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EXCITATION OF ISOMERIC ACTIVITIES IN Rb, Y, Pd, Cd, W, OS AND Pb USING 14.8 MeV NEUTRONS

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Activation cross-sections of ^{84m}Rb, ^{86m}Rb, ^{89m}Y, ^{107m}Pd, ^{109m}Pd, ^{111m}Cd, ^{185m}W, ^{190m}Os and ^{203}Pb for 14.8 MeV neutrons were measured using Ge(Li) and NaI(Tl) detectors. The following values (in millibarns) were obtained: ^{85}Rb$(n,2n)$ ^{84m}Rb(20.5 min) 412 ± 40; ^{87}Rb$(n,2n)$ ^{86m}Rb (1 min) 432 ± 45; ^{89}Y$(n, n'\gamma)$ ^{89m}Y (16.5 s) 438 ± 44; ^{107}Pd$(n, 2n)$ ^{107m}Pd (21 s) 590 ± 60; ^{110}Pd$(n, 2n)$ ^{109m}Pd(4.8 min) 554 ± 55; ^{112}Cd$(n, 2n)$ ^{111m}Cd (48 min) 812 ± 80; ^{111}Cd$(n, n'\gamma)$ ^{111m}Cd (48 min) 167 ± 17; ^{186}W $(n,22n)^{185m}$ (1.7 min) 1152 ± 110; ^{190}Os$(n, n'\gamma)$ ^{190m}Os (10 min) 15 ± 1.5; ^{204}Pb$(n, 2n)$ ^{203m}Pb (6.1 s) 1020 ± 100.

Experimental results for isomeric ratios in $(n, 2n)$ reaction were compared with statistical theory predictions.

1. *Introduction*

As a part of our continuing interest [1-4] in the determination of cross-section for excitation of short-lived isomeric states in the odd and doubly odd mass nuclei between nickel and tin, the isomers of ^{84m}Rb, ^{86m}Rb and ^{89m}Y as well as E-3 isomers of ^{107m}Pd, ^{109m}Pd and ^{111m}Cd were excited in $(n, 2n)$ and $(n, n'\gamma)$ reactions using 14.8 MeV neutrons. Recent years have seen increasing development of level structure studies in the transition regions between deformed and spherical nuclei. Short-lived isomeric states of ^{185m}W, ^{190m}Os and ^{203m}Pb from this region were also investigated in the present work. Measurements of cross-sections for excitation of these isomers number but a few. Although the cross-section for some isomers have been studied previously, the discrepancy between the results obtained by various investigators is significant and it was felt that an independent measurement using newer data on the decay properties of the isomeric states would be worthwhile.

The results of the measurements in this study were used for an estimation of the spins of some isomeric states based on statistical theory computations of the $(n, 2n)$ reaction.

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2. *Experimental procedure*

The cross-section measurements were carried out by the activation method as described in Refs [3, 4]. Only additional details particular of the present measurements are given below. The 14.8 MeV neutrons were produced by bombarding a thick tritium target with a 200 keV deuteron beam. Neutron intensities were monitored by counting alfa particles from the $T(d, n)^4$He reaction. A solid state detector was used. The detector was placed at 170° with respect to the direction of the deuteron beam. The neutron intensity was kept constant up to $\pm 1\%$ during short irradiations.

Natural spectrally-pure mixtures of isotopes of Rb, Y, Pd, Cd, W, Os and Pb, and an enriched sample of ^{112}Cd were irradiated with 14.8 MeV neutrons. The absolute intensity of gamma rays in all samples were determined by following the decay of the photopeaks with an 8 cm^3 Ge(Li) and 1.5″×1″ NaI(Tl) spectrometers connected with a 400-channel pulse-height analyser. The activities sutdied were unambigously indentified in all the cases according to half-lives and gamma-ray energies. During neutron irradiations the samples (surrounded by cadmium sheet) placed in a plexiglass container were precisely positioned in front of the tritium target. A fast-rabbit system (transit time 800 msec) between the neutron generator and gamma spectrometer was used to measure short-lived activities.

3. *Results and discussion*

The cross-section formula which is useful in calculations has been presented in our earlier work [4]. Table I summarizes the cross-sections obtained in the present work together with the values of half-lives, gamma energies and conversion coefficients used in calculations. The experimental errors indicated for the cross-sections include the uncertainty in the counting efficiency, peak-to-total ratios, statistics and geometry, sample weight and neutron flux. The literature values for the half-lives were used in the cross-section determination as it was assumed that these were more accurate than our observed values. The threshold energies

TABLE I

Cross-sections for $(n, 2n)$ and $(n, n'\gamma)$ reactions with 14.8 MeV neutrons from the present work

Target, reaction and isomeric nucleus	Half-life	E_γ keV	Total conversion coefficient α_r	Measured cross-section (mb)
^{85}Rb $(n, 2n)$ ^{84m}Rb	20.5 min	464	0.1	412±40
^{87}Rb $(n, 2n)$ ^{86m}Rb	61.2 sec	556	0.0184	432±45
^{89}Y $(n, n'\gamma)$ ^{89m}Y	16.5 sec	915	0.01	438±44
^{108}Pd $(n, 2n)$ ^{107m} Pd	21 sec	216	0.54	590±60
^{110}Pd $(n, 2n)$ ^{109m}Pd	4.8 min	188	0.72	554±55
^{112}Cd $(n, 2n)$ ^{111m}Cd	48 min	147	2.32	812±80
^{111}Cd $(n, n'\gamma)$ ^{111m}Cd	48 min	147	2.32	167±17
^{186}W $(n, 2n)$ ^{185m}W	1.7 min	131	19.5	1152±110
^{190}Os $(n, n'\gamma)$ ^{190m}Os	10 min	187	0.43	15±1.5
^{204}Pb $(n\ 2n)$ ^{203m}Pb	6.1 sec	825	0.22	1020±100

required for the $(n, 2n)$ reactions in the investigated nuclei are in excess of 3 MeV neutrons carried off by the d–D reaction. When a tritium target is used more and more of these neutrons are generated. This is because the tritium in the target is replaced with deuterium.

