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GAMMA DE-EXCITATION OF FISSION FRAGMENTS. II. DELAYED RADIATION

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Nuclear Physics

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GAMMA DE-EXCITATION OF FISSION FRAGMENTS. II. DELAYED RADIATION

Sven A. E. Johnansson

October 1964

Gamma de-excitation of fission fragments

II Delayed radiation

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Abstract: The delayed part of the gamma radiation emitted from fission fragments of Cf^{252} has been studied. The fission fragments were detected with solid state counters and the gamma radiation with a scintillation spectrometer. Mass-ratio selection was employed so that the properties of the gamma radiation could be studied as a function of fragment mass. The delayed radiation was found to have an intensity of 6% relative to the prompt one. The half-life varies in the range 15-100 nsec and depends on the mass and on the delay. The mass spectrum of the fragments associated with delayed gamma radiation was found to exhibit a pronounced fine structure with most of the delayed gamma emission concentrated in deformed and magic fragments. The gamma-ray spectra have a shape consistent with rotational cascades in deformed nuclei and vibrational cascades in magic nuclei, respectively.

Of special interest is the fact that the gamma emission from some of the fragments in the mass range 92-110 has the same characteristics as the emission from the deformed fragments in the rare earth region. It is therefore concluded that these fragments have a stable deformation. Various theoretical and experimental evidence for the existence of this new region of deformation is discussed.

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1. Introduction

It was shown by Maienschein et al[1] that the gamma radiation emitted in neutron-induced fission of U^{235} has a delayed component with a half-life of about 100 nsec, its intensity being as much as 5.7%. The present paper reports on a detailed investigation of the gamma radiation from fission of Cf^{252}. Here, too, a delayed component is shown to be present.

The results of the investigation of the prompt radiation, reported in the fist part[2] of the present paper, show that the characteristic feature of the deexcitation is that it involves high spin states. It is therefore natural that isomeric transitions occur and a study of these transitions might give valuable information about the high spin states. Since the spin of the fragments is determined by the scission configuration, such a study might also shed light on the mechanism of the fission process. Another reason for studying the deexcitation of fission fragments is that they cover regions of the nuclear periodic table which are not accessible in any other way. They can provide information about the nuclear properties of very neutron-rich nucleides.

The aim of the work reported here was to make a preliminary survey of the properties of the delayed radiation and to find an explanation for this rather unusual form of deexcitation.

2. Experimental arrangement

The experimental arrangement has been described in the first part of this paper. The fission fragment were detected by two solid-state detectors which gave pulses proportional to the kinetic energy of the fragments. Since the mass ratio is inversely proportional to the ratio of the kinetic energies of the two fragments, it could be determined by dividing the pulses from the two detectors. This was done electronically in a circuit which produced an output pulse proportional to the mass ratio. Selection of a certain pulse height from the divider hence selected fission events with a particular mass ratio.

The gamma radiation was detected by a 5.0 cm × 7.5 cm sodium iodide crystal placed at 90° relative to the flight-direction of the fragments, which orientation minimised the neutron background. The distance between the source and the scintillation spectrometer was 10 cm. This was chosen to give good detection efficiency and, at the same time, to avoid disturbing summing effects from coincident gamma rays. This effect is of some importance since the multiplicity of the radiation is high.

Most of the delayed radiation was emitted after the fragments had already reached the fission counters which were placed at a distance of about 1 cm from the source. This meant that the two fragments of a fission events were well departed at the time of emission and made it possible to study the radiation from only one of the fragments by placing a lead absorber over the other fission counter. Selecting different mass ratios then permitted investigation of the gamma radiation as a function of mass.

The time distribution of the gamma radiation was investigated by introducing cables with different delay in the fission channels. The curves so obtained show a peak corresponding to the prompt radiation and a tail of delayed radiation. Since the tail is very small relative to the prompt peak, there is a possibility, that it could have resulted from some spurious effect in the electronics. It was therefore considered desirable to confirm the existence of the delayed radiation using another method. The experimental arrangement is shown in Fig. 1. A very strong Cf^{252} source ($\sim 10^7$ fissions per minute) was placed at one end of an evacuated tube. At the other end was a fission counter. A heavy lead shield was placed so that the gamma radiation and neutrons from the source could not reach the scintillation spectrometer. Only radiation which was emitted after tha fragments had travelled about 10 cm could be recorded. Hence the delayed radiation could be studied without interference from the prompt radiation.

The main correction to the gamma-ray spectra is the subtraction of the background caused by neutrons. A sodium iodide crystal is an efficient detector of fast neutrons, due, mainly, to inelastic scattering in the iodine. One might think that the neutron intensity should be quite small, since the time it takes the neutrons to travel from the source to the

scintillation spectrometer is small compared to the delays used here. However, there is also a contribution from neutrons scattered in the surroundings and these neutrons take a longer time to reach the spectrometer. The number of neutrons decreases with increasing delay, but the intensity of the gamma radiation is also decreasing. The net result is that the relative amount of background (about 25%) is virtually independent of the delay. The background was determined by absorbing the gamma radiation in a lead absorber. Since most of the gamma radiation of interest here is of low energy, it was in most cases possible to use a thin absorber which did not affect the neutron intensity to any measurable extent. Sometimes it was necessary to use a thicker absorber. In these cases, a correction was applied for the attenuation of the neutron flux in the lead absorber.

Correction for accidental coincidences was in general of little importance. It was determined by introducing a suitable delay in the gamma-ray channel and amounted to about 0.03% of the counting rate at the prompt peak. However, when the decay curve was followed to long delays the accidental coincidences became increasingly important and they eventually set a limit on how far the decay curve could be investigated.

3. Results

3.1. Decay curve

The decay curve for all fragments is shown at the top of Fig. 2. It exhibits a prompt peak and a tail. The width of the prompt peak is determined by the resolving time of the coincidence circuit. It could be varied from 5 nsec to hundreds of nanoseconds by using clipping cables of different length. The decay curve was recorded with many different resoving times and in all cases similar tails appeared. The resolving time shown in Fig. 2 was used in most of the measurements. It was determined by the following considerations. Since, under all circumstances the tail is of low intensity, it is important to choose experimental conditions which enable the available counting rate to be utilised to the fullest possible extent. This means that when investi-

gating the properties of the delayed radiation the delay should be set to correspond to a point close to the prompt peak. At a given delay the counting rate is proportional to the resolving time. However, when the resolving time is increased, the prompt peak gets wider and covers part of the tail. Hence the delay has to be increased so that the prompt peak does not interfere with the measurements. This, of course, leads to a lower counting rate. Consequently there are two tendencies which work in opposite directions. A closer analysis shows that the highest counting rate is obtained when the resolving time is about the same as the half-life of the tail.

