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SPONTANEOUS FISSION OF THE HEAVIEST ELEMENTS

Sven A. E. Johansson

September 25, 1962

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ABSTRACT

The spontaneous-fission rates of nuclei with $Z \geqslant 98$ have been calculated. Deviations of these fission rates from the general trend predicted by the liquid-drop model are attributed to the fine structure of the single-particle level diagram. Our calculations reproduce the experimental values reasonably well, particularly the rapid drop in half-life with increasing neutron number just above neutron number 152. Contrary to previous predictions, our results show that this drop is a local effect and that the half-lives soon start to increase with increasing neutron number. Heavy, neutron-rich nuclei therefore have considerable stability against spontaneous fission.

Based on the predicted half-lives, the possibilities of producing very heavy nuclei are discussed. The half-lives indicate that prolonged neutron irradiation or heavy-ion bombardment are not very promising methods of producing very heavy nuclei, because of the short fission half-lives of the reaction products. The most promising method appears to be production by means of nuclear explosions.

The implications of the present results for neutron capture in supernovae explosions are discussed. An interpretation of the light curves of Type I supernovae is given.

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INTRODUCTION

Spontaneous fission of the heaviest elements is of great importance in several respects. For example, spontaneous fission sets a limit for the stability of heavy nuclei. The heaviest nuclei produced in the laboratory are not too far from this limit, and in any attempt to proceed further it is highly desirable to have some estimate of their spontaneous-fission half-lives. The half-life for α and β emission can be fairly well estimated, and in most practical cases the spontaneous-fission rate is the decisive factor.

Spontaneous fission also plays an important role in the creation of heavy elements in nature. It is now generally assumed that these elements are formed in stellar explosions by neutron capture on a fast time scale. This process can proceed until the fast decrease of the spontaneous-fission half-lives sets an upper limit. To determine the position of this limit, one must know the fission half-lives of the very heavy nuclei, which are of interest here. Still another application of fission half-lives is in the light curves of Type I supernovae. The peculiar exponential decline of these novae has been associated with the fission decay of Cf^{254}, but more detailed treatment of this problem requires knowledge of the half-life systematics for all nuclei in this mass region.

The difficulty of predicting spontaneous-fission rates stems from the fact that they vary in a very irregular way which is contrary to what one expects on the basis of the liquid drop model. The present author recently proposed a theory to account for these fluctuations.[1] They are assumed to be caused by the fine structure of the single-particle level diagram. By using this assumption, it was possible to account for the half-life systematics of the experimentally studied nuclei. The purpose of the present investigation is to extend this work to heavier nuclei, to predict half-lives in this region, and to use the predicted values in a discussion of the problems mentioned above.

Before going into details we discuss which nuclei are of greatest interest in our study. We must consider several ways of producing new elements. One which has been successfully used for production of elements 102 and 103 is bombardment with heavy ions. The type of reaction that takes place is, for example, $X(C^{12}, 4n)$. This reaction evidently leads to nuclei slightly on the neutron-deficient side of the valley of beta stability. Another way of producing heavy nuclei is successive neutron capture on a long time scale in a high-flux reactor. This reaction leads to heavier elements through alternating steps of neutron capture and β decay. The path followed is on the neutron-rich side of the valley of beta stability, but the distance to the path from the bottom of the valley is small. The same reaction, but on a short time scale (10 to 100 sec) is supposed to take place in novae explosions. Here the reaction goes via β decays of much shorter half-lives than in the previous case, and consequently the reaction path is further away from the line of beta stability. Finally, heavy elements can be produced in nuclear explosions, as demonstrated by the "Mike" experiment.[2] Here the time during which the target is exposed to the neutron flux is so short that there is no time for β decays. Hence a series of very neutron-rich uranium isotopes is produced. They decay subsequently by β emission to the stable end products. These various possibilities are schematically illustrated in Fig. 1. This figure demonstrates which nuclei are of greatest importance from this point of view; such nuclei have been selected for the calculation presented here.