In the case of ^{111m}Cd and ^{190m}Os the isomeric state could also be produced with 3 MeV neutrons from a d–D self-formed source in the titanium layer. The effect of 3 MeV neutrons was minimized by using a new tritium target. Experiments showed that the 3 MeV neutron flux at sample position was about 10^{-3} of that of the 14 MeV flux. Some comments about the nuclei considered are given below.

^{84m}Rb and ^{86m}Rb

The following activities are produced by irradiating natural Rb with 14.8 MeV neutrons: ^{86m}Rb with a half-life of 1.04 min and ^{84m}Rb with a 20.5 min half-life.

Fig. 1 shows a typical example of an observed gamma-ray spectrum taken with Ge(Li) and NaI(Tl) spectrometers.

The ^{84m}Rb spectrum includes the 464 keV gamma-ray peak corresponding to the transition of ^{84}Rb to the ground state and the parallel cascade of the 216 and 248 keV gamma-rays; the ^{86m}Rb spectrum includes only a 556 keV transition of ^{86}Rb to the ground state (see Fig. 1). The half-life and energy of the isomeric transition in ^{86m}Rb were remeasured in order to have a check of the assignment of isomeric activity. Excellent agreement was obtained with the result of Ref. [5]. On the basis of the life-time, gamma-transition energy and conversion coefficients a spin 6^- was assigned in this work to the isomeric state in ^{86}Rb. The experimental values compared with theoretical ones indicate that the 556 keV isomeric gamma-transition is $E4$, but $M3$ is also not excluded. A spin estimate of isomeric states based on statistical model calculations described in our previous works [1, 2] indicates we should apply a similar technique to ^{86m}Rb. In order to check our procedure, the known spin value in ^{84m}Rb was estimated using the weighted mean experimental value of the cross-section for the ^{85}Rb $(n, 2n)$ ^{84}Rb reaction [7–12]. The decay scheme of ^{84}Rb [6] is shown in Fig. 1. The spectroscopic data [13] establish the ground state as 2^-, the first excited state as 3^+ and the second (isomeric) state as 6^+. There would thus be an $M3$, $E1$ cascade parallel to the $M4$ transition. As is seen from Fig. 2 the statistical model estimate and the spectroscopic data give the same value for the spin of isomeric state in ^{84m}Rb. The result of the calculations do not distinguish between the two possible parities. The same procedure was applied to ^{86m}Rb taking into account the weighted mean value of the total cross-section for ^{87}Rb$(n, 2n)$ ^{86}Rb from Refs [7–9, 11, 12]. The result of calculations in Fig. 3 suggests the isomeric state to have spin 6 and the scheme in Fig. 1 for ^{86m}Rb. Keeping in mind the risk connected with the application of the statistical approach to the explanation of the individual properties of the nuclei, we will discuss the result obtained here.

The decay of the 18.6d ground state of ^{86}Rb, $\log ft$ values and branching to the ground state and the first excited state of ^{86}Sr as well as atomic beam measurements definitely characterise the ground state spin as 2^- [13]. The 2^- assignment was established also in the (d, p), (d, t) and (n, γ) reaction [14]. Since the ^{86}Rb nucleus contains 37 protons and 49 neutrons, the lowest-lying states should belong to configurations with one neutron hole (in the $1g_{9/2}$ subshell) and nine protons distributed on the $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$ and $1g_{9/2}$ subshells.