The shape of the tail shows that it is composed of several components with different half-lives. In the range 20-30 nsec after fission, the half-life is of the order of 15 nsec and in the period 200-300 nsec later it has increased to about 100 nsec. Fig. 2 also shows partial decay curves for the mass ratio intervals 1.0 - 1.2, 1.2 - 1.48, and > 1.48. The reason for selecting these particular intervals is that they correspond to well-separated regions with a high yield of delayed radiation, as will be shown in the next section. All these partial decay curves have a pronounced tail, but the shape and mean half-life are different. The curve for R = 1.2 - 1.5 has the shortest half-life, 32 nsec, and a rather pure exponential decay. For R > 1.5 the mean half-life is ∿40 nsec, but there appear to be components with shorter half-lives. Finally, the curve for R = 1.0 - 1.2 is complex, with a half-life that increases to about 100 nsec.

It is evidently difficult to analyze the decay curves of Fig. 2 in the vicinity of the prompt peak. Decay curves were also recorded with shorter resolving times and they are more satisfactory in this respect. However, the best results were obtained with the method described above, in which the fragments were made to travel a certain distance before the gamma radiation was recorded. The resulting decay curve is shown in Fig. 3. From intensity considerations, no selection according to mass ratio was possible and hence the curve corresponds to the total radiation. There is no sign of a prompt peak. The result of this experiment confirms that there exists a delayed component and that the tails of the decay curves in Fig. 2 are real. The agreement between the two methods is quite good. In the region where the curves overlap, they are identical

within the statistical errors. The second method makes it possible to extend the decay curve down to 10 nsec after fission. There is no essential change in shape. The slope of the curve increases with decreasing delay and corresponds at 10 nsec after fission to a half-life of about 15 nsec.

A comparison with the results of Maienschein et al shows that, in the region where the two measurements overlap, a faster decay was found in the present work, However, since different fissioning nuclei were investigated, there is probably only an apparent discrepancy. It can be explained as a result of the differences in the mass yield curves of U^{235} + n and Cf^{252}.

The intensity of the delayed radiation was determined in different ways. The ratio of the areas under the delayed distribution and the prompt peak in Fig. 2 gives its relative intensity. Since the spectra of the prompt and delayed radiation are different, a small correction has to be applied for the differences in efficiency of the scintillation spectrometer. Knowing the geometry of the experimental arrangement and the efficiency of the spectrometer, it is possible to make an absolute determination of the yield of delayed radiation. The data of Fig. 3 can also be used for a determination of the yield.

Regardless of the method used, a large uncertainty is introduced by the fact that the shape of the decay curve is not known for times shorter than 10 nsec and longer than 200 nsec after fission. It is therefore necessary to perform an extrapolation. The half-life of the decay for times shortly after fission is assumed constant and equal to the value for t = 10 nsec, i.e. 15 nsec. For times longer than 200 nsec after fission the half-life is also set constant, 100 nsec. These assumptions essentially correspond to limiting the intensity determination to the half-life interval 15 - 100 nsec. In the present work the main interest is confined to this interval since the investigations of the delayed radiation reported below have been performed with delays in the range 40 - 90 nsec. In this region, the main contribution comes from components with the half-lives mentioned above. Hence when, in the following, we talk about delayed radiation, it is defined by these limits.

The different determinations all gave nearly the same result. The average value for the intensity of the delayed radiation relative to the prompt radiation was 6.5%. This corresponds to 0.65 photons per fission.

3.2. Mass distribution

The mass distribution of the fission events associated with delayed gamma radiation was determined with the arrangement described above. The delay in the fission channels was adjusted to select a time interval between 30 and 70 nsec after fission. The mass ratio for coincident events was recorded by a multichannel analyzer. Since the two complementary fragments are well separated at the time of gamma emission, it was easily arranged with a lead absorber that gamma radiation from only one of the fragments was recorded by the scintillation spectrometer. The mass-ratio distribution could then be transformed directly into a mass distribution. The mass distribution associated with the neutron background was determined in a separate experiment and subtracted. Division by the normal mass distribution in fission of Cf^{252} gives the yield of delayed gamma radiation as a function of mass.

Fig. 4 shows the result of this experiment. Similar curves were obtained for other delays. The delayed radiation is evidently mainly associated with particular mass regions. Noteworthy is the fact that at the peaks of the mass yield curve ($A \sim 106$ and 142) the yield of delayed radiation is low. There is a prominent peak at mass 132. The fragments in this region are tin nuclei, especially the doubly-magic nucleus Sn^{132}. An even higher yield is exhibited by fragments with $A > 148$. It is very interesting to note that these fragments should be deformed. As a matter of fact the limit $A = 148$ corresponds for fission fragments to neutron number 90 which is known to be associated with the transition from spherical to deformed nuclei. For the light fragment the delayed gamma radiation is mainly associated with low mass values. There is a broad distribution with peaks at 92, 96 and 110. As will be discussed in detail below, there is strong evidence that fragments with these masses are deformed. Hence there appears to be a strong correlation between fragment deformation and delayed gamma emission. The significance of this correlation will be discussed below.

3.3. Energy spectra

Energy spectra of the delayed radiation were studied for a few selected mass regions. In general, the delay was 50 nsec, but a few

measurements with slightly different delays gave similar results. The neutron background was determined in a separate experiment and subtracted.

A few spectra are shown in Fig. 5. It is evident that they exhibit a great deal of fine structure, in contrast to the spectrum of the prompt radiation. Especially the two lower spectra have a rather regular shape. They consist of a series of peaks with a spacing, which decreases regularly with increasing energy. This structure resembles that of rotational spectra. It is therefore interesting to note that fragments with A $\sim$ 152 are certainly deformed and that there are reasons to believe fragments with A $\sim$ 110 to be deformed also, as will be discussed in detail below. If the lowest peak is identified with the ground state rotational transition, the energy values of the other transitions in the rotational cascade can be calculated. They are indicated with arrows in Fig. 5.

4. Interpretation

The existence of delayed gamma radiation is not entirely unexpected. It has recently become evident that a characteristic feature of the fission process is that the fragments are formed in states with a high spin. The neutrons evaporated take away most of the excitation energy, but only a little of the available angular momentum. At the beginning of the gamma-ray cascade the fragment have a high spin and it is natural that various isomeric states are populated. However, the delayed radiation has many unusual and interesting features which warrant a more detailed discussion.

The average yield is rather high, but since the yield curve (Fig. 4) has pronounced peaks, the yield will be particularly high in certain regions. For example, the heavy fragments in the rare earth region emit 20% delayed radiation. This means that in each gamma-ray cascade on the average one isomeric level is populated. Such a situation is quite unusual, especially in view of the peculiar yield curve. Most of the delayed radiation is emitted from deformed or magic fragments. However, the systematics of isomeric transitions show that for these types of nuclei the number of isomers is relatively very small. On the other hand one would expect most of the delayed radiation to be emitted from fragments

in the "islands of isomerism" just before the closure of a shell. Such a region should exist for A = 120 but there the yield of delayed radiation is particularly low.

