6 keV level. In order to explain the estimated half-life values we are forced to assume that the ^{201m}Bi isomeric state de-excites by as yet undetected low-energy transition, which is probably also the case in ^{199m}Bi.

4. Discussion

In fig. 10 the positions of the 2^+ and 4^+ states of the adjacent even lead isotones [17] are compared with the positions of the hitherto known odd bismuth states. The ^{207}Bi levels were taken from Bergström et al. [3]. For ^{199}Bi the rather speculative supposition of $I^\pi = 15/2^-$ and $17/2^-$ was made for the 1776.9 and 1922.5 keV levels, respectively. Disregarding some energy shifts the $11/2^-$ Bi -levels follow the trend of the 2^+ Pb-levels, whereas the $13/2^-$, $15/2^-$ and $17/2^-$ Bi -levels are related to the 4^+ Pb-states. It may be concluded that the $11/2^-$ levels belong to the $2^+ \otimes h_{9/2}$ configuration, whereas the $13/2^-$, $15/2^-$ and $17/2^-$ levels are members of the $4^+ \otimes h_{9/2}$ multiplet. The calculations for ^{207}Bi showed [3] that the $13/2^-$ state mainly contains the $2^+ \otimes h_{9/2}$ configuration.

A coupling of the $1/2^+$ proton hole state to the 5^-, 7^- or 9^- two-neutron hole states of the lead core seems improbable because those multiplets should not be expected below 3 MeV. The $21/2^+$ isomeric state at 2101.5 keV in ^{207}Bi is formed by coupling of the $h_{9/2}$ proton to the 7^- two-neutron hole state of ^{206}Pb. The isomeric states in ^{199}Bi and ^{201}Bi might be formed by coupling of the $h_{9/2}$ proton to the 5^-, 7^- or 9^- states, which were observed in the lighter even lead nucleides [17].

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Table 1

Energies and relative intensities of delayed γ-ray transitions, obtained from the $^{191,193}Ir(^{12}C,4n)^{199,201}Bi$ reactions and from the $^{199m,201m}Po$ decay /2/.

Nucleus	E_γ (keV)	I_γ (prompt)	I_γ (Po-decay)
	145.6 ± 0.2	76 ± 3	-
	274.6 ± 0.2	86 ± 6	10 ± 2
^{199m}Bi	494.2 ± 0.5	50 ± 8	-
	499.8 ± 0.3	86 ± 9	25 ± 2
	1002.5 ± 1.0	100 ± 12	100
	185.5 ± 0.2	55 ± 6	-
	272.0 ± 0.2	68 ± 5	7 ± 1
^{201m}Bi	412.0 ± 0.2	81 ± 10	27 ± 2
	617.1 ± 0.4	58 ± 9	-
	967.1 ± 0.4	100 ± 10	100

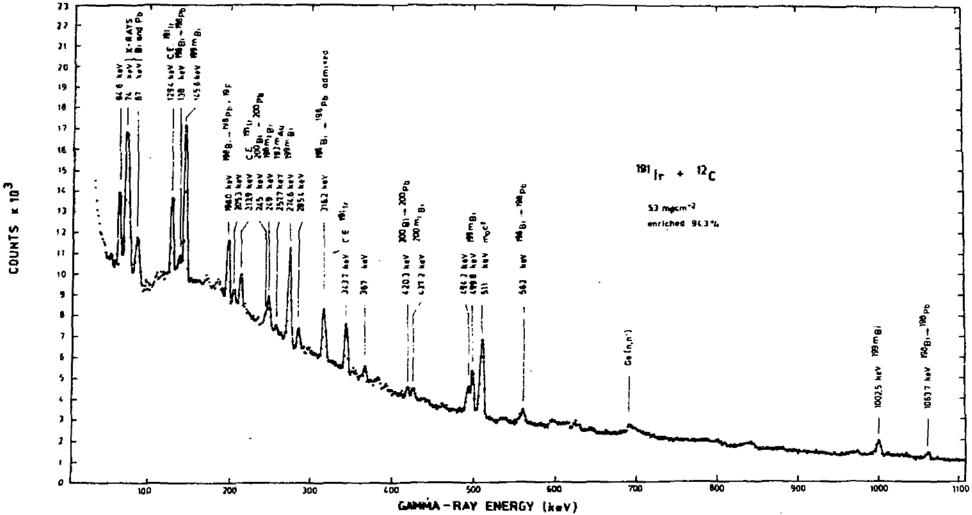
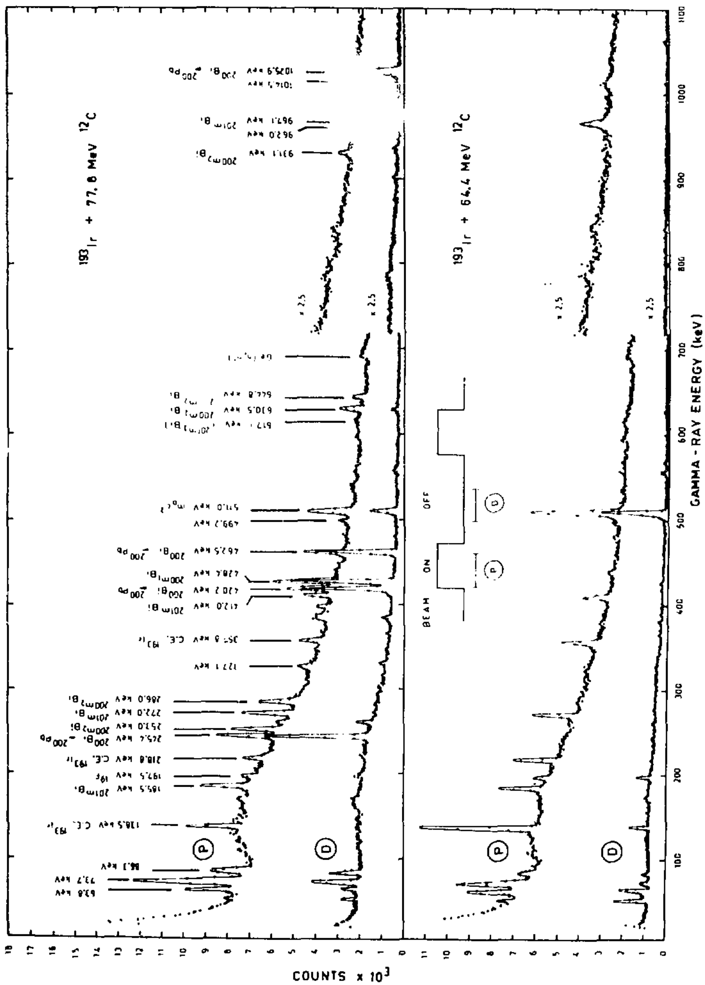


