SPIN DEPENDENCE OF DENSITY OF RESONANCE LEVELS

K. G. IGNAT'EV, I. V. KIRPICHNIKOV, and S. I. SUKHORUCHKIN

Institute for Theoretical and Experimental Physics

Submitted to JETP editor April 12, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) 45, 875-881 (October, 1963)

The spin dependence of the density of resonance levels has been investigated. The relative number of resonances with a given spin J (J = 0 or 1) is in agreement with the law $N_J \sim (2J + 1)$.

THE capture of a neutron by a nucleus gives a state with an excitation energy of order 6 MeV. Resonances are observed in the neutron cross section; each is characterized by a number of parameters which contain physical information about the nature of the highly excited nuclear states. This information can be gotten after one eliminates the fluctuations which are natural to a complex quantum mechanical system, i.e., after one averages all quantities. Since for most nuclei neutrons can excite two systems of resonances with spins $J = I_0 \pm 1/2$ (for s neutrons and a target nucleus with spin I_0), finding the average values for these two systems is of interest for comparison with theory. In the present work we have determined the density of neutron levels as a function of J (more precisely, the frequency of occurrence of levels with spin 0 and 1 in even-even excited nuclei). The apparatus used in the experiments has been described earlier.[1-3]

Several years ago, Sailor concluded that the number of levels with J = 0 is anomalously small. One could assume that there is a statistical law for the level frequency of the type $N_J \sim (2J + 1)^2$, (where N_J is the number of levels), which follows from thermodynamic considerations.[4]

Recently several methods have been developed for determining spins of levels. The direct method of determining the level spin by measuring the scattering is not suitable for resonances with small neutron width Γ_n. The indirect methods—measurement of radiative transitions to the ground state, measurement of γ correlations (cf. Appendix 1), and interference between resonances, are free of this defect. Of these the first two are supplementary to one another, since one is good for finding spins J = 1, the other for J = 0. Both are based on the property of even-even nuclei that their first excited states have the spins and parities 0^+, 2^+, 4^+. The radiative transitions $0 \to 0^+$ and $0 \to 2^+$ are improbable, and the presence of a transition to the ground state thus indicates J = 1. From a level with J = 0, we should get intense two-step cascades $0 \to 1 \to 0$ and $0 \to 1 \to 2$, which give strong anisotropy of the γ quanta. Thus, in the first cascade there are twice as many coincidences at 180° as at 90°. The anisotropy in the cascades $1 \to 1$, $2 \to 0$, 2 has the opposite sign. Finally, the third method for determining the spin is based on the fact that interference can occur only between levels with the same spin, so that from the presence (or absence) of interference in the partial cross sections for fission and radiative capture we can draw conclusions about the spins of the levels. For example, from the absence of interference in the partial cross section for radiative capture between the first two resonances of Hf, it was concluded that these levels had different spins,[3] and this was confirmed by direct measurements.[5] Thus, if one of a group of close-lying levels has a known spin, interference can be used to determine the spins of the others.

We have made use of all four methods for determining spins of levels. The results are shown in the table.

Seventeen resonances in various isotopes were studied, and the resonances were taken in turn, i.e., there were no other resonances between them and thermal. The scattering, i.e., the factor g, was measured only for the first levels of Pt^{195} (cf. Appendix 3), since there were contradictory values of the spin of the 19.6-eV level;[8,9] the data from all the methods give J = 1. For the W^{183} resonances at E = 7.6, 27, and 103 eV we found spins J of 1, 1, and 0, in agreement with [9]. The spins of the last nine levels listed were obtained from analysis of the measurement of ν_{eff} and the total cross section of Pu^{239}, [2] and partially were taken from a paper of Fraser and Schwartz.[6] From the table (col. 7) we see that

