SPECTRA OF GAMMA RAYS PRODUCED IN THE CAPTURE OF THERMAL NEUTRONS BY HEAVY NUCLEI. I

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The experimental data on the γ spectra from the thermal neutron $(n\gamma)$ reaction are compared with the theoretical spectra calculated for two laws of variation of the level density. The effect of the energy gap in the level spectrum of even-even nuclei on the γ ray spectrum in the 0.8 — 4 Mev region is discussed. The presence of an energy gap leads to a large difference in the spectra of odd-odd and even-even nuclei.

In the last few years we have measured the spectra of gamma rays due to radiation capture of thermal neutrons for a large number of elements. The measurements were conducted with a magnetic Compton spectrometer having a resolution of 2%. The results obtained have been gathered in an atlas published in 1958,[1] and in several subsequent articles.

In the present paper we consider several laws for the gamma spectra of heavy elements (A = 100 — 200), located not too near the magic nuclei. At a resolution of 2%, the principal fraction of the gamma transitions in the spectra of such elements lies in the unresolved part, the form of which is essentially of interest to us. To analyze the general form of the spectrum, measurements with a magnetic Compton spectrometer are quite convenient, since this instrument makes it possible to measure, under identical conditions, almost the entire gamma-ray spectrum from the $(n\gamma)$ reaction, namely in the energy interval from 0.3 to 12 Mev.

The question of the form of the unresolved portion of the gamma spectrum for heavy elements was considered by us earlier in a paper delivered to the Second Geneva Conference on Peaceful Uses of Atomic Energy.[3] In this paper we compared the unresolved portions of the spectrum for heavy nuclei with different parities of the numbers of protons and neutrons and established, in particular, the manifestation of the nucleon pairing effect on the form of the gamma spectrum in its upper portion. The nucleon pairing effect manifests itself in the fact that the upper boundary of the unresolved portion of the spectrum in even-even nuclei lies approximately 1.5 Mev below the binding energy of the neutron in the particular nucleus, whereas in odd-odd nuclei these two quantities practically coincide. This fact illustrates quite clearly the presence of an energy gap near the ground state of even-even nuclei. In this article we consider again the problem of the general form of the spectrum and its dependence on the energy level distribution in heavy nuclei. This is made necessary, on the one hand, by the completion of calculations on the shape of the spectrum, made with the aid of a computer,[4] and on the other hand by the appearance of additional conclusions with respect to the shape of the spectrum of different nuclei at low energies.

To exhibit the singularities of interest to us in the low energy region, it is more convenient to plot the spectrum with the ordinates representing the values of $\nu(E)$ — the number of photons per neutron capture and per unit energy interval in Mev (E — energy of gamma quantum), instead of $\nu(E)H\rho$, as was done in preceding investigations.[3] The absolute values of $\nu(E)$ were usually obtained by normalizing the energy radiated by the nucleus to the neutron binding energy.

Figure 1 shows by way of an example the gamma spectra of the even-even nucleus Gd^{158} and of the odd-odd nucleus Ho^{166}. As can be seen from the diagram, in the case of Gd^{158} separate peaks are separated in the upper and lower regions against the background of the unresolved portion. These peaks correspond to monochromatic lines. An analogous picture is characteristic also of other even-even nuclei. For odd-odd nuclei such peaks are observed only in the upper portion of the spectrum.

In this article we confine ourselves to an examination of gamma spectra only for even-even and odd-odd nuclei with $100 < A < 200$. All the spectra, with the exception of that of gadolinium, are obtained with natural mixtures of isotopes. In the