CALCULATIONS

The principles of the calculation have been described previously.[1] Essentially, the change of energy caused by addition of one or two nucleons to a given nucleus is determined as a function of the deformation. The energy of the added nucleons is determined from the single-particle level diagram. The irregular behavior of the spontaneous-fission rates is caused by the large fluctuations in level spacing. For details of the calculations the reader is referred to the previous paper.[1]

Depending on the type of nuclei considered we have several cases. The first is the even-even nuclei. Here we consider the addition of two protons or two neutrons to a given nucleus. As discussed previously, since the two

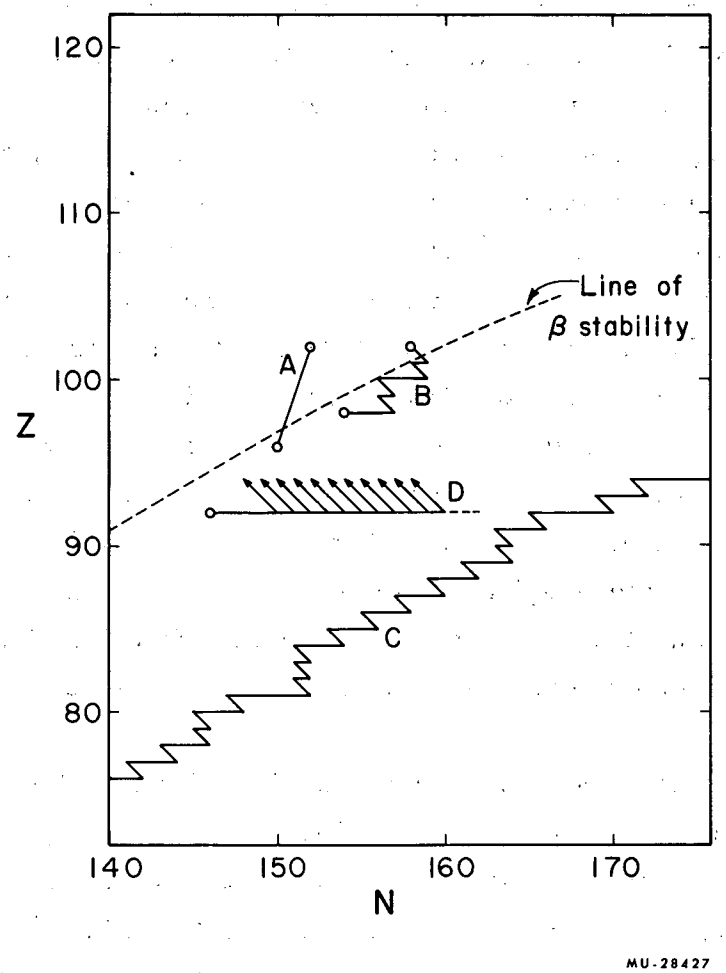

Fig. 1. Schematic representation of some possible ways of producing heavy nuclei:
A. heavy-ion reactions
B. Neutron capture on a long time scale
C. Neutron capture on a short time scale
D. Neutron capture on a very short time scale.

extra nucleons are paired, they can move in the level diagram so that the total energy is minimized.[1] The influence of the extra nucleons on the barrier can then easily be found and the change in penetrability calculated.

In the case of odd nuclei the situation is different. Since the spin and parity of the nucleus has to be conserved, the odd nucleon cannot jump in the level diagram but must stay in its original orbit. For the nuclei of interest here this means that the addition of an odd nucleon increases the barrier height, and hence this can account for odd nuclei having considerably longer half-lives than neighboring even-even nuclei. In odd-proton nuclei, however, the situation is complicated by the Coulomb energy of the extra proton. Since the extra proton stays in the same level all the time, the charge distribution of this proton might be quite different from the total charge distribution of the nucleus. This effect will be discussed in connection with the results of the calculations.