Another peculiar feature is that the half-life of the delayed radiation shows such a small variation. Most of it appears to have a half-life in the comparatively narrow range 15-100 nsec. Here, however, some experimental limitations are of importance. As discussed above, it is difficult to investigate the decay for times shorter than 10 nsec after fission. If this were possible, one would probably find delayed radiation with shorter half-lives. Similarly, there are in all probability delayed components with half-lives longer than 100 nsec, but they are difficult to detect. The counting rate decreases with increasing half-life and the background therefore sets a limit on how far the decay curve can be followed.

Hence the small spread in half-life is partly of instrumental origin. However, this does not change the fact that 6% of the total gamma radiation is delayed, with a half-life in the range 15-100 nsec. This high yield has to be explained regardless of the presence of delayed radiation of shorter or longer half-life.

The delayed radiation emitted by fragments of mass $\sim$ 132 is perhaps easiest to explain. In this mass region, the line of most probable charge goes close to the magic numbers 50 and 82, as is illustrated in Fig. 6. A clue might therefore be obtained from level schemes of magic nuclei, particularly those in which high spin states are populated. In several of these, for example Zr^{90}, Mo^{92} and Sn^{120}, there is a regular series of states 2+, 4+, 6+ etc., which resembles a vibrational cascade. Since it is known that the fission fragments have a high initial spin, it is not unlikely that these states are populated in the deexcitation of the fission fragments. The interesting fact is that the level distance decreases with increasing spin. The 2+ state comes at about 1.5 Mev, but the distance between the 4+ and 6+ and between the 6+ and 8+ states is only 100 - 300 kev. Transitions between the higher states will therefore have a comparatively long half-life. Using the well-known expression for the transition probability and normalizing to the experimentally known half-lives of the first 2+ state in spherical nuclei, the half-life of a 100 kev transition is found

to be 50 nsec. This is very close to the half-life of the delayed gamma radiation. In this energy region, the half-life does not depend too much on the energy because of the influence of internal conversion. A change of a factor of two in energy changes the half-life only about the same amount. This might explain why there is so little apparent variation in the half-life, despite the fact that the delayed radiation probably comes from a number of different fragments.

If the delay is indeed caused by a transition between these high-spin states, then the corresponding energy spectrum would be expected to exhibit this transition together with the following transitions in the cascade. The experimental spectrum (Fig. 5) is seen to consist of some peaks between 100 and 300 kev and a high-energy part. If the low-energy gamma-rays are E2 transitions, they will cause a delay in good agreement with the experimental value. The high-energy distribution extends up to 1.6 Mev which is a very reasonable energy value for the first 2+ state in magic nuclei. Hence both the half-life and the shape of the spectrum are in agreement with the interpretation proposed here.

The rest of the delayed radiation is associated with either deformed fragments or fragments which, most probably, are deformed (see the subsequent section). In this case it is more difficult to get a quantitative interpretation. One can find a plausible explanation for the occurrence of isomeric transitions, but the details depend on factors which are not known very well. Let us first consider the deexcitation of a high-spin state in an even-even deformed nucleus. At first one expects a cascade of fairly fast transitions of relatively high energy which take away most of the excitation energy but only a small part of the available angular momentum. When the excitation energy has decreased to 1.5-2.0 Mev, i.e. just above the energy gap in the level diagram, there are only a small number of high spin states available. At this point there is a very limited choice of levels for further transitions and the natural way of deexcitation appears to be a transition to one of the higher members of the ground state rotational band and then a cascade of rotational transitions to the ground state. The delayed transition should be the one leading to the rotational band. Several cases of such isomeric transitions are known, for example in Hf^{178}, Hf^{180} and Os^{190}, where E1 and M2 transitions go to the 8+ rotational level. The difficulty in predicting the delay stems from the fact that large hindrances can occur because of K-forbiddenness. Since the K-value of the states involved in the

deexcitation is not known, nothing can be predicted about life-times and multipolarities. If the K-forbiddenness is small, the transitions here are most likely to be of E2 type, and if large, E1 or M1.

If this interpretation is correct, the spectra of the delayed radiation should exhibit a series of rotational transitions. That this is indeed the case is the strongest single piece of evidence for the interpretation proposed here. In Fig. 5 the calculated energy values of the rotational transitions are indicated by arrows. The details of the calculation are discussed below. Even if the statitics are poor, there is an agreement which can hardly be fortuitous. Although this discussion has been limited to even-even nuclei, the situation is similar for other types of nuclei. However, since they have no energy gap, there are high spin states also at low energies. The limitations imposed on the deexcitation by the high initial spin are therefore not quite so important and isomeric transitions are less likely to occur.

The interpretation of the isomeric transitions discussed here is not limited to deformed nuclei. However, experimentally the isomeric transitions seem to occur in deformed nuclei only. There must therefore be some fundamental difference between the deexcitation of deformed and spherical fragments. Since the basic reason for occurence of isomeric transition is a high initial spin, the most natural assumption is that deformed fragments have a higher initial spin. Considerations of the conditions at scission makes such an assumption rather plausible. Fragments with a stable deformation are at that point very elongated, which should favour a high spin. Classically a high spin can be thought of as a rapid rotation caused by a scission configuration which does not possess axial symmetry. This problem has been treated by Strutinski[3] and Hoffman[4]. It can be shown that the initial spin increases with increasing deformation. Hence the difference in delayed gamma emission for spherical and deformed fragments is, according to this view, caused by differences in the elongation at scission.

5. Evidence for a new region of stable deformation

The experimental results presented here suggest that part of the light fragments have a stable deformation. The main evidence is the

great similarities which exist in the emission of delayed gamma radiation from these fragmetns and from the rare earth fragmetns, which certainly are deformed. Of especial importance is the fact that the radiation from some light fragments has a rotational-type spectrum similar to the spectrum of the rare earth fragments. There are also other reasons for believing the fragments in question to be deformed. Since it is of a considerable interest to estabilsh the existence of a new region of deformation, a more detailed discussion seems warranted.

As remarked above, the experimental spectra agree well with the values calculated for a rotational spectrum. Since this is a crucial point, this calculation will now be discussed in more detail. The low energy peak in the spectra is identified with the transition from the 2+ state. For the fragments with $A \sim 152$ an energy of 95 kev is obtained. This value cannot be compared directly with the deformed rare earth nuclei, since the fragments are slightly lighter and have a different neutron excess, but a closer study of how the energy varies with the nucleon numbers makes it appear very reasonable. The value of B, the coefficient in front of the second order term, is extrapolated from the well-known spectra in the rare-earth region. A value of 0.02 kev is obtained.