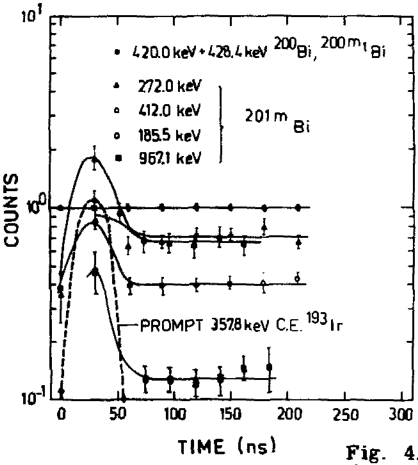
Fig. 1. Prompt γ -ray spectrum of the reaction $^{191}Ir + ^{12}C$, measured during the 1 ms beam pulse.

Fig. 2. Gamma-ray spectra of the reaction $^{193}Ir + ^{12}C$, each measured for 1 ms, during (upper curves) and between (lower curves) beam pulses.



193Ir + 77.8 MeV 12C
193Ir + 64.4 MeV 12C
BEAM ON OFF
GAMMA - RAY ENERGY (keV)
COUNTS x 10^3

Fig. 3. Nanosecond time spectra of the long-lived γ-ray transitions of ^{201m}Bi, compared with the behaviour of the total intensity of the 420/428 keV group of the ground-state and isomeric decay /9/ of ^{200}Bi.



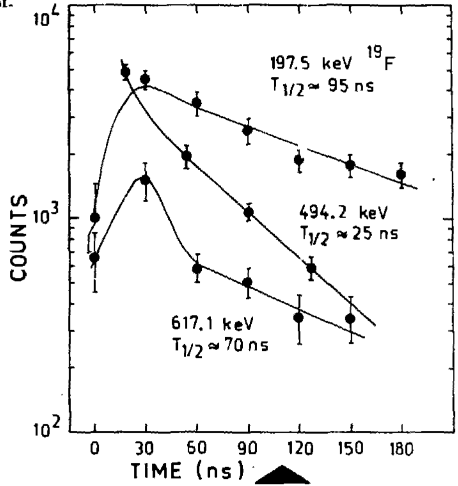
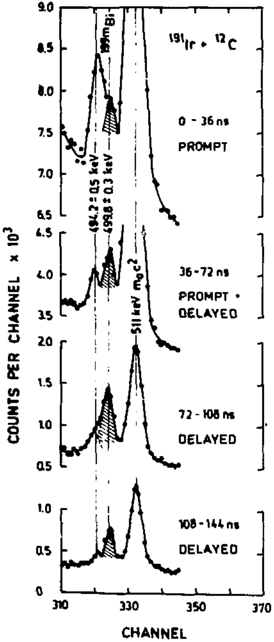
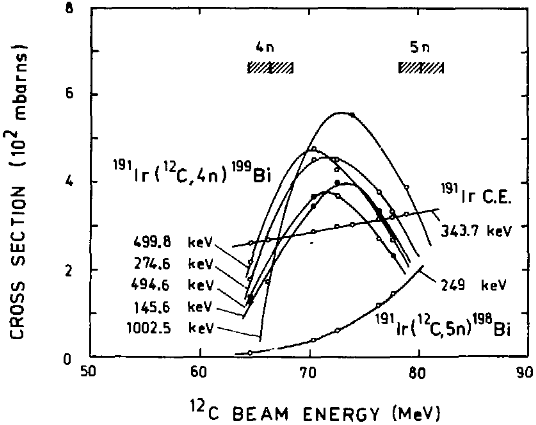