Finally, there is the case of odd-odd nuclei. Here the odd proton and the odd neutron couple to give the total spin and parity of the nucleus. When the deformation increases there are various possible ways to change the proton-neutron configuration while conserving spin and parity. However, neither the level diagram nor the coupling rules are known well enough to permit a quantitative calculation. One would expect the half-life to fall between the values of neighboring odd-even and even-even nuclei. This case will be briefly discussed below.

The calculations were performed as described in the previous paper. However, since we are now interested in heavier nuclei, we must include more levels in the level diagrams. The neutron diagram is complemented by the following levels: 9/2 + [615], 1/2 + [880], 3/2 + [871], 5/2 + [862], and 1/2 - [990]. In the proton diagram the following levels are added: 1/2 + [651], and 1/2 - [770]. These levels affect slightly the calculations reported in the previous paper, but they do not change the basic features. However, they are essential for the present calculations.

RESULTS

We first report the results for the very neutron-rich uranium isotopes, which are of interest in neutron capture on a very fast time scale. In Fig. 2 experimentally known half-life values are shown as squares. The circles represent calculated values. A striking feature is the rapid drop for neutron numbers right above 152. This is in agreement with the behavior of heavier elements (Cm, Cf, and Fm). However, the present calculation shows that

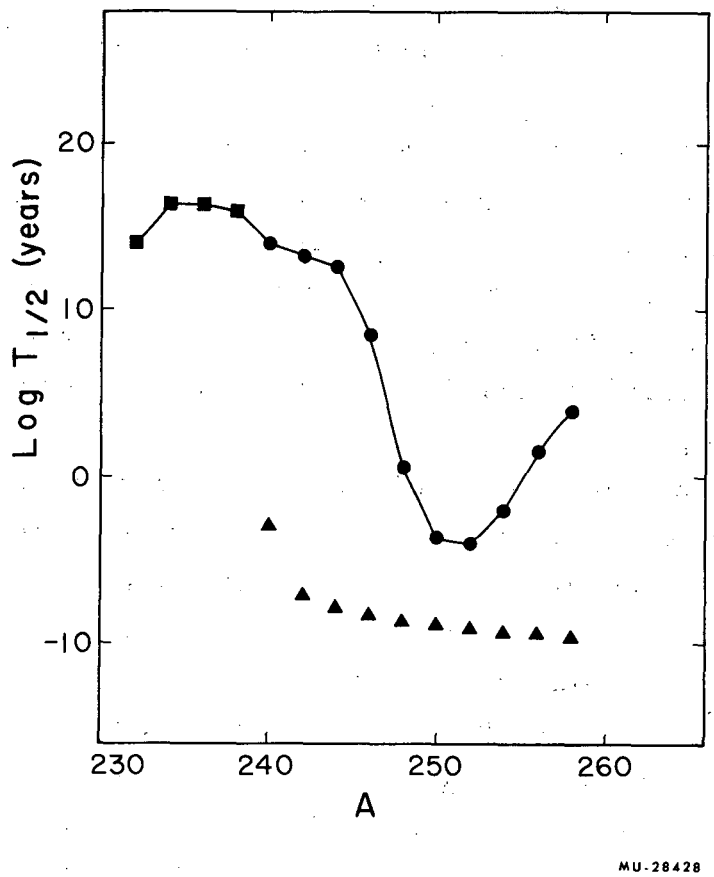

Fig. 2. Spontaneous-fission half-life of even-even uranium isotopes: squares denote experimental values; circles, predicted values; and triangles calculated β half-lives.

this tendency does not persist, but that the half-lives soon start to increase again as one would expect from the liquid-drop picture. This increase, which was also mentioned in the previous paper, is of great importance for the stability of very heavy nuclei. It disagrees with previous estimates. In some predictions[3] the decrease in half-life above N = 152 is extrapolated linearly to heavier nuclei, leading to very short half-lives. Dorn[4] used the method of Swiatecki[5] and obtained also very short half-lives.