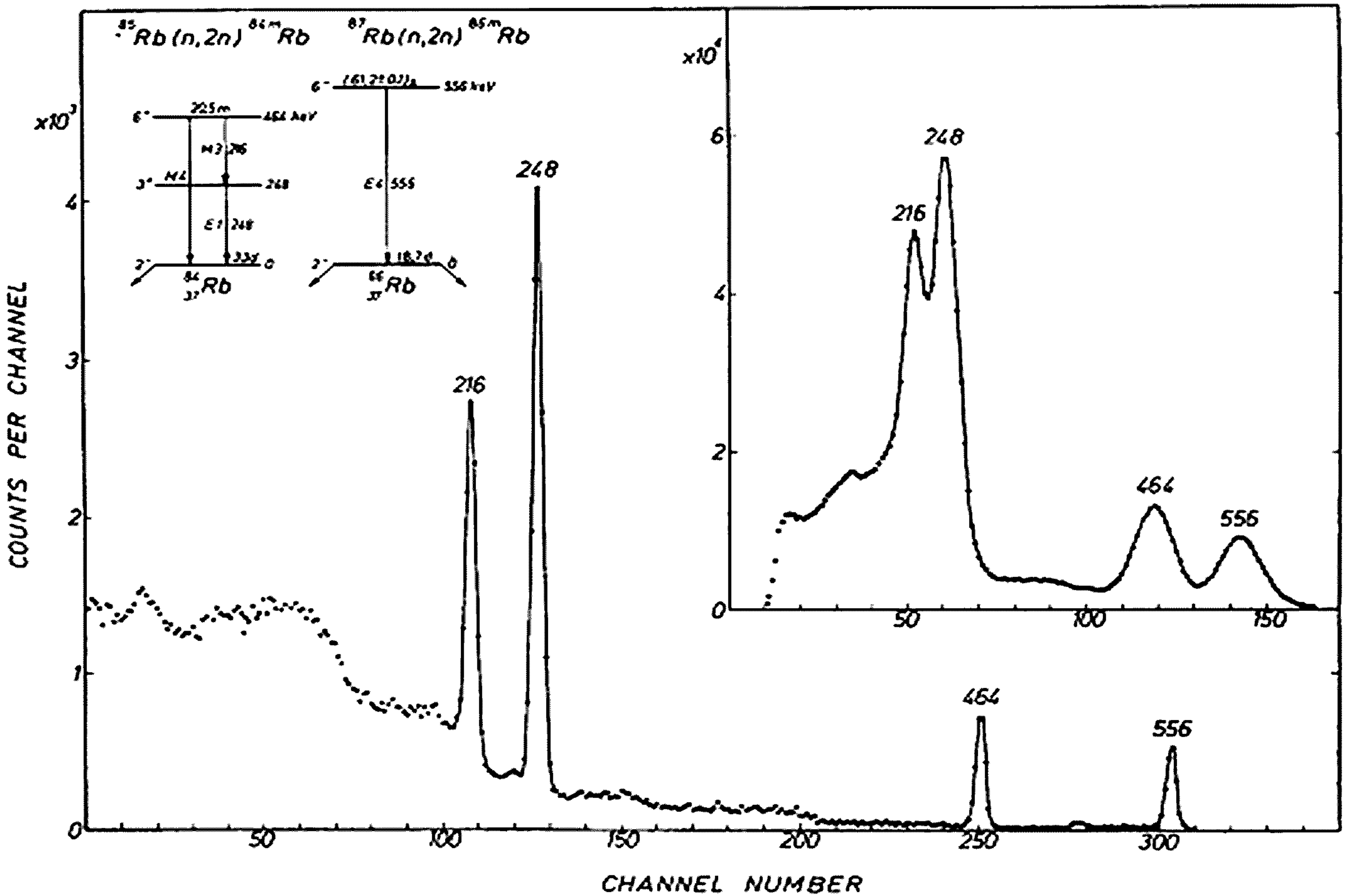

Fig. 1. Gamma-ray spectrum from the decay of ^{84m}Rb and ^{86m}Rb taken with Ge(Li) and NaI(Tl) spectrometers

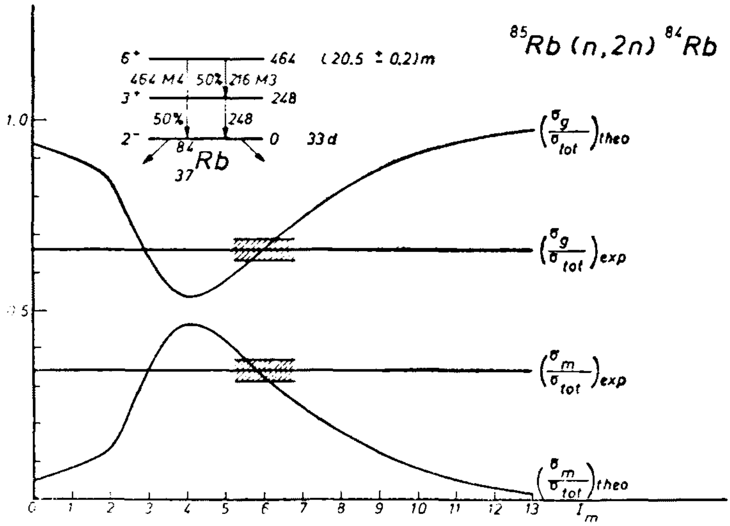

Fig. 2. Isomeric cross-section ratios for ^{84}Rb *versus* spin value of ^{84m}Rb. The solid lines are the results of calculations using Gilbert and Cameron level density formulas [23]

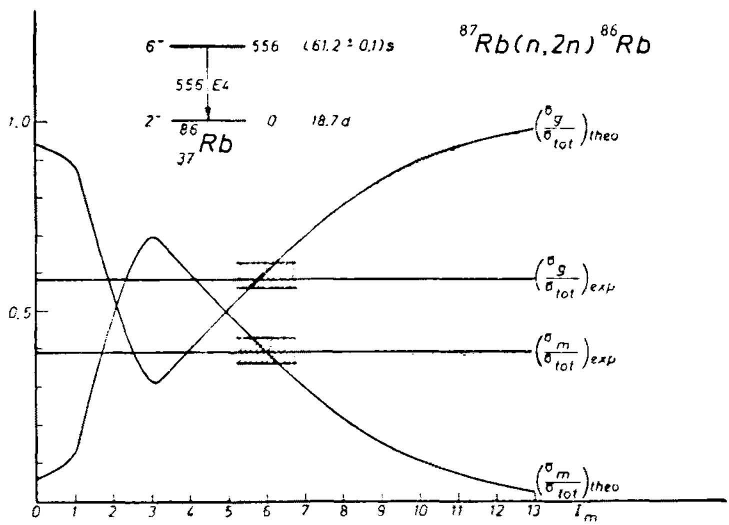

Fig. 3. Isomeric cross-section ratios for ^{86}Rb *versus* spin value of ^{86m}Rb. The solid lines are the results of calculations using Gilbert and Cameron level density formulas [23]

A simple proton configuration which yields the observed spin $I = 3/2^-$ for ^{87}Rb placed three of them in the $2p_{3/2}$ and the remaining six in the $1f_{5/2}$ subshells. Assuming that the same proton configuration exists in ^{86}Rb, the observed spin $I = 2^-$ can arise from the coupling of an odd $g_{9/2}$ neutron with an odd $p_{5/2}$ proton hole. This is in agreement with the strong--coupling rule given in [15, 16] which predicts $I = 9/2 - 5/2 = 2$. The spin 6^- of the isomeric state is formed by coupling a $p_{3/2}$ proton and a $g_{9/2}$ neutron according to Nordhein's weak rule $I = 9/2 + 3/2 = 6$.