For the fragments with $A \sim 110$, the values of the energy of the 2+ state and of B must be extrapolated from those of the heavier fragments. The energy of the 2+ state varies with mass as $A^{-5/3}$, if one assumes that the deformation is constant. Since this is not the case, it is better to use an empirical relation. The best fit for the well-known deformed regions is obtained with the expression $A^{-1.54}$. The energy of the 2+ state for $A \sim 110$ should then be 140 kev. The experimental value is 130 kev which must be considered as a satisfactory agreement. The constant B varies as A^{-3} and should have a value of 0.06 kev in this mass region[5]. The theoretical energy values calculated with these constants fit well with the experimental spectrum (Fig. 5). On the whole, the interpretation of the spectra as rotational transitions gives a consistent account of the spectrum shape.

Another important piece of information is the yield curve for emission of delayed gamma radiation (Fig. 4). This shows that in the mass region of interest here, the delayed radiation is preferentially

emitted from fragments of certain masses, implying that only part of the nuclei in this mass region are deformed. We will first see if it is possible to decide from theoretical considerations which nuclei are most likely to be deformed. Fig. 6 shows part of the nuclear periodic table with the line of beta stability and the location of the fission fragments. One would perhaps guess that the most favourable position for occurence of a stable deformation would be somewhere in the middle of the region bounded by the magic numbers Z = 28,50 and N = 50,82. However, this is not the case since the nucleon number 40 is known to have semimagic properties. It is therefore necessary to investigate in more detail how the various orbitals influence the deformation. In Fig. 7 we reproduce part of the level diagram of Nilsson[6]. It is known[7] that a straightforward addition of the single-particle energies gives a curve for the total energy which can be used to get a surprisingly accurate estimate of the deformation. Even without quantitative calculations, one can see that nuclei with Z = 30 and 38 are the ones most likey to have a stable deformation. The deforming forces should be considerably less for Z = 40 but should increase again slightly, so that nuclei with Z = 44 and perhaps Z = 46 might be deformed. The influence of the neutrons is more regular. The first orbitals above N = 50 have a strong deforming tendency and a stable deformation could occur as low as N = 56, provided that the protons also had a configuration favouring deformation. From about the middle of the neutron shell (N = 66), the deforming tendency should decrease again. This might make it less likely that fragments with Z = 46 are deformed. In conclusion we can say that the greatest probability for the occurrence of a stable deformation is to be found for fragments with Z = 36, 38 and 44. Fig. 6 shows that this corresponds to the masses 91, 96 and 110.

We can now compare these results with the yield curve in Fig. 4. The delayed radiation yield has pronounced peaks at the masses 92, 96 and 110. The agreement with the mass values above is perfect. It is hard to believe that this agreement could be fortuitous and it is therefore a strong support for the assumption of a correlation between delayed gamma-emission and deformation.

Another way of getting information about the deformation is to study the energy of the first 2+ state in even-even nuelci. It is

well known that this energy decreases towards the deformed regions and, when it reaches a certain critical value, there occurs a sudden transition to a rotational type spectrum. The critical value is given by Alder et al[8] as 13 h^2/J_{rig}, where J_{rig} is the rigid body moment of inertia. The level diagrams in the transition regions can also be used to get a value of the critical energy. In the rare earth region the highest energy of a 2+ state belonging to a well developed rotational spectrum is 186 kev (Os^{190}) and the lowest energy of a 2+ state belonging to a spectrum definitely showing no rotational structure is 300 kev (Nd^{148}). Hence we can conclude that the critical energy in the rare earth region is somewhere between 200 kev and 300 kev and, for the mass region of interest here, somwwhat higher, around 300 kev. In order to use this criterion, we have plotted the energy of the first 2+ state for a number of nuclei with Z = 42-48 (Fig. 8). It will be noted that the nuclei with Z = 44 have the lowest energy values and hence are the ones most likely to be deformed in agreement with the discussion above. Fragments with Z = 44 have N values around 66. It is evident that if the curve for Z = 44 is extrapolated to N = 66 with the same slope as the curve for Z = 46, the energy of the first 2+ state is predicted to be close to 200 kev. Since this is well below the critical value, it seems to be very likely that fragments with Z = 44 are deformed. For Z = 46 the situation is less clear, but it appears most likely that these fragments are not deformed.

Hence there are several facts, both theoretical and experimental, which speak in favour of a new region of stable deformation.

Conclusions

The present investigation of the delayed gamma radiation in fission demonstrates that this radiation has many unusual and interesting properties. If both mass and time selection are employed systematically, it should be possible to disentangle the complicated radiation mixture and to study the deexcitation of particular fragments. The gamma transitions seem to be mainly of rotational and vibrational type and the study of their properties should be of value for the systematics

of collective transitions. Since the fission fragments cover regions of the nuclear periodic table which are not accessible in any other way, the fission gamma radiation can give information about nuclear properties in these regions. Of special interest is the mass region 90-110 which appears to be a new region of stable deformation. Further study of the delayed radiation will probably shed more light on these problems.

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Figure captions

Fig. 1. Experimental arrangement for studying the decay curve of the delayed radiation.

Fig. 2. Decay curves for the fission gamma radiation. The upper curve shows the prompt peak and the delayed component for the radiation from all fragments. The other curves show the shape of the delayed component for a number of mass-ratio intervals.

Fig. 3. Decay curve recorded with the apparatus shown in Fig. 1.

Fig. 4. Relative yield of delayed radiation as a function of mass.

Fig. 5. Pulse height spectra of the delayed radiation for a number of fragment masses. The arrows indicate the calculated position of the peaks in a rotational-type spectrum.

Fig. 6. Nuclear periodic table with the line of beta stability (full curve) and line of most probable charge in fission of Cf^{252} (dashed curve). The circles indicate fission fragments, which are most likely to be deformed.

Fig. 7. The single-particle level diagram in a deformed potential between the nucleon numbers 28 and 50 according to ref 6. The circles indicate the highest occupied proton level in the nuclei most likely to be deformed.

Fig. 8. The energy of the first 2+ state as a function of neutron number for even-even nuclei with Z-values from 42 to 48.