Parameters of neutron resonances

Target nucleus	Parity	E_0, eV		Ground-state transition	$\frac{180°}{90°}$ *****	Spin
1	2	3	4	5	6	7
Cd^{111}	+	28			0.92	1 *
Xe^{129}	+	9.4			0.93	1 *
W^{183}	—	7.6		yes****	1.03	1
		27		yes	1.03	1
		103			1.29	0 *
Pt^{195}	—	11.9	3/4	yes	0.89	1
		19.6	3/4	yes	1.02	1
		67		yes	0.82	1
Pu^{239}	+	0.3				0 **
		7.9	3/4 [6]			1
		11.0	3/4 [6]			1
		11.9	3/4 [6]			1
		14.3				1 ***
		14.7	1/4 [6]			0
		15.5				1***
		17.6	3/4 [6]			1
		22.2	3/4 [6]			0

*Spin determined from anisotropy of emission of γ rays. Isotropic emission corresponds to N(180)/N(90) = 1.0.
**Spin determined from absence of interference with the negative level with which the 7.9-eV level interferes. A similar conclusion was reached in [7].
***Spin determined from interference with the 17.5-eV level and absence of interference with the 14.7-eV level.
****Indicates presence of γ transition from the neutron level to the ground state. (Cf. Appendix 2.)
*****The errors are ~ 8%.

the ratio of the numbers of resonances with spin 0 and 1 is 4 : 13, which is close to the ratio 1 : 3, i.e., to the law $N_J \sim 2J + 1$. If we find the analogous quantity from [9] for Cd^{113}, W^{183}, Pt^{195} and Hg^{199}, we get 3 : 15 (not counting the values given in the table), and all together we have $N_0 : N_1 = 7 : 28$. If we treat separately the levels 0^+ and 1^+ and 0^- and 1^-, we get the respective ratios 4 : 14 and 3 : 14. We see that a relation of the type $N_J \sim 2J + 1$ holds if we consider a large number of levels of different nuclei with spin J equal to 0 or 1.

We must express our gratitude to A. P. Soldatov, N. M. Kozodaeva, A. P. Kharitonov and V. V. Pavlov, who participated in this work.

APPENDIX 1

Measurement of Correlations of Cascade γ Quanta

The angular correlation measurements were made using the neutron spectrometer at the pulsed beam of the cyclotron of the Institute. The sample to be studied (diameter 120 mm) was placed at the end of the 8.5 meter flight path. Scintillation counters with NaI(Tl) crystals (diameter 140 mm, height 80 mm) recorded coincidences of γ rays at angles of 180 and 90° (Fig. 1). The pulses from the photomultipliers were added, and we recorded cases of double coincidences when the amplitude of the sum pulse was above a threshold set at ~ 2 MeV below the binding energy of the particular nucleus. The pulses from the coincidence circuit were fed to a 256-channel time analyzer.[1]

We thus obtained the energy dependence of the two-step cascade after neutron capture for angles of 180 and 90°. The areas under the resonance peaks were compared. A numerical correction was also made for the finite solid angle subtended by the crystal. For example, the computed value of the ratio of the number of γ-ray pairs at 180° to the number at 90° is 1.6 instead of 2.0. To reduce the effect of inhomogeneity of the neutron flux incident on the sample, one of the counters was made movable, and measurements were made for two positions of this counter (Fig. 1). The results of the measurements are shown in the table (col. 6).

To test the assumption that in Cd^{112}, Xe^{130} and Xe^{132} there are intense transitions from the upper excited states, measurements of γ-ray spectra from neutron resonances of these nuclei were made using a counter with a small crystal (d = 30 mm, h = 40 mm). Such a counter has a quite simple line shape for medium energy γ rays (4—9 MeV), corresponding to interaction of the γ quanta in the crystal with pair production and subsequent emergence of the annihilation quanta. The pulses from the counter were analyzed according to pulse height and time in a 2048-channel automatic three-dimensional analyzer with an electrostatic tube memory.[10] The analyzer was connected with 32 time selectors having 64 channels each; each selector time-analyzed pulses of a definite amplitude. With a channel width of 1 μsec, the time resolution was 0.25 μsec/m. The energy (pulse height) scale