^{89m}Y

Three activities with half-lives 390μs, 14 ms and 16 sec were observed in pulsed irradiations of yttrium with 14.8 MeV neutrons, and they have been identified as belonging to ^{88m1}Y, ^{88m2}Y and ^{89m}Y, in accordance with the results of earlier publications. Marked discrepancies are observed between the published experimental values of the cross-sections for

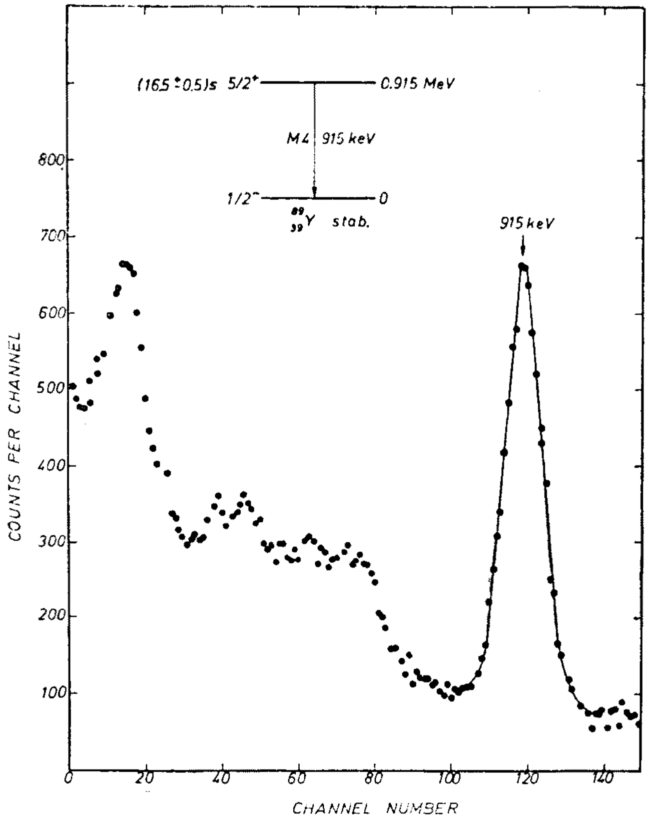

Fig. 4. Gamma-ray spectrum from the decay of ^{89m}Y taken with NaI(Tl) spectrometer

excitation of isomeric activities in Y [17]. Because ^{89m}Y has a 16 sec isomer it can be measured in cyclic and shuttle rabbit techniques. We measured the cross-section for the population of the ^{89m}Y and referred to it the cross-sections for excitation of isomers ^{88m1}Y and ^{88m2}Y [18]. Gamma radiation of an energy of 915 keV (Fig. 4), with the half-life of 16 sec, is used as an internal monitor reaction.

^{107m}Pd, ^{109m}Pd and ^{111m}Cd

^{107m}Pd, ^{109m}Pd and ^{111m}Cd nuclides were known to possess short-lived $E3$ isomers with high spin (11/2⁻). The values of cross-sections for production of ^{107m}Pd (21 s) from ^{108}Pd *via* the $(n, 2n)$ reaction and ^{109m}Pd (4.8 min) from ^{110}Pd *via* the $(n, 2n)$ reaction were determined by measuring the 216 and 188 keV transitions, respectively (Fig. 5).