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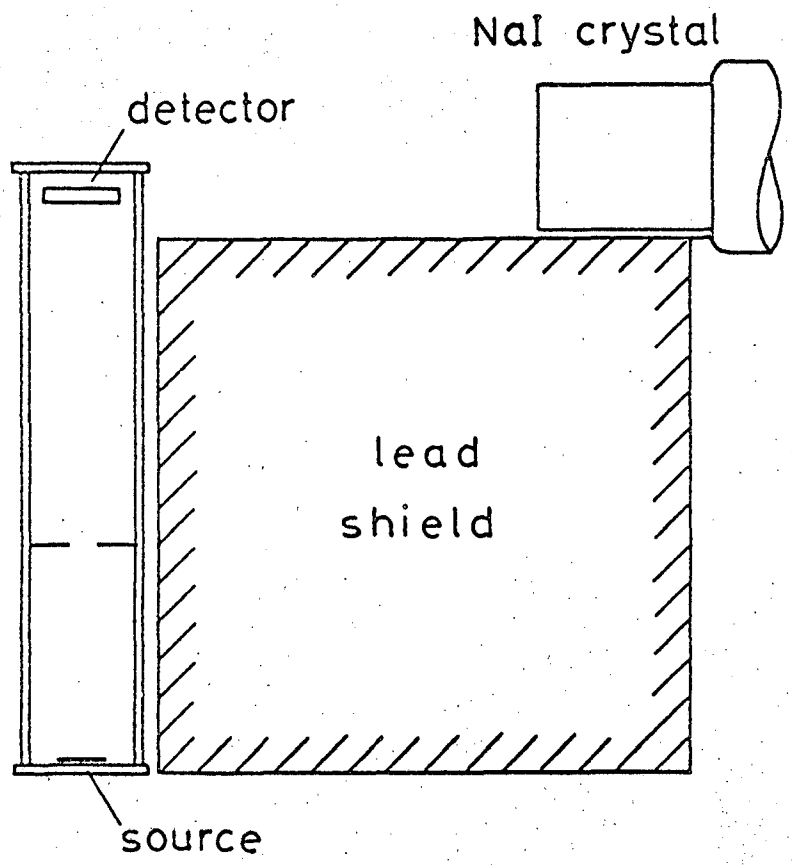

Fig. 1

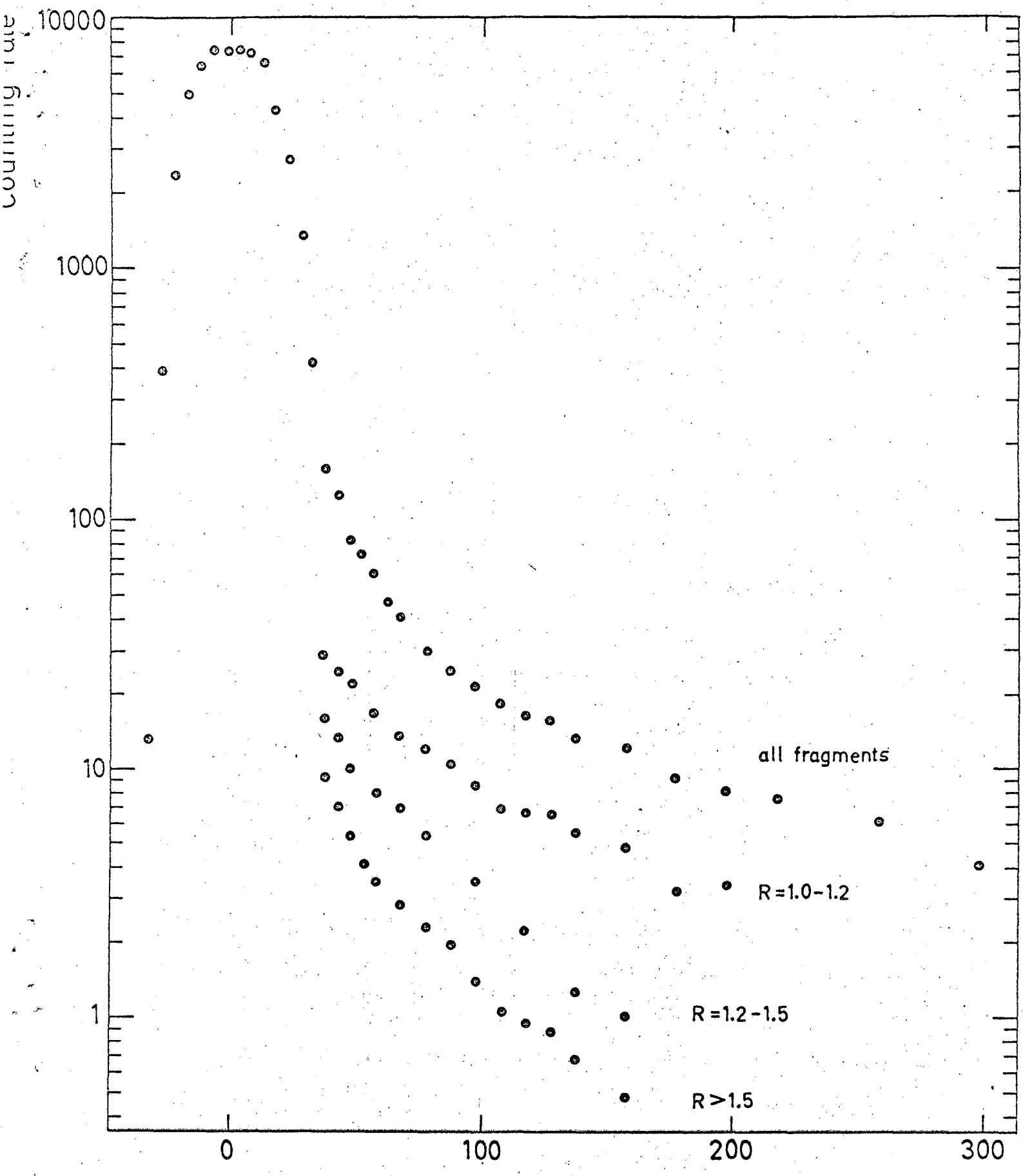
Counting rate
10000
1000
100
10
1
0
100
200
300
all fragments
R=1.0-1.2
R=1.2-1.5
R>1.5
Delay, nsec.