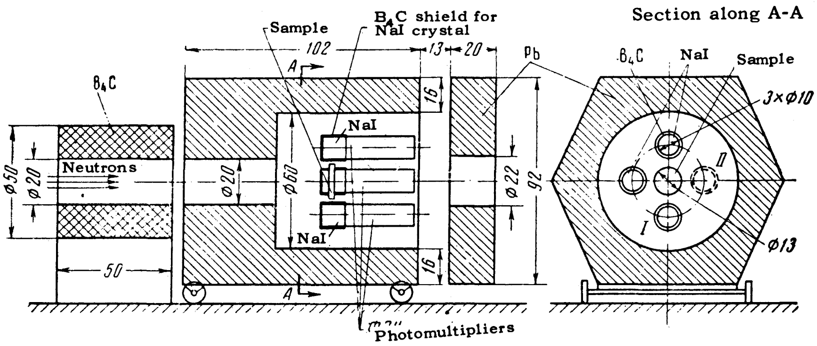

FIG. 1. Arrangement of apparatus for measuring γ-ray correlations (dimensions in cm). I,II are two positions of the movable photomultiplier with NaI.

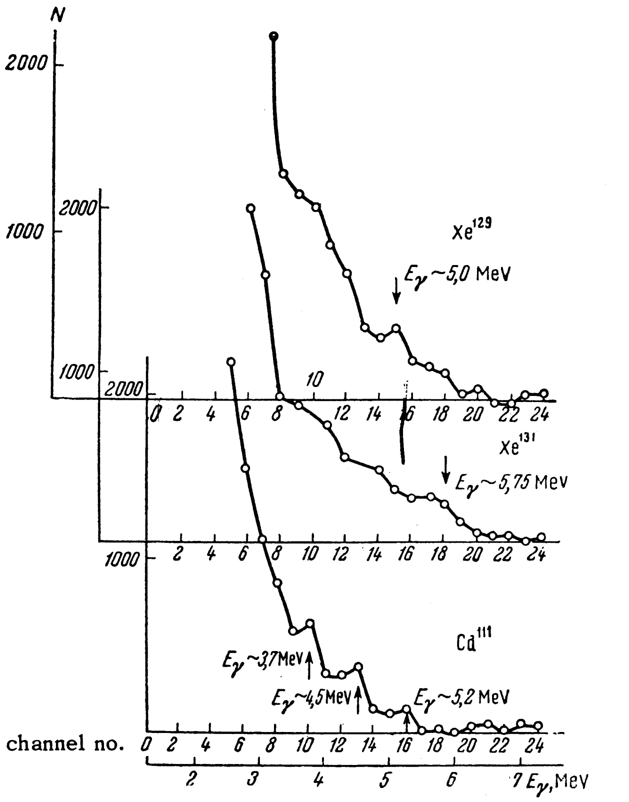

FIG. 2. Gamma-ray spectra from resonance levels of Cd^{111}, Xe^{131} and Xe^{129}.

of the analyzer was calibrated using γ rays from Co, Cs, and Po sources.

The γ-ray spectra after subtracting the background (the spectrum between resonances) are shown in Fig. 2. The figure also gives some energies of γ-ray lines which might cause irregularities in the spectra. The results may be regarded as a confirmation of the existence of strong transitions from the upper excited state to intermediate levels in these nuclei.

APPENDIX 2

Measurement of Relative Intensities of Main Transitions for Tungsten Resonances

The measurements to be described were made in the summer of 1958 to compare the intensities of the principal transitions for the resonances of W^{183} (and also Pt^{195}) in order to identify the spins of these levels. Basically the assumption was made that complete absence of a transition from the neutron excited state to the ground (0^+) and first excited (2^+) states would indicate spin 0 for the excited state. Using values of the binding energies of nuclei with even and odd numbers of neutrons, one could assume, and this was confirmed by experiment (cf. Fig. 3), that with good