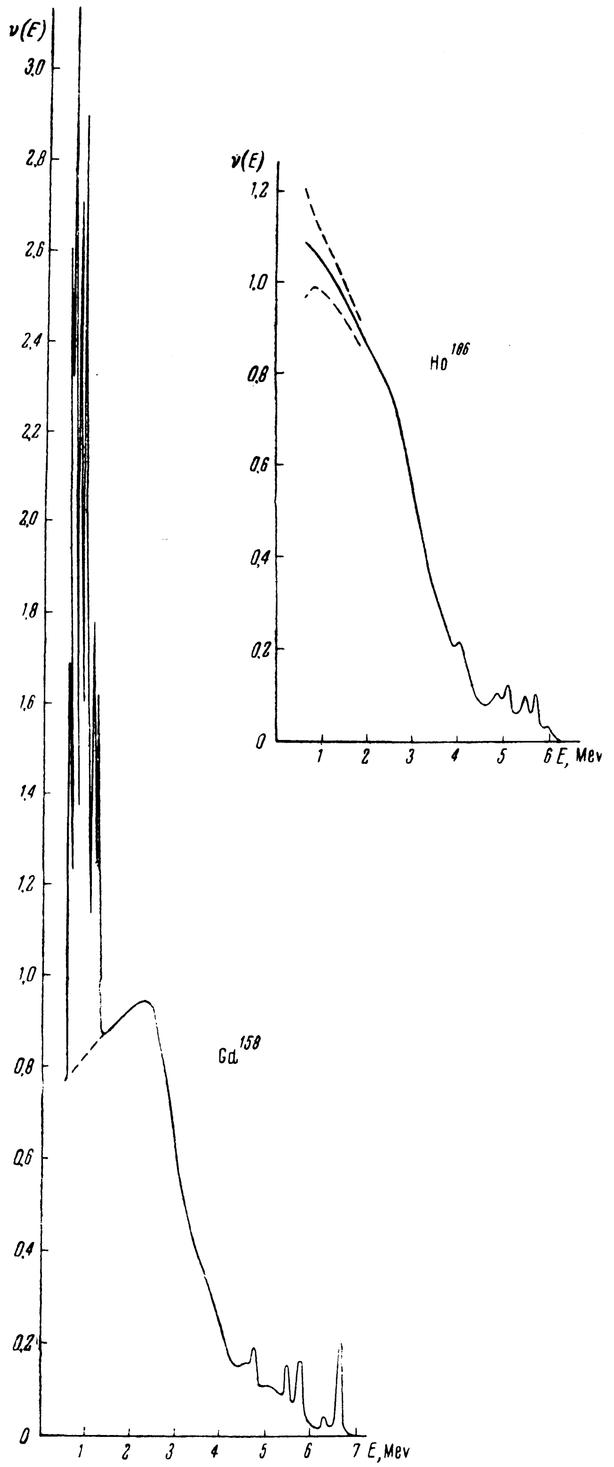

FIG. 1. Gamma ray spectra Gd^{158} and Ho^{166}.

notation given, we shall indicate the isotope (or isotopes) which makes the principal contribution to the investigated spectrum. The atomic weight of the isotope is referred in all cases to the radiating nuclei, produced after neutron capture.

In the case of odd-odd nuclei we have spectra for Rh^{104}, Ag^{108}, Ag^{110}, In^{116}, Sb^{122}, Sb^{124}, La^{140}, Eu^{152}, Ho^{166}, Tm^{170}, Ta^{182}, Re^{186}, Re^{188}, Ir^{192}, Ir^{194}, and Au^{198}. Figure 2a shows spectra for Rh, Ag, In, and Sb, while Fig. 2b shows the spectra for Ho, Tm, Ta, and Ra. The nuclei of the first group have an atomic weight A ~ 110 and are spherical. Those of the second group have A ~ 175 and are all prolate.

In the case of even-even nuclei we have the spectra of Mo^{96}, Cd^{114}, Sn^{116}, Sn^{118}, Sn^{120}, Nd^{144}, Sm^{150}, Gd^{156}, Gd^{158}, Er^{168}, Hf^{178}, Pt^{196}, and Hg^{200}. Figure 2c shows the spectra for the four prolate nuclei Gd^{156}, Gd^{158}, Er^{168}, and Hf^{178}. These spectra have been obtained from those experimentally measured by cutting off the peaks with energies less than 2 Mev. For Gd^{158} (see Fig. 12) such a cut-off is shown dotted. We discarded the lines in the low-energy regions for convenience in comparison of the spectra of different nuclei.

In the curve for Ho^{166} in Fig. 1, and also later in Figs. 7 and 8b, the dotted lines indicate the experimental errors in the measurement of the spectrum. Since the errors increase with decreasing photon energy, all the experimental spectra were plotted for energies ≥ 0.8 Mev.