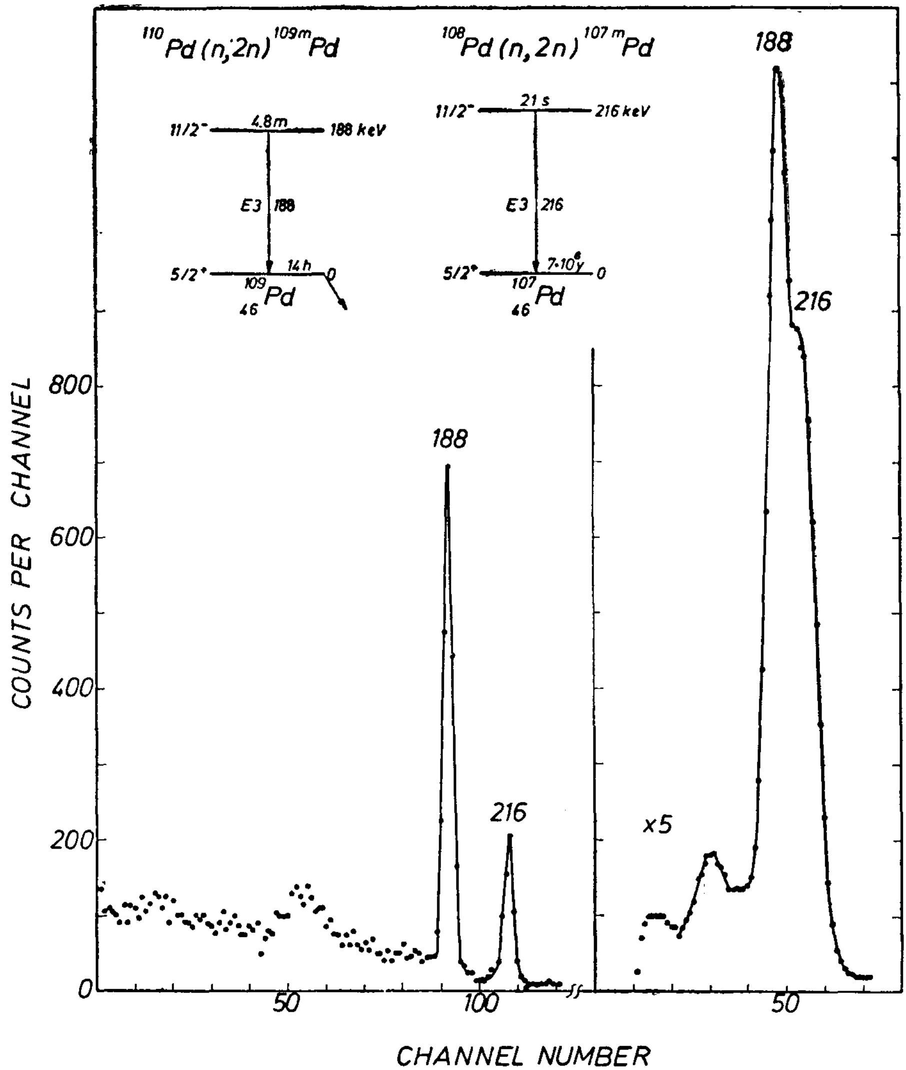

Fig. 5. Gamma-ray spectrum from the decay of ^{107m}Pd and ^{109m}Pd taken with Ge(Li) and NaI(Tl) spectrometers

The excitation of ^{111m}Cd isomeric level ($T_{1/2} = 48$ min) is expected in inelastic scattering of neutrons on ^{111}Cd as well as in the ^{112}Cd$(n, 2n)$ ^{111m}Cd reaction. ^{111m}Cd lies 396 keV above the ground state and decays *via* a two step gamma-ray cascade (see Fig. 6). Discs of natural and enriched Cd were irradiated and their activity measured. By comparing the ^{111m}Cd activity produced in the case of a natural sample with that of an enriched ^{112}Cd sample it was possible to determine both $(n, n'\gamma)$ and $(n, 2n)$ cross-sections.

^{185m}W

The level scheme of 1.7 min ^{185m}W has recently been well established [19–21]. The purpose of our work was to determine the cross-section for excitation of the isomeric state in

^{185m}W *via* the $(n, 2n)$ reaction on ^{186}W at a 14.8 MeV neutron energy using recent spectroscopic data. Earlier measurements of this cross-section were performed with a scintillation spectrometer and an inaccurate level scheme. We have performed gamma-ray measurements of ^{185m}W using both Ge(Li) and NaI(Tl) detectors (Fig. 7). The value of the cross-section for the production of ^{185m}W was determined from the 131.5 keV transition taking into account transition intensity branching and the total internal conversion coefficient α_T from [19]. The σ_g cross-section can be evaluated by subtracting the experimental σ_m value from the total cross-section. To our knowledge Druzhinin *et al.* [22] determined the ^{186}W $(n, 2n)$ ^{185}W reaction cross-section at 14.8 MeV neutrons and obtained a value of 2300 ± 200 mb.

The isomeric ratio should yield information about the spin cut-off parameter which characterizes the spin dependence of the nuclear level density (Cameron's model [23] in our case). Some experimental results [4] for the deformed nuclei seem to suggest a different value of spin cut-off parameter than predicted by the Cameron model. There has been in-

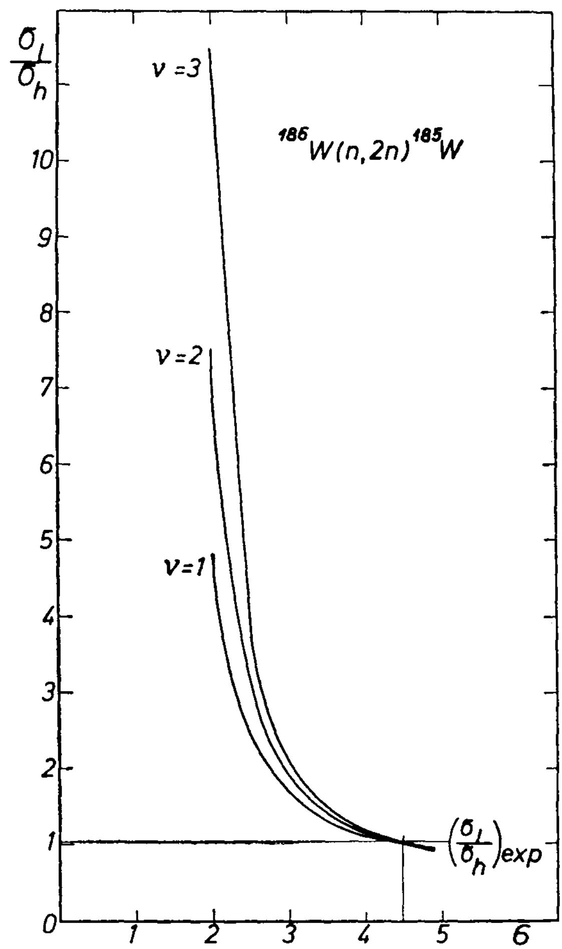

Fig. 8. Comparison of measured isomeric cross-section ratios with theoretical curves plotted in terms of the spin cut-off parameter σ and the multiplicity ν of gamma-rays in the cascade