Fig. 4. Decay curves of the short-lived γ-ray transitions 494.2 keV ($^{199m_2}Bi$) and 617.1 keV ($^{201m_2}Bi$). For comparison the decay curve of the 197.5 keV transition (^{19}F) is also drawn.

Fig. 5. Part of the energy-time spectrum for the reaction ^{191}Ir + ^{12}C.

Fig. 6. Excitation functions of the reaction ^{191}Ir+ ^{12}C, normalized to the Coulomb-excited 343.7 keV transition in ^{191}Ir.





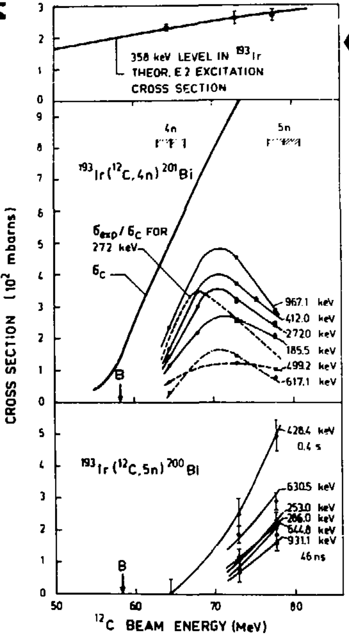


Fig. 7. Excitation functions of the reaction $^{193}Ir + {}^{12}C$, normalized to the Coulomb-excited 357.8 keV transition in ^{193}Ir.

Fig. 8. Proposed level schemes of ^{199}Bi and ^{201}Bi.

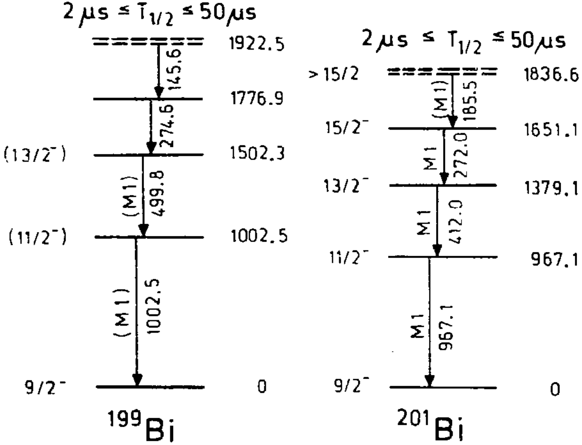
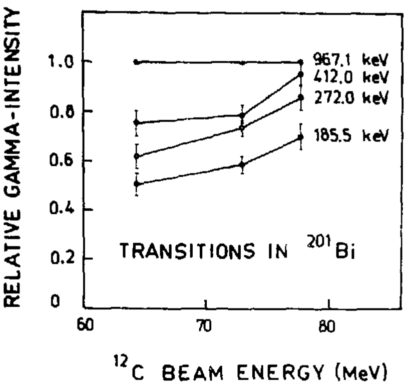


Fig. 9. Relative excitation functions of the long-lived ^{201m}Bi transitions, normalized to the 967.1 keV transition.



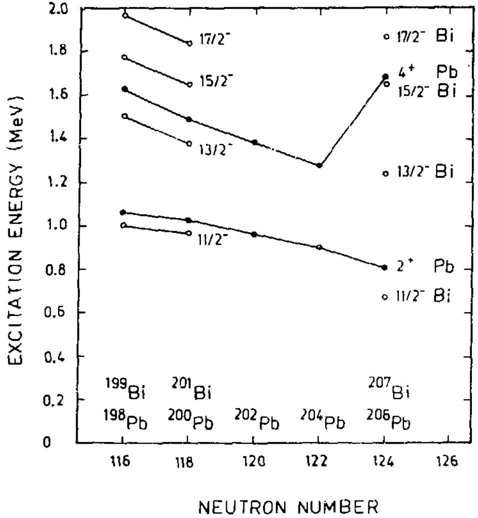


Fig. 10. Comparison of the odd bismuth high-spin states with the 2^+ and 4_1^+ levels of the neighbouring even lead isotones.