Fortunately, some experimental information on this point is available. It is known that in the "Mike" experiment, nuclei with masses up to 255 were produced. However, if the previous predictions were right one would not expect to get anything above A = 250. A detailed calculation by Dorn[6] shows this quantitatively. Hence this experimental fact confirms the result of the present calculation. Of course, not too much significance should be attached to the precise values obtained here. The important thing is the general tendency of the predictions.

In Fig. 2 we also show calculated values for the beta half-lives. They were calculated from decay energies obtained from the mass formula of Seeger[7] by assuming allowed transitions with a log ft value of 3.8. Note that for all nuclei in question, fission is considerably slower than β emission. One gets the same result for elements above uranium. This means that fission does not interfere with the beta-decay chain. After being formed the neutron-rich uranium isotopes decay towards the line of beta stability before fission takes place. This situation is, of course, very favorable for the production of heavy elements in nuclear explosions.

Next, we show the results for even-even nuclei of Cf, Fm, 102, and 104. They are displayed in Fig. 3 and Table I. The experimentally known values are deonted by squares. The calculated values for these nuclei reproduce the experimental values fairly well, which given some support to the correctness of the calculations. Calculated values for the nuclei, obtained by adding two neutrons each time, are denoted by circles. It must be realized that in each such step there is a certain error and that the errors add up. They may cancel each other to some extent, but still one expects fairly large errors for the heaviest nuclei shown in Fig. 3. Therefore, it is mainly the general trend that is significant and not the details.

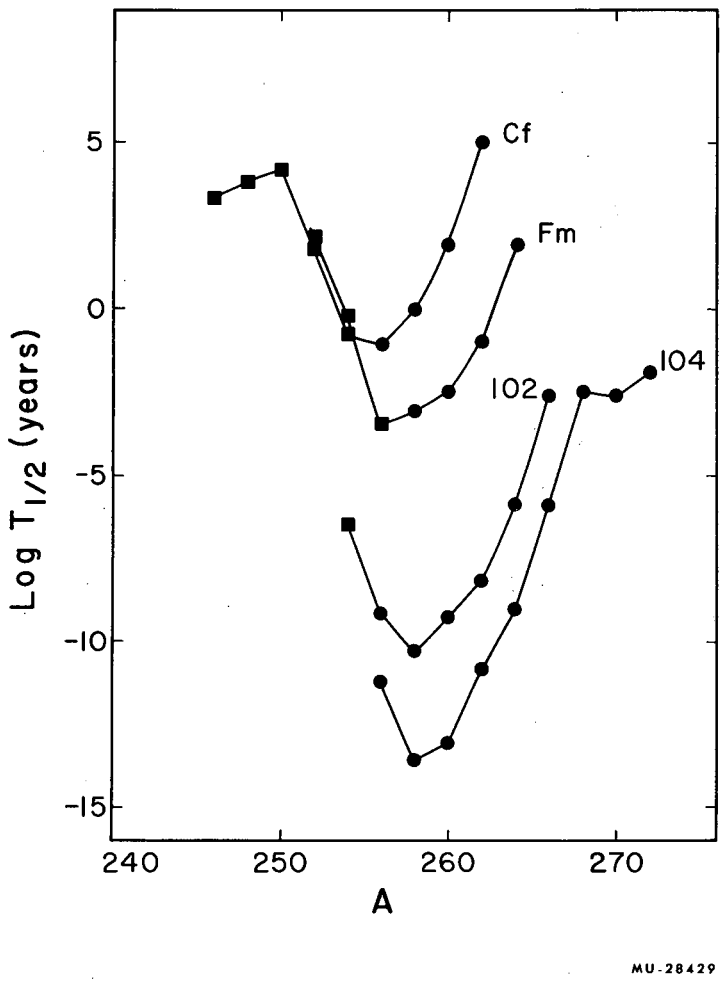

Fig. 3. Spontaneous-fission half-life of even-even isotopes of the elements Cf, Fm, 102, and 104: squares denote experimental values; cirlces predicted values.