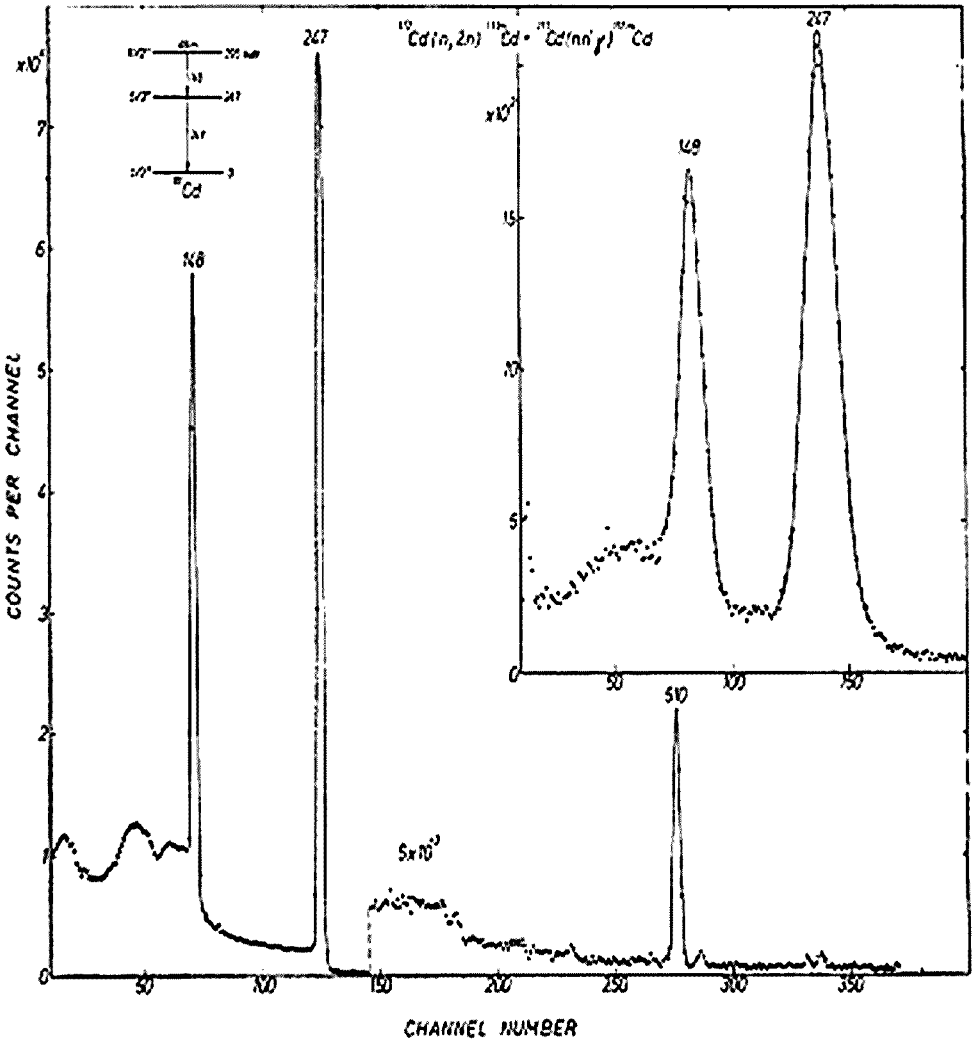

Fig. 6. Gamma-ray spectrum from the decay of ^{111m}Cd taken with Ge(Li) and NaI(Tl) spectrometers

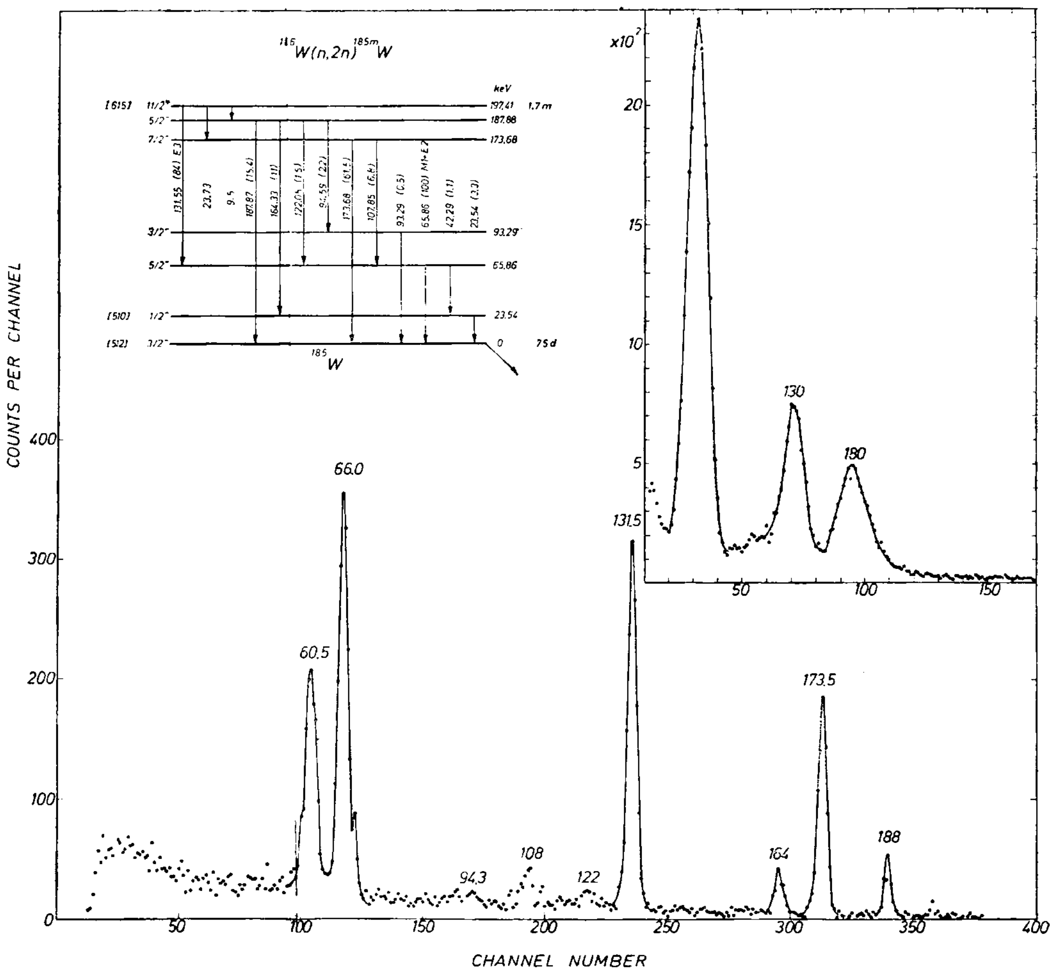

Fig. 7. Gamma-ray spectrum from the decay of ^{185m}W taken with Ge(Li) and NaI(Tl) spectrometer