It is seen from Fig. 2 that, within the limits of each of three groups, the spectra can be represented by an average curve. The average spectra obtained in this manner are shown separately in Fig. 3. It is seen from this diagram that the spectra for the two groups of odd-odd nuclei (curves I and II) do not differ greatly from each other. One should therefore take an average spectrum for all eight odd-odd isotopes, as we have done in the beginning. However, a more detailed analysis shows the presence of one singularity, which repeats in all spectra with A ~ 175, and which is missing in nuclei with A ~ 110. We have in mind here the presence of a small convexity in curve II in the energy region 2 — 3 Mev. Such a difference in the spectra appears also in the theoretical calculations (for more details see reference 4).

Another logical reason for breaking up the spectra of the odd-odd nuclei into two groups is that the binding energy of the neutron, B_n, for nuclei with A ~ 110, is on the average somewhat higher than that for nuclei with A ~ 175, as can be seen from the table.

Nucleus	B_n	Nucleus	B_n
Rh^{104}	6.8	Ho^{166}	6.2
Ag^{108} (30%)	7.27	Tm^{170}	6.6
Ag^{110} (70%)	6.6	Ta^{182}	6.06
In^{116}	6.6	Re^{186} (48%)	6.2
Sb^{122} (66%)	6.8	Re^{188} (52%)	5.94
Sb^{124} (34%)	6.3		
Average	6.7	Average	6.2

The parentheses contain the contribution of the given isotope to the absorption cross section for thermal neutrons.

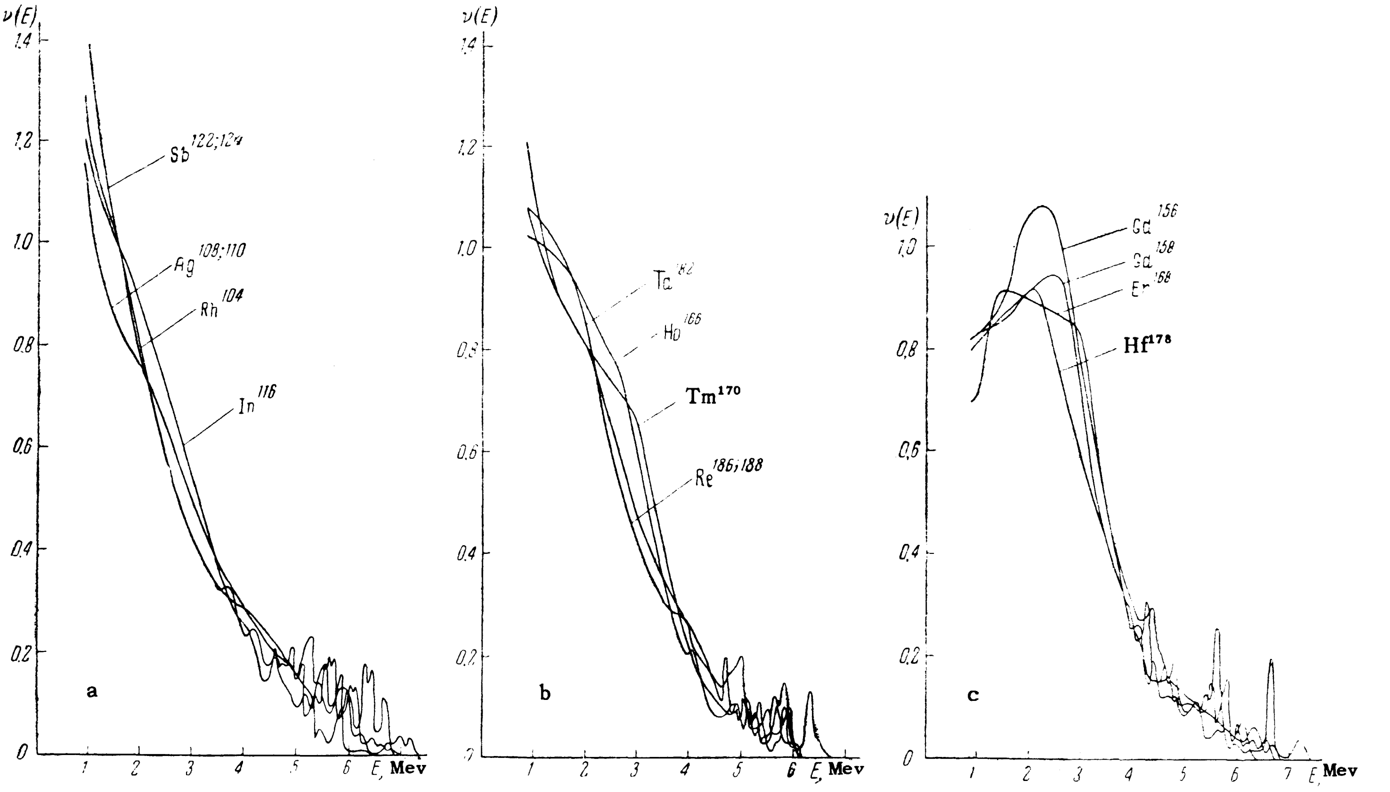

FIG. 2. Experimental gamma-ray spectra: a – odd-odd nuclei with A ~ 110, b – with A ~ 175, c – even-even nonspherical nuclei.