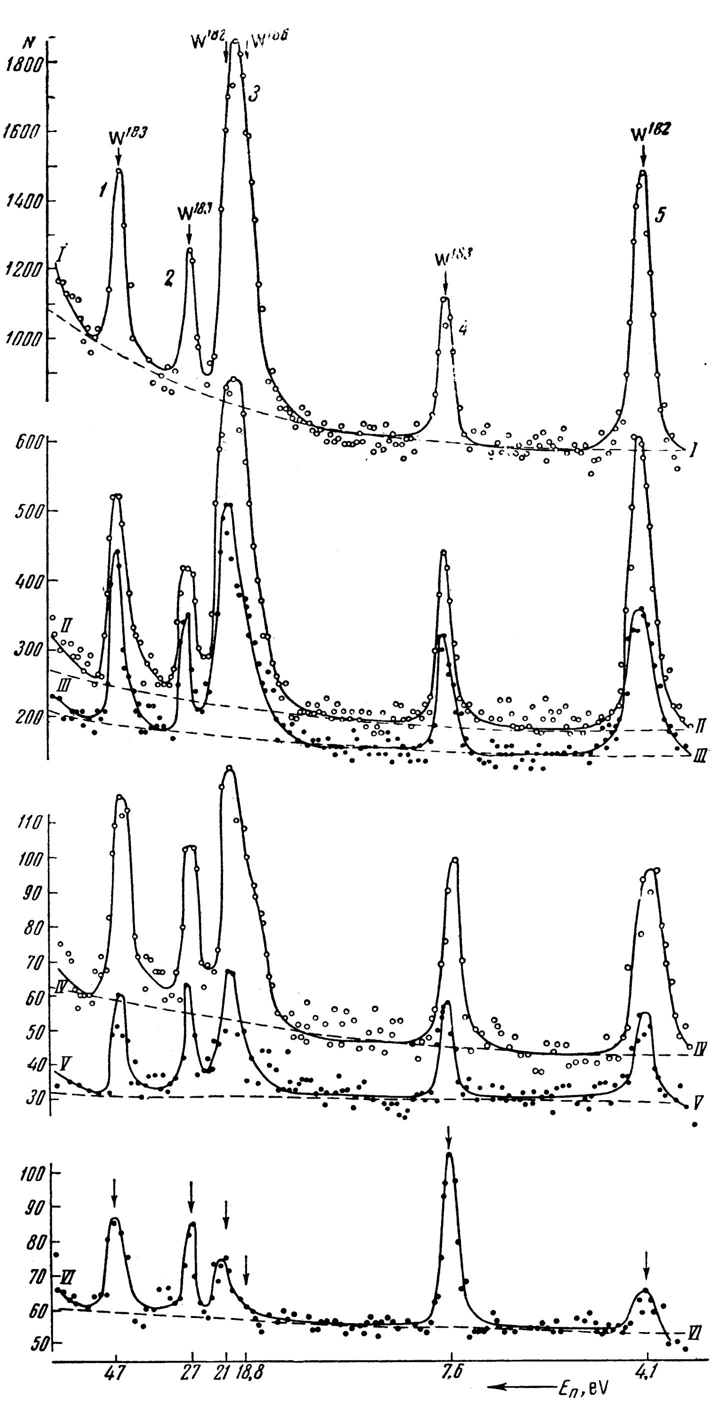

FIG. 3. Yield of γ rays of different energies from neutron levels of W: o – sample 0.6 g/cm², • – sample 1.8 g/cm²; dash line is background. For the areas of the resonances, see the following table.

Spectrum No.	Resonance No.					E, MeV
	1	2	3	4	5	
I	113	74	451	100	191	0.5—1.5
II	116	78	398	100	223	1.5—2.5
III	127	78	359	100	221	0.7—2
IV	127	70	234	100	166	4.5—6.0
V	90	56	176	100	125	4.5—6.0
VI	69	46	62	100	43	>6.0

discrimination there should be an almost complete disappearance of the resonances (in the γ-ray yield) attributable [9] to the isotopes W^{182} and W^{186}. In that case, the presence on the curves at high bias (d > 6 MeV) of resonances in W^{183} (with energies 7.6, 27, and 40 eV) showed that their spin was J = 1. A direct measurement of scattering of neutrons from the 7.6 eV resonance level, done by V. V. Okorokov (cf.[11]) gave J = 0, but our value J = 1 is also in better agreement with the measured γ-ray spectrum for thermal neutrons.[12]

As we see from Fig. 3 (and the table), the intensities of the ground state transitions (relative to the total yield of γ rays) from emission of γ rays from the 7.6- and 27-eV resonance levels differ by almost a factor of two. Analogous results (strong fluctuations of relative strength of ground state transitions) were found for the Pt resonances at E_0 = 11.9, 19.6, and 67 eV.

APPENDIX 3

Measurement of Resonance Scattering from Pt

To get an independent determination of the spins of the Pt levels, in 1960 measurements were made of scattering of neutrons in the range from 8 to 25 eV. The spin of the resonance level at 11.9 eV, according to [9] and also from our present results (γ-ray correlation and intensities of ground state transitions) is equal to unity. A scattering experiment was done to identify the spin of the level at E_0 = 19.6 eV.

The Pt sample was placed at an angle of 45° in a collimated neutron beam. The neutron detector (a ZBS photomultiplier and a scintillator of the alloy $B_{10}H_{14}$ + ZnS(Ag)[13]) was put as close as possible to the sample, outside the direct neutron beam. The background was quite high, (the effect was ~ 50% of background), but because of the resonance character of the scattering (thin sample) the magnitude of the effect could be determined quite accurately.

The sample transmission was measured with the detector in the same position; a scatterer of 5 mm of iron was put in place of the Pt sample, which was moved to a "good geometry" position. The measurements were made for various sample thicknesses: from 0.05 to 0.5 mm. The results for all thicknesses agree within the limits of error and are in accord with a value of unity for the spin of the 19.6 eV level.

The transmission measurements with samples of different thicknesses enabled us to improve the values for the total Γ and radiative Γ_γ widths of the first levels in Pt. For the level at E_0 = 11.9 eV, we found Γ = 109 ± 12 mV, Γ_γ = 99 mV, for the level at E_0 = 19.6 eV we have Γ = 104 ± 12 mV and Γ_γ = 96 mV. The values of the radiative width are constant within the errors of the measurements.

[1] Ignat'ev, Kirpichnikov, and Sukhoruchkin, PTÉ 4, 25 (1959).

[2] Ignat'ev, Kirpichnikov, and Sukhoruchkin, Materials from the Working Conference on Physics of Slow Neutrons, 1961; preprint Joint, Inst. Nuc. Res. No. 956, p. 28.

[3] Ignat'ev, Kirpichnikov and Sukhoruchkin, ibid, p. 62.

[4] L. D. Landau and Ya. A. Smorodinskiĭ, Lectures on Nuclear Theory, Gostekhizdat, 1955, p. 93, translation, Consultants Bureau, 1958.

[5] H. Ceulemans and F. Poortmans, J. phys. radium **22**, 707 (1961).

[6] J. S. Fraser and R. B. Schwartz, Nuclear Phys. 30, 269 (1960).

[7] E. Vogt, Phys. Rev. **118**, 724 (1960).

[8] Galanina, Shvartsman, and Diament, JETP **38**, 1446 (1960), Soviet Phys.-JETP **11**, 1045 (1960).

[9] Hughes, Magurno, and Brussel, Neutron Cross Sections, BNL-325, Suppl. 1, 1960.

[10] Ignat'ev, Kirpichnikov, and Sukhoruchkin, IAEA, Nucl. Electronics, II, Vienna, 1962, p. 215.

[11] Vladimirskiĭ, Kirpichnikov, Panov, and Sukhoruchkin, Second Int. Conf. on Peaceful Uses of Atomic Energy, Reports of Soviet scientists. Glavatom, 1959, p. 504.

[12] Groshev, Demidov, Lutsenko, and Pelekhov, Atlas spektrov γ-lucheĭ radiatsionnogo zakhvata teplovykh neĭtronov (Atlas of γ-ray Spectra from Capture of Thermal Neutrons), Glavatom, 1958.

[13] I. V. Kirpichnikov, IAEA, Nucl. Electronics, I, Vienna, 1962, p. 139.

Translated by M. Hamermesh
153