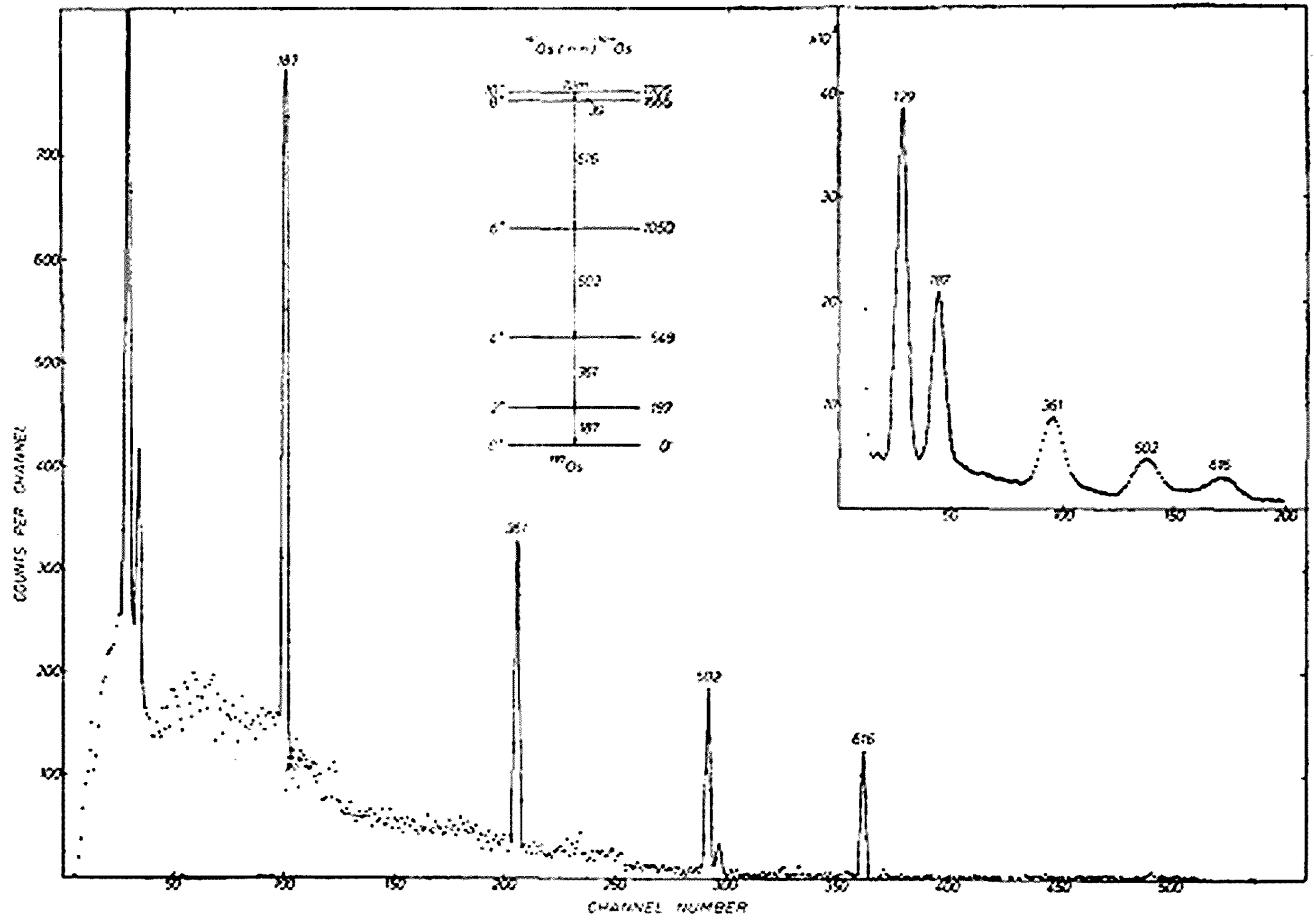

Fig. 9. Gamma-ray spectrum from the decay of ^{190m}Os taken with Ge(Li) and NaI(Tl) spectrometers

terest aroused in this nucleus because W lies in the transition region between deformed and spherical nuclei. The isomeric ratio was calculated for different spin cut-off parameters and different numbers ν of gamma-rays emitted in the deexcitation cascade. The spin cut-off parameter was considered energy independent. The results of calculations are given in Fig. 8. The isomeric ratios are defined as the ratio of the cross-section σ_l of the reaction leaving the