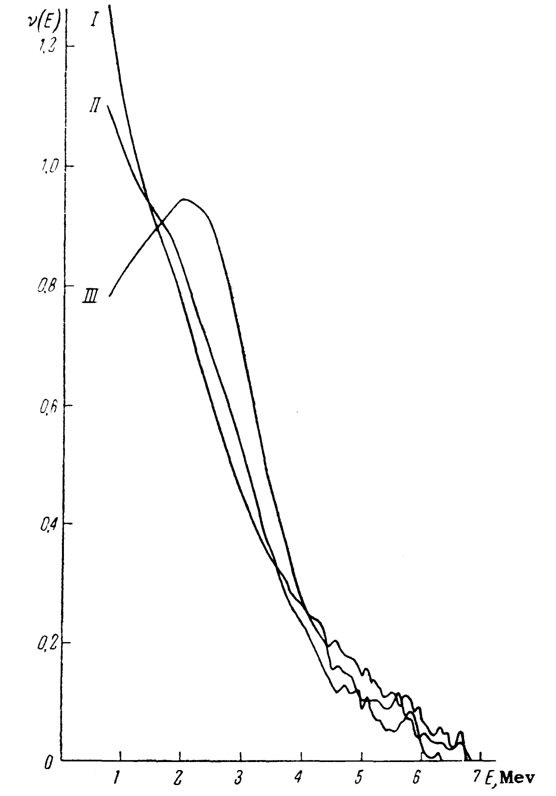

FIG. 3. Average experimental curves: I – for odd-odd nuclei with A ~ 110, II – odd-odd nuclei with A ~ 175, III – even-even non-spherical nuclei.

For the even-even isotopes indicated in Fig. 2c, the binding energy of the neutron is 8.46, 7.87, 7.76, and 7.55 Mev respectively. From the figures given it is seen that as a rule, within the limits of each group of nuclei, the neutron binding energies do not differ greatly. For this reason we have not reduced the spectra to one and the same value of the binding energy.

The average experimental spectra shown in Fig. 3 can be compared with the theoretical calculated spectra (see reference 4). These calculations have been made for a neutron binding energy of 6.4 Mev in odd-odd nuclei and 7.6 Mev in even-even nuclei. The calculations were made for two types of variations of the level density with excitation energy.

$$\rho(u) = \rho_0 \exp \sqrt{au}, \tag{1}$$

$$\rho(u) = \rho_0 \exp(u/\tau) \tag{2}$$

At constant a and τ, and in the case of even-even nuclei, it was assumed that these variations hold starting with a certain energy Δ, the width of the energy gap at the ground state.

For even-even nuclei the principal calculations were made for Δ = 1.2 Mev, which is equal to the difference between the neutron binding energy assumed for even-even and odd-odd nuclei. For this reason, the effective excitation energy for even-