Table I. Predicted half-lives for some even-even nuclei.

Nucleus	Log $T_{1/2}$ (years)
Cf^{256}	-1.1
Cf^{258}	-0.1
Cf^{260}	1.9
Cf^{262}	5.0
Fm^{258}	-3.1
Fm^{260}	-2.5
Fm^{262}	-1.0
Fm^{264}	1.9
102^{256}	-9.2
102^{258}	-10.3
102^{260}	-9.3
102^{262}	-8.2
102^{264}	-5.9
102^{266}	-2.6
104^{256}	-11.2
104^{258}	-13.6
104^{260}	-13.1
104^{262}	-10.8
104^{264}	-9.0
104^{266}	-5.9
104^{268}	-2.5
104^{270}	-2.6
104^{272}	-1.9

In Fig. 3, as in Fig. 2, we see the rapid drop in half-life for neutron numbers just above 152. It is also obvious that the nuclei recover rather soon and resume the trend of increasing half-life with increasing neutron number. Another important feature is the short half-lives for elements with $Z \geqslant 102$. This shows up both in the experimental value[8] for 102^{254} and in the calculated values. The cause of this sudden decrease in half-life is the same one that causes the decrease for neutron numbers above 152. The two highest protons of element 102 are originally in the 7/2-[514] level. When the deformation increases, the two protons transfer to the 1/2 + [651] level, which slopes steeply downwards. This tends to decrease the energy of the two protons relative to the smooth energy dependence expected from the liquid-drop model. Hence the barrier becomes relatively lower and the half-lives shorter. As a matter of fact, the neutron-level diagram at N = 152 and the proton-level diagram at Z = 100 are very similar. This is what one would expect from the general similarity of the level systems for various values of the quantum number N. If we take the shell between 126 and 184 and scale it down to the size of the shell between 82 and 126, we find that the position at 152 in the former shell corresponds to a position at about 102 in the latter shell. This is, of course, a very crude comparision, but it indicates that the sudden drop in lifetime at element 102 is in line with the behavior of nuclei having neutron numbers just above 152.

The results for the even-odd nuclei are presented in Table II. Here we must know which level the odd neutron populates, since the retardation of fission is entirely determined by the character of this level. Fortunately, information[9] has recently appeared about the α decay of Fm^{255}, which leads to Cf^{251}. The intrinsic levels of Cf^{251} directly give the single-particle levels above N = 152. The assumed spin values are listed in Table II.

One can get some idea of the accuracy of these values by comparing them with some experimental values that became available after the completion of this work. For Fm^{255} the theoretical value 2×10^4 years shall be compared with the experimental value 1×10^4 years.[10] A fission activity with a half-life of 11^{+10}_{-6} days has recently been discovered[11] and attributed to Fm^{257} or possibly Fm^{258}. The theoretical values are 2 months for Fm^{257} and about 1 day for Fm^{258}. Hence, in either case, the agreement is satisfactory. This agreement is somewhat better than can be expected in general.

Table II. Predicted half-lives for some odd-A nuclei.

Nucleus	Spin and Parity of odd nucleons	Log $T_{1/2}$ (years)
E^{255}	7/2 +	3.2
Fm^{259}	9/2 +	3.0
Fm^{261}	11/2 -	3.7
Mv^{259}	7/2 -	3.4
Mv^{261}	7/2 -	4.0
102^{261}	9/2 +	-3.7
102^{263}	11/2 -	-3.2
Lw^{265}	9/2 +	-0.9
Lw^{267}	9/2 +	2.4

However, here one has the advantage of knowing the values for the neighboring even-even nuclei. If one has to start out from the calculated values of Table I, the uncertainty is, of course, considerably greater.