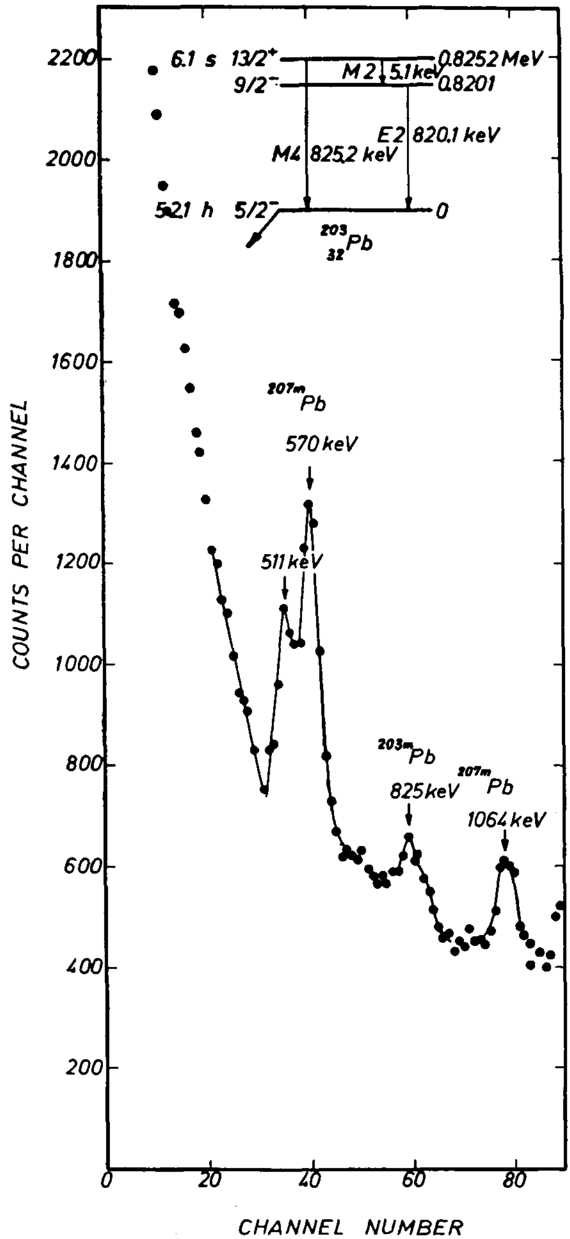

Fig. 10. Gamma-ray spectrum from the decay of ^{203m}Pb taken with NaI(Tl) spectrometer

residual nucleus in a state with lower spin I_l and the cross-section σ_h of the reaction producing the residual nucleus in a state with higher spin I_h. Assuming spin $I = 3/2$ for the ground state and spin $I = 11/2$ for the isomeric state, and comparing the experimental and theoretical isomeric ratios, a mean value of the spin cut-off parameter can be evaluated, namely, $\sigma=4.5$. This value is lower than the calculated one ($\sigma = 4.9$) obtained from the formula given in Ref. [23].

^{190m}Os

To our knowledge there have been no reports on the 14 MeV neutron cross-section for excitation of the 10 min isomeric level in ^{190}Os until now. The purpose for these measurements was to furnish more cross-section data in this important region of A. We were able to confirm the existence of the 10 min activity from the $(n, n'\gamma)$ reaction on ^{190}Os using 14.8 MeV neutrons. The 10^- state in ^{190}Os lies 1705 keV above the ground state and decays *via* a five step gamma-ray cascade. A typical example of the gamma-ray spectrum of ^{190m}Os recorded with the Ge(Li) and NaI(Tl) spectrometers is show in Fig. 9.
The 187 keV transition was used to determine the amount of ^{190m}Os produced. The internal conversion coefficient of this transition has been reported to be $\alpha_T = 0.43$ [24].

^{203m}Pb

The decay of the 6.1 sec isomer of ^{203}Pb has been the subject of a number of investigations, but new spectroscopic data were recently obtained which modify the results. Doebler *et al.* [25] found that the radiation of ^{203m}Pb includes a 825.2 keV gamma-ray ($M4$, 92%) corresponding to the transition to the ground state of ^{203}Pb and a parallel transition of two cascading gamma-rays of energies 5.1 keV ($M2$, 8%) and 820.1 keV ($E2$). The isomeric level in ^{203}Pb was excited in the reaction ^{204}Pb $(n, 2n)$ ^{203m}Pb using 14.8 MeV neutrons.

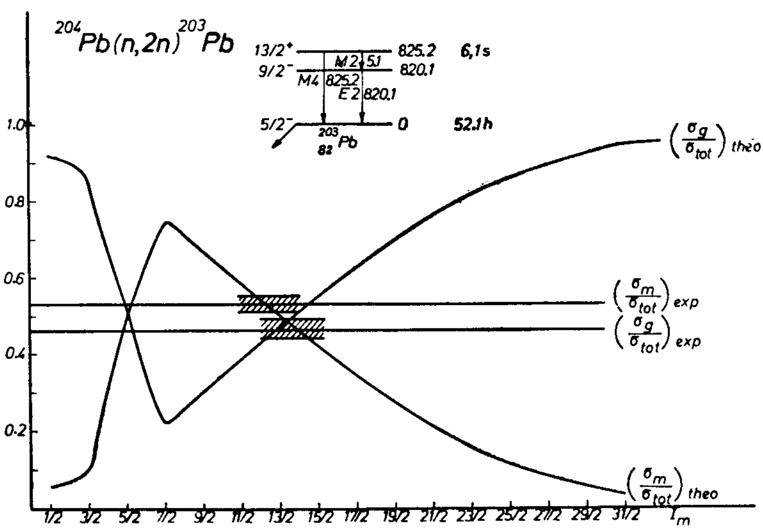

Fig. 11. Isomeric cross-section ratios for ^{203}Pb *versus* spin value of ^{203m}Pb. The solid lines are the results of calculations using Gilbert and Cameron level density formulas [23]

Since the abundance of ^{204}Pb is only 1.48%, the detected activity is relatively low. The γ spectra were taken with the NaI(Tl) spectrometer (Fig. 10).

The spin value of ^{203m}Pb was also estimated (Fig. 11) using experimental values of total cross-sections for the ^{204}Pb $(n, 2n)$ ^{203}Pb reaction taken from Refs [26, 27]. As can be seen from Fig. 11, we obtained good agreement with the known spectroscopic data.

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