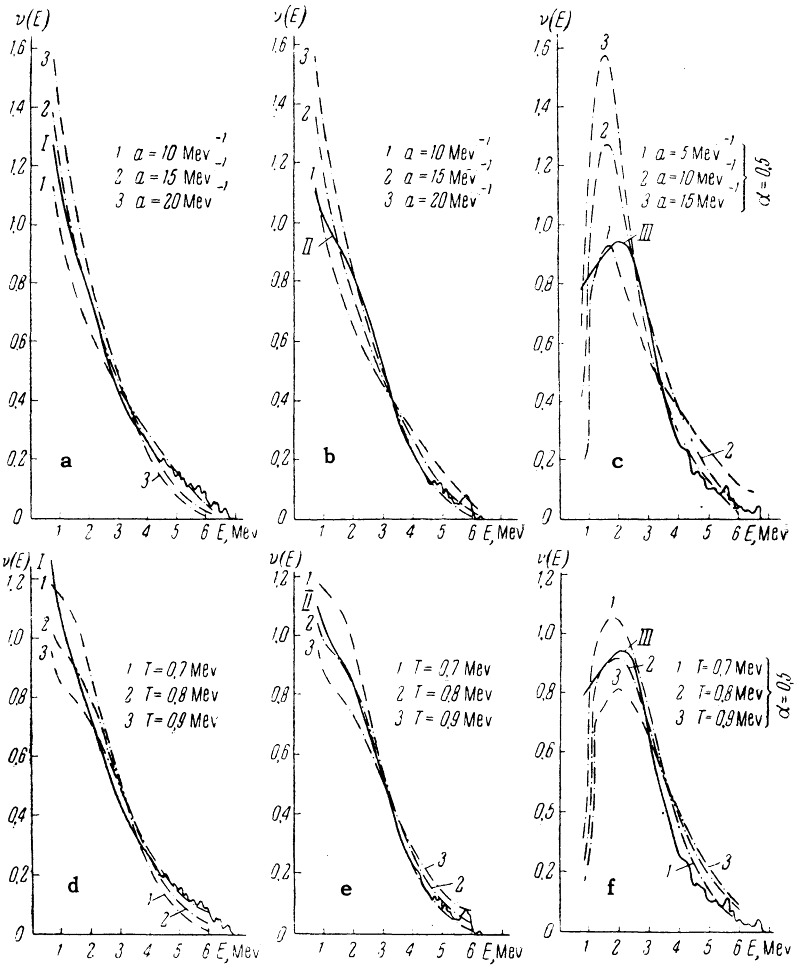

FIG. 4. Comparison of the average experimental spectra for odd-odd nuclei with A ~ 110 (a and d), odd-odd nuclei with A ~ 175 (b and e), and even-even non-spherical nuclei (c and f) with the spectra calculated theoretically for two variations of the level densities: a, b, c – following Eq. (1), and d, e, f – following Eq. (2) (τ has been designated T on the diagram). The theoretical spectra are shown by dash-dot lines.

even nuclei (the energy is measured from the upper ridge of the gap) is 6.4 Mev, and consequently the calculations are carried out in the same energy interval for both categories of nuclei.

For assumed variation (1), the theoretical calculations have been made for values of a in the interval from 5 to 60 Mev^{-1}, and for assumed variation (2) — for values of τ varying in steps of 0.1 Mev from 0.4 to 1 Mev and for τ = 1.2 Mev. In the case of even-even nuclei, the parameter $\alpha = \rho_0^{-1}\overline{M}_B^2/\overline{M}_A^2$ was also varied, where M_B and M_A are the matrix elements of parallel transitions from the given excited state, going respectively through the gap into the ground state or into states located above a gap (for more details see reference 4).

A comparison of the average experimental spectra with the theoretically calculated curves makes it possible to choose the values of the parameter a, if variation (1) is used, or of the parameter τ, if (2) is used. Such a comparison is shown in Fig. 4. It contains, along with the average experimental spectra for nuclei of different categories, three theoretical curves each, calculated for variation (1) (the upper part of Fig. 4) and for variation (2) (lower part of Fig. 4). The theoretical curves have been plotted in all cases for three different values of τ or a, chosen such that at intermediate values of τ and a these curves approach the closest to the experimental spectra (an exception is Fig. 4c).

It is seen from Fig. 4c that in the case of odd-odd nuclei, for either variation of the density, the curves calculated with suitably chosen parameters are sufficiently close to the experimental spectra. However, a more detailed comparison of the curves of Fig. 4 shows (see Figs. 4a and 4d) that in the case of spherical nuclei with A ~ 100, using variation (1) and a = 15 Mev^{-1}, the agreement between the experimental and theoretical spectra is somewhat better than for the other type of variation in ρ. This agreement can be improved even further by changing the value of a somewhat.

The situation is reversed for the prolate nuclei with A ~ 175.

Here the experimental spectrum is in best agreement with the theoretical curve, calculated for variation (2) at τ = 0.8 Mev. The presence of a small difference in the spectra of odd-odd nuclei with A ~ 110 and A ~ 175 may be due (see reference

4) to the difference in the variation of the level densities in spherical and prolate nuclei. It must be recalled again that the difference in the spectra for these two categories of odd-odd nuclei is not particularly essential and appears only in the details of the curves.