Fig. 2

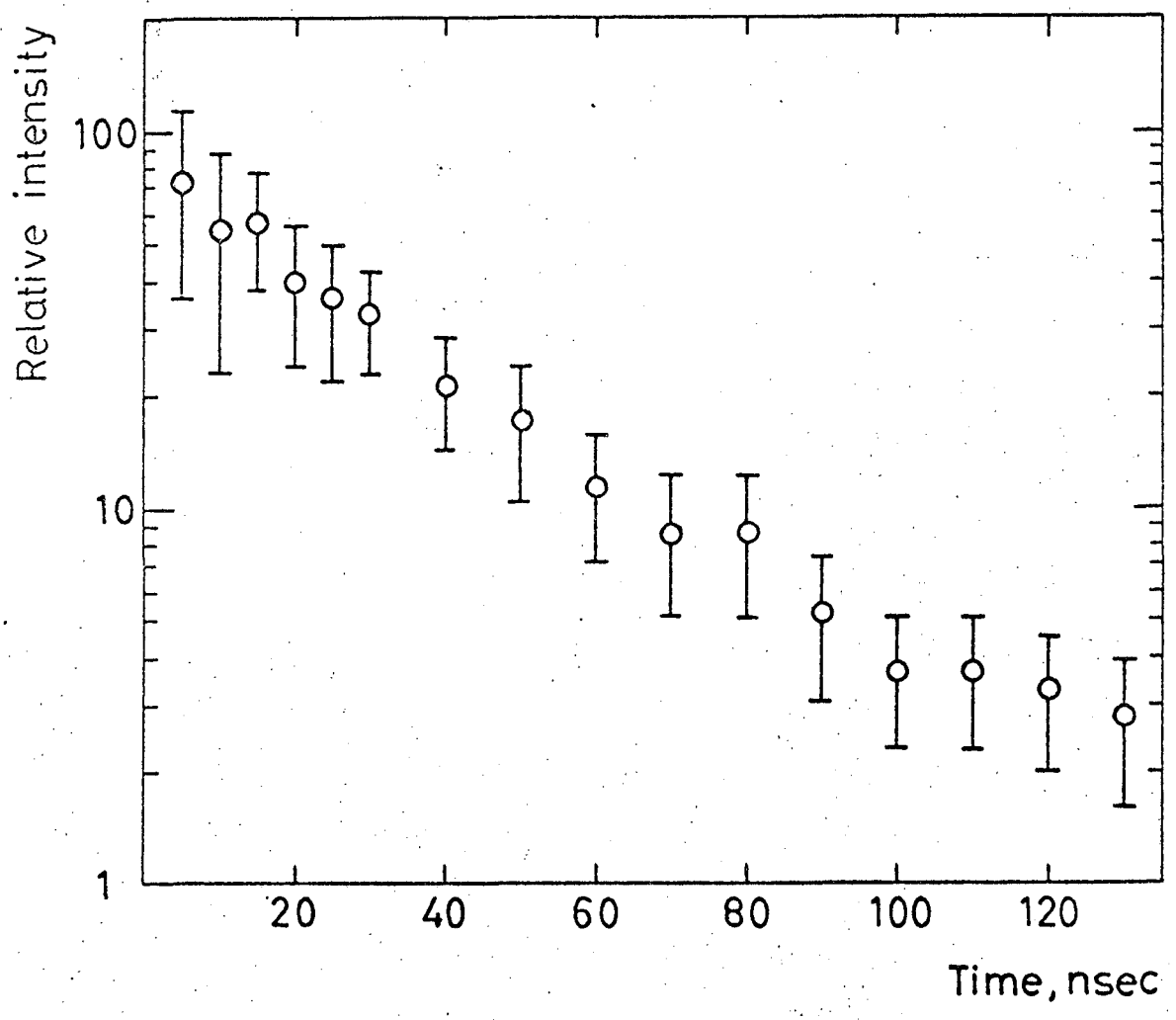

Fig. 3

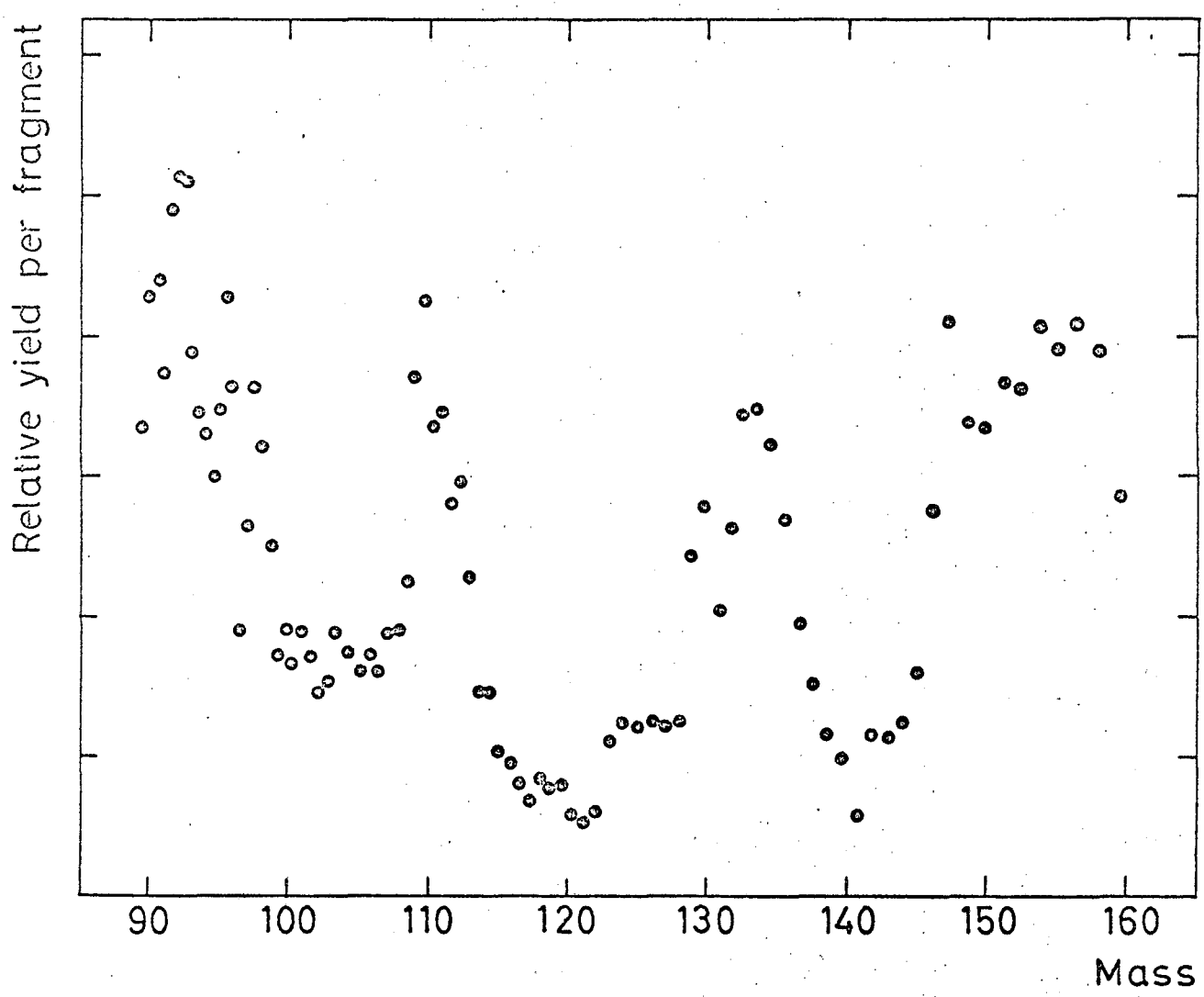
Relative yield per fragment
90
100
110
120
130
140
150
160
Mass