The case of odd-even nuclei is in general the same as the previous one. However, when calculated and experimental values are compared, the calculated retardation factor is about 1000 times too small. This probably has something to do with the Coulomb energy of the odd proton. Since this proton stays in the same level all the time, its charge distribution is determined by the wave function of this level. This charge distribution might be quite different from the charge distribution of the whole nucleus. For the nuclei treated here the levels in question have small n_z values. This means that the wave function is concentrated in the region around the symmetry plane, perpendicular to the symmetry axis. Hence the charge distribution of the nucleus is not quite uniform. When the deformation of the nucleus increases, the Coulomb energy does not change exactly in the same way as if the charge distribution were uniform. Whether this effect is of the right order of magnitude to explain the discrepancies in the hindrance factor can only be decided by detailed calculations. However, in view of the considerable uncertainty of the predicted half-lives, it did not seem worth-while to spend a great amount of work on this special problem. A value for the hindrance resulting from this effect was estimated from a comparison of experimental and calculated hindrance factors for Bk and E. Half-lives estimated on this basis for some selected odd-Z nuclei are shown in Table II.

No reliable results can be obtained for odd-odd nuclei. The only experimental value known for nuclei of this type--that for E^{254}--is 1.5×10^5 years. If one assumes that both the odd proton and the odd neutron stay in their original levels, one obtains a value of 2×10^{10} years. This large discrepancy is caused by the fact that the proton and the neutron can couple together in several ways to give the total spin and parity of the nucleus. This permits the odd nucleons to jump in the level diagram so that the total energy is lower than in the limiting case considered above, in which they stay in the same orbit all the time. As a rough lower limit, one can use the mean value for the two neighboring even-even nuclei. In the case of E^{254} the experimental value falls in the middle between the upper and the lower limit, but there is no reason to believe that this is true in general.

DISCUSSION

It must be emphasized that half-lives obtained in this work cannot be expected to be quantitively correct. The level diagram used is not supported by detailed experimental information in the region of interest. There is, therefore, a considerable uncertainty in the assumed position of many of the levels that have a decisive influence on the calculations. Another difficulty is that the potential-energy surface of the fissioning nucleus is not known very well. In this work we have used results based on the liquid-drop model. It is conceivable that they can be changed by various single-particle effects.[12] An effect that has been neglected is the pairing correlation. It smears out the effect of a certain level in the level diagram and hence tends to smooth the curves of Figs. 2 and 3. However, it does not change the general trend.

Despite these difficulties the present method seems to give results that agree reasonably well with the experimental data. It is therefore likely that the main features of the extrapolation to heavier nuclei described here are correct. Of course, the most important result is that, contrary to previous estimates, the very heavy nuclei seem to be rather stable against fission. The sharp drop in half-life for nuclei with neutron numbers just above 152 is local. This is obvious also from an inspection of the level diagram. The "subshell" at N = 152 is caused by an accidental, large level distance between the neutron levels 76 and 77. This disturbance cannot be expected to have any influence over a large region of the periodic table. Furthermore, it is compensated for by the small level spacing between the next few higher levels.

It is important to realize that there is a closed neutron shell at N = 184. Nothing, of course, is known experimentally about this magic number. The only thing one can do is to calculate the levels in this region from a potential that gives good agreement in the known region. Using a Nilsson-type potential, we obtain a level diagram that shows that the magic number 184 should have an effect almost as strong as the magic number 126. Since this is only a small extrapolation from the known region, the result should be fairly reliable. This will have a decisive influence on the equilibrium shape of nuclei in this region. From what is known for lighter nuclei we expect these nuclei to have a spherical equilibrium shape. The tendency of the proton levels to deform the nucleus is not strong enough to support a stable deformation when the neutrons have a closed-shell configuration. The situation here is similar to

that in the La-Ce region where N = 82. There it is known that a stable deformation does not occur until the neutron number has increased to 90. Using these numbers we can try to estimate where the transition to a spherical equilibrium shape occurs for heavy nuclei. If we scale the size of the shells, a crude estimate of the location of the transition point gives N = 172. At this point we expect also a sudden increase in the spontaneous-fission half