In the case of even-even nuclei, the agreement between the experimental and theoretical spectra is not as good (see Figs. 4c and 4f) as for the odd-odd nuclei. However, if (2) is used, the smallest discrepancy between the various curves is obtained for the same value $\tau = 0.8$ Mev, as for the prolate odd-odd nuclei with $A \sim 175$. When using variation (1) and $\alpha = 0.5$, the theoretical curves are in much poorer agreement with the experimental spectra. At a value of $a = 15\ \text{Mev}^{-1}$, obtained from a comparison of the spectra for odd-odd nuclei, the theoretical curve differs greatly from the experimental spectrum. For smaller values of a, the discrepancy is somewhat reduced, but nevertheless remains considerably greater than in the case of curve 2 of Fig. 4f.

We note still another important fact, that in the foregoing comparison of the experimental and theoretical spectra, we compare not only the overall course of the curves, but also the absolute values of $\nu(E)$.

Let us proceed now to a comparison of the average experimental spectra of odd-odd and even-even nuclei, shown in Fig. 3. It is seen from this figure that there is a substantial difference in the lower portions of these spectra. Due to the fact that in going from odd-odd nuclei to even-even ones, the number of photons of low energy, with $E < 1.5$ Mev, decreases considerably in the unresolved portion of the spectrum, while the number of photons with energies 2 — 4 Mev increases.

This change in the spectrum of the even-even nucleus is readily explained by the presence of an energy gap in the level spectrum of the nucleus, due to evaporation of nucleons. Qualitatively this reduces to the following. When the excited states of an even-even nucleus are de-excited, the presence of the gap results not only in γ transitions, which gradually bring the nucleus to the upper boundary of the gap (type A transitions), but also in parallel transitions (type B), which carry the nucleus through the gap into the ground state or states close to it, corresponding to collective excitations. In the case of an odd-odd nucleus only type A transitions take place. The photons emitted in type B transitions have considerably greater energy than those of type A transitions and result from the exclusion of the latter. Such an outflow of type B photons will play a considerably smaller and smaller role as the nuclear excitation energy increases. On the other hand, as the excitation energy is decreased to 1.5 — 2.0 Mev, although the de-excitation into the ground state is energetically more convenient, such transitions may nevertheless be forbidden. In the case of spherical nuclei, the usual spin forbiddenness will be effective here, and in the case of prolate nuclei K-forbiddenness enters into the picture. These forbiddennesses lead to an increase in the population of levels located in the region ~ 1 Mev, a fact that manifests itself most strongly in non-spherical nuclei. In the spectra of such nuclei, as shown earlier,[5] a group of intense lines of similar energy arises (see, for example, Fig. 1). It follows from the experimental data that the de-excitation of the non-spherical even-even nuclei goes in approximately 50% of the cases through levels which are located directly above the gap and in approximately the same number of cases via type B transitions, which go into the more highly excited levels.

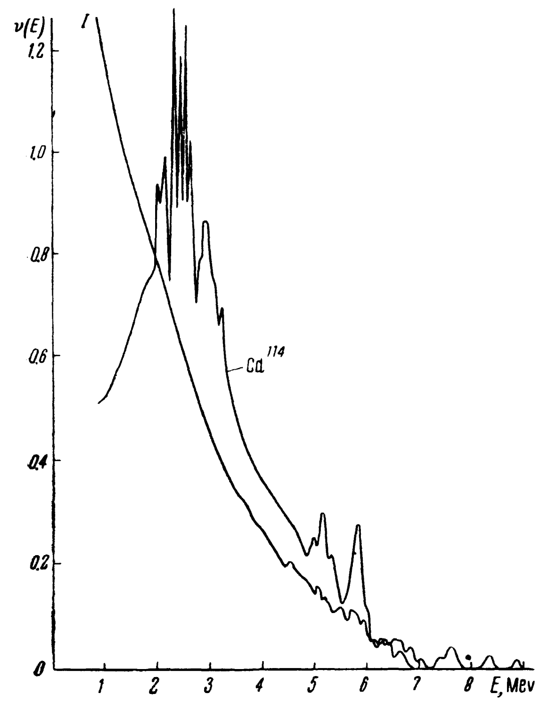

FIG. 5. Comparison of the spectrum of Cd^{114} with the average experimental spectrum for odd-odd nuclei with $A \sim 110$ (curve 1).

Let us consider the γ spectra of other nuclei. Figure 5 shows along with the average spectrum for spherical odd-odd nuclei also the experimental spectrum for Cd^{114} (as in all other even-even nuclei, lines of energy less than 2 Mev have been cut off here). In this case there is approximately the same qualitative difference in the spectra of even-even and odd-odd nuclei, as above. The spectrum of Cd^{114} was not included in the averaging over the

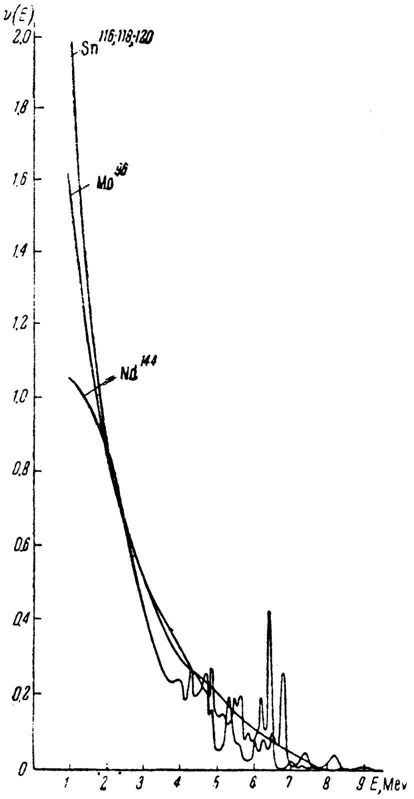

FIG. 6. Gamma-ray spectra of Mo^{96}, Sn^{116}, Sn^{118}, Sn^{120}, and Nd^{144}.

even-even nuclei, since this isotope has a considerably greater neutron binding energy, 9 Mev.

Figure 6 shows the spectra of the following even-even nuclei: Mo^{96}, Sn^{116}, Sn^{118}, Sn^{120}, and Nd^{144}. The unresolved portion of these spectra have a form close enough to that of odd-odd nuclei. This result can be understood by examining in greater detail the type B transitions, i.e., the transitions that cause an outflow into the ground state. The point is that this outflow may go not only to the ground state, but also to the lower excited states. Whereas in the non-spherical even-even nuclei the excited levels, to which the effective outflow is possible, are located at low excitations (100 — 300 kev), in spherical nuclei, particularly in Mo^{96}, Sn^{118}, and Nd^{144}, even the first excited level is located at 0.78, 1.2, and 0.7 Mev respectively. With this, the first level gathers in up to 90% of all the cascades. Inasmuch as the evaporation energy of the nucleons in these nuclei is 1.5 — 2 Mev, a noticeable outflow not into the ground state, but to lower excited levels decreases noticeably the effective width of the energy gap in these nuclei. Thus, in these nuclei the energy of type B transitions differs from that of type A transitions not by 1.5 — 2 Mev, but by a smaller quantity, equal to the effective width of the energy gap, which indeed leads to a considerable smoothing of the difference in the γ spectra of the indicated even-even and odd-odd nuclei.

For the Cd^{114} nucleus we also have a greater population of the first level, which has an energy 0.56 Mev. However, apparently, the effective energy gap in this case is still large, enough to influence substantially the form of the spectrum of Cd^{114}.

Let us dwell now on the two neighboring nuclei, Eu^{152} and Sm^{150}. The spectra of these nuclei differ noticeably from the average spectra given above. For Sm^{150} this difference lies in the greater height of the maximum, and for Eu^{152} by the fact that in the region of lower energies its spectrum lies higher than the spectra of other odd-odd nuclei. It is interesting to note, however, that in comparing the spectra of Sm^{150} and Eu^{152} (see Fig. 7) we observe qualitatively the same picture, which was established above in comparing the spectra of even-even and odd-odd nuclei (see Fig. 3).

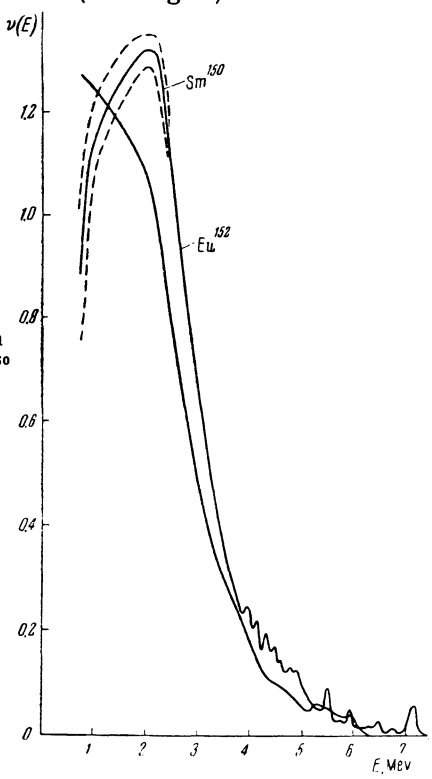

FIG. 7. Comparison of γ-ray spectra of Sm^{150} and Eu^{152}.

As already noted earlier[3,6] for elements located near the twice-magic nucleus Pb^{208}, the γ-ray spectra differ considerably in shape from the foregoing spectra of heavy elements which are far from magic. Figure 8a shows as an example the spectrum of Au^{198}. The same figure shows the theoretical spectrum, calculated under the assumption that the level densities are given by Eq. (1) at $a = 5\ \text{Mev}^{-1}$. Both curves are quite close to each other. We have already noted, however,[3] that such a great reduction in the value of a for Au^{188} is not verified by other experiments, and another reason was indicated in

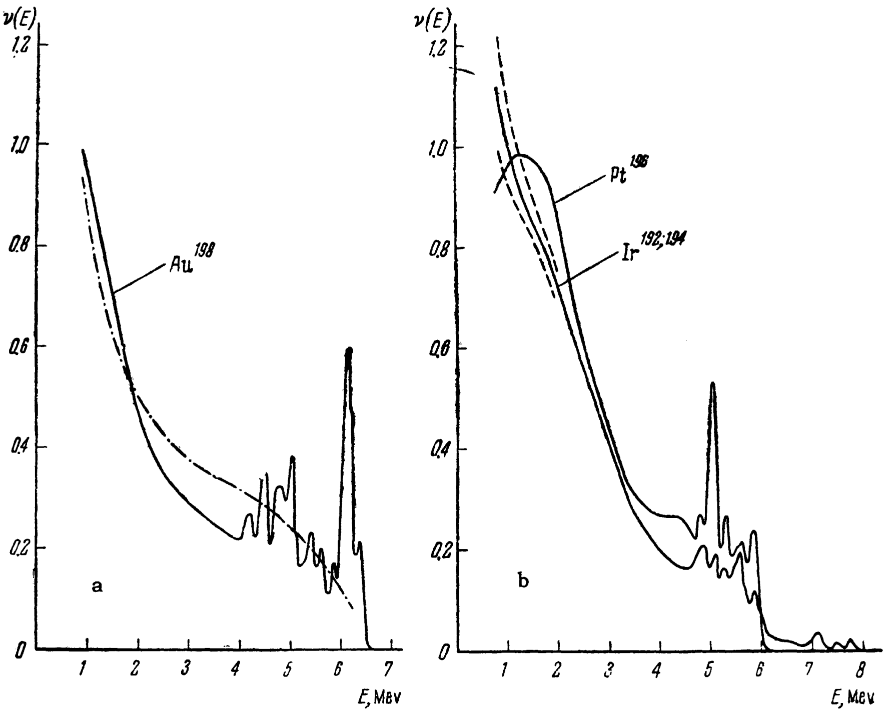

FIG. 8. Gamma-ray spectra of nuclei close to Z = 82 and N = 126: a – comparison of the experimental spectrum of Au^{188} with the theoretical one, calculated for Eq. (1) and at a = 5 Mev^{-1} (dash-dot curve), b – comparison of the spectra of Ir^{192}, Ir^{194}, and Pt^{196}.

that reference for such a substantial change in the form of the Au^{188} spectrum as compared with the spectra of nuclei that are not close to magic.

We note that in this region one sees quite clearly the manifestation of an energy gap in the γ spectra. Figure 8b shows the experimental spectra for the neighboring nuclei, the odd-odd Ir^{192} and Ir^{194} and for the even-even Pt^{196}. It is seen from the figure that if we disregard the change in the form in the upper portion of the spectrum, due to the approach to Z = 82 and N = 126 (see reference 3), we observe qualitatively the same difference in the spectra of the even-even and odd-odd nuclei, which is illustrated in Fig. 3.

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