Fig. 4

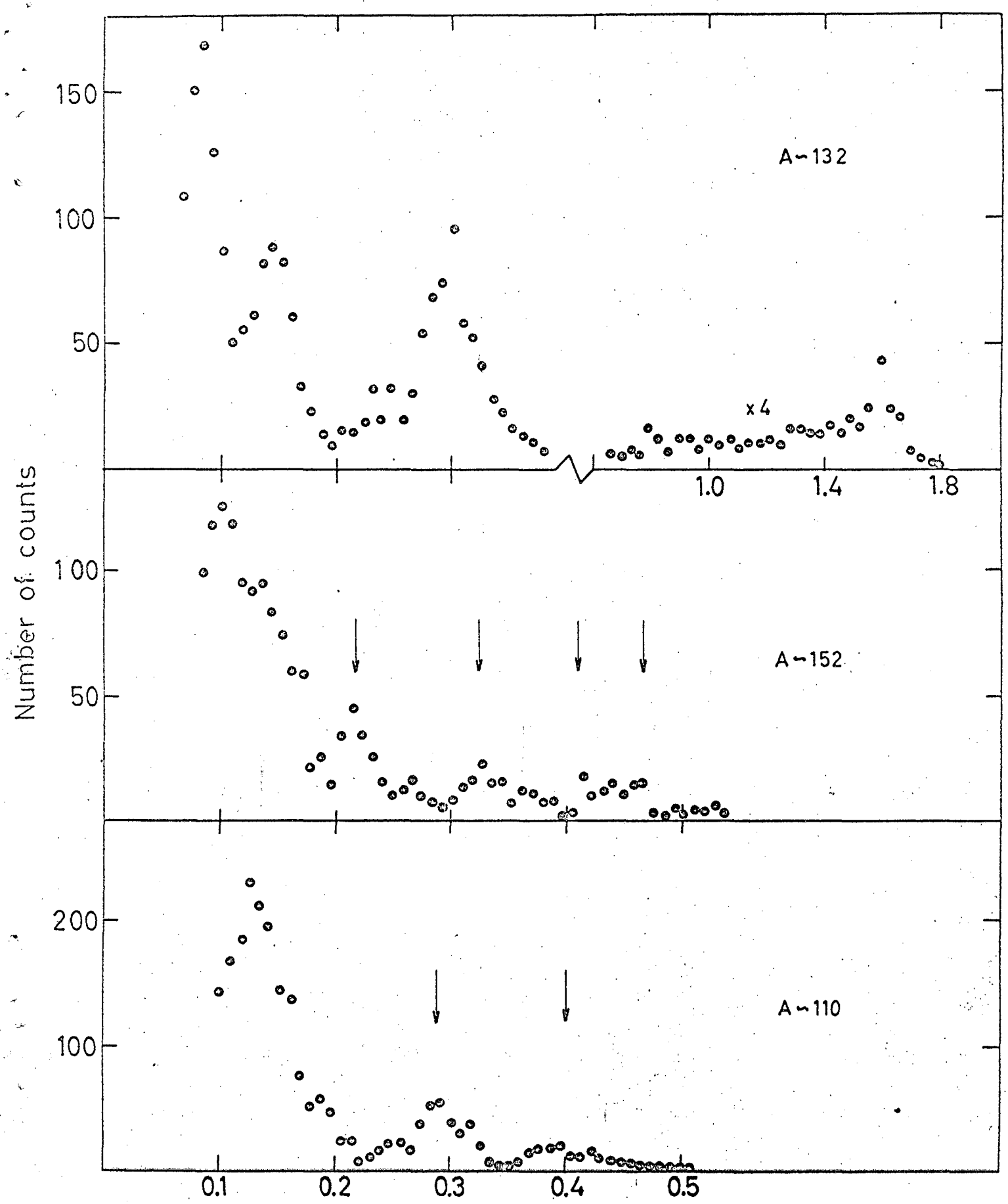
150
100
50
A~132
x4
1.0
1.4
1.8
100
50
A~152
200
100
A~110
0.1
0.2
0.3
0.4
0.5
Number of counts
Energy, Mev

Fig. 5

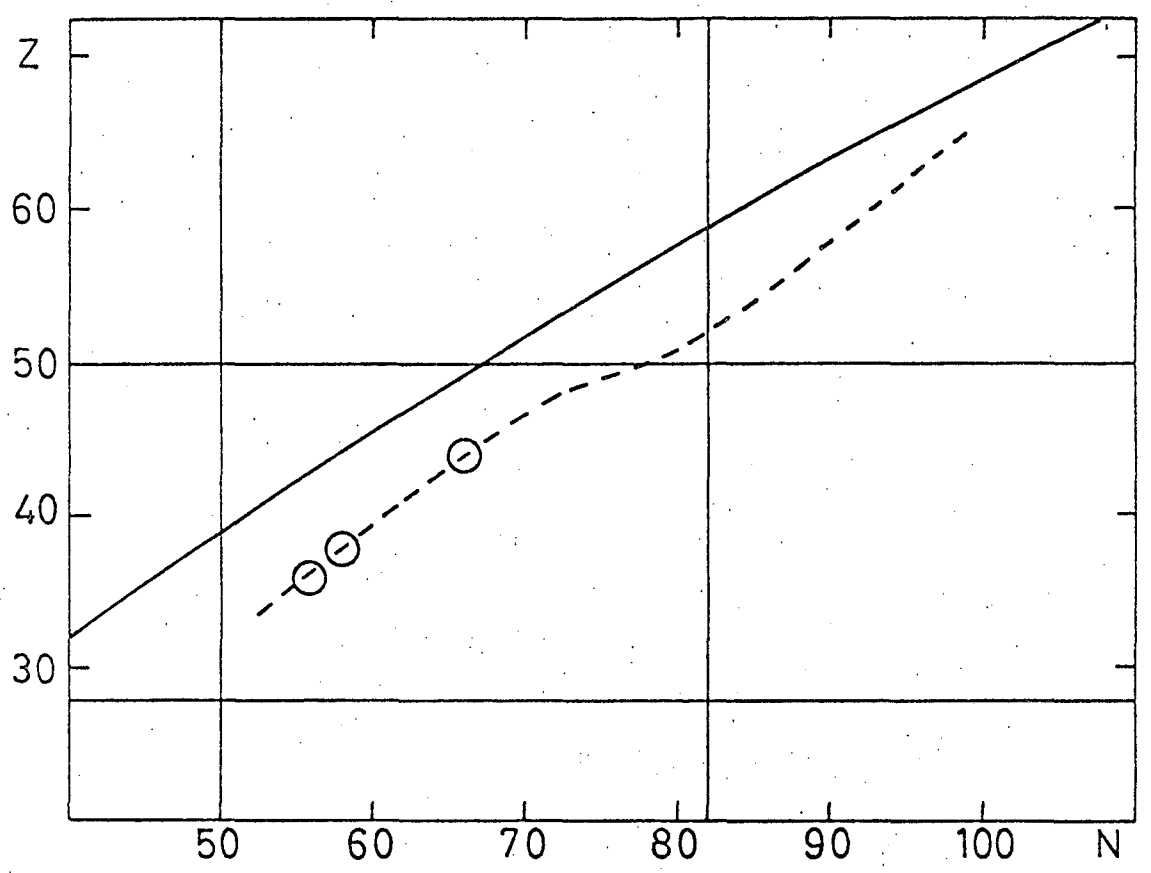

Fig. 6

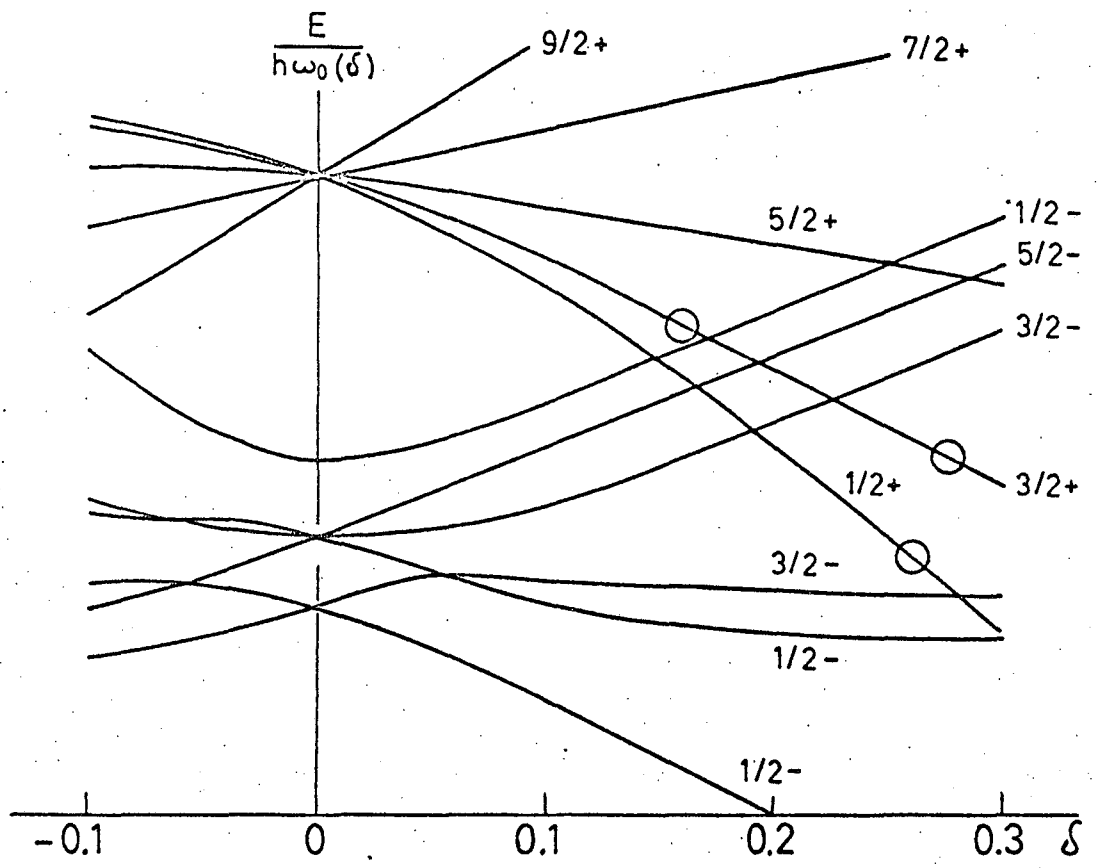

Fig. 7

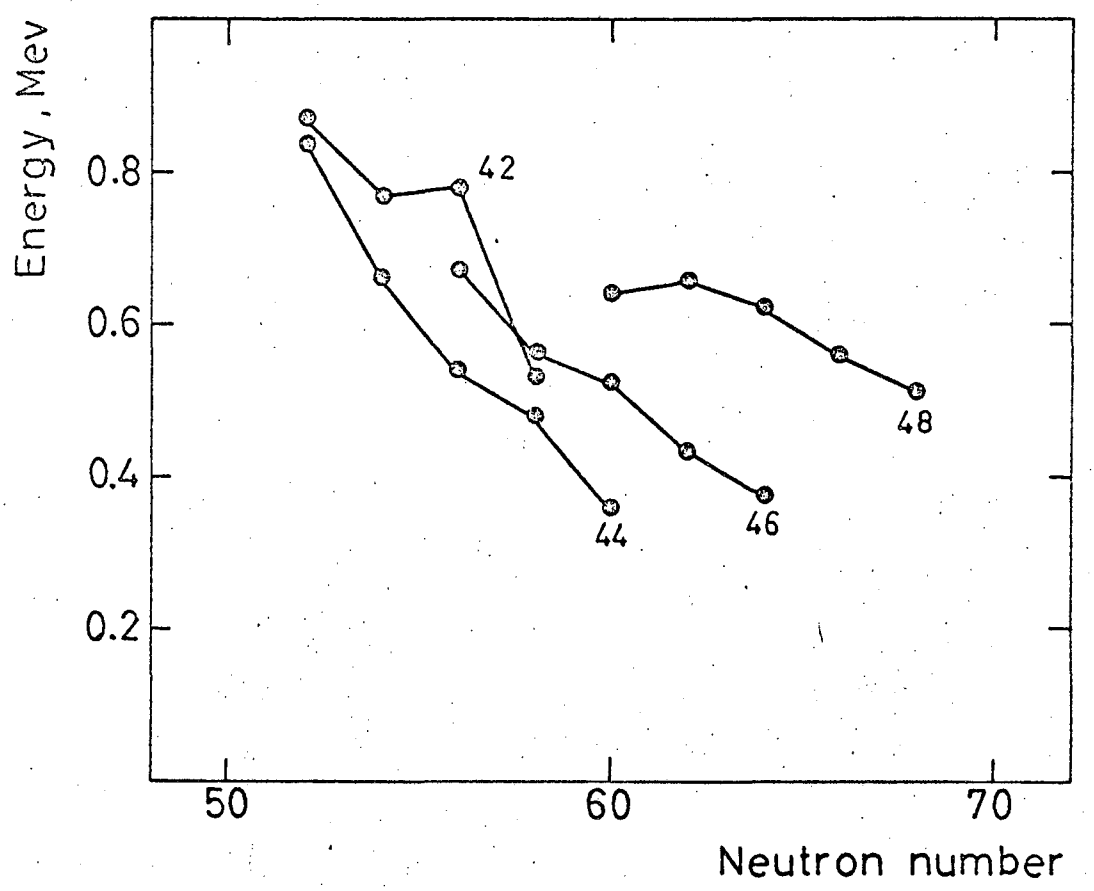

Fig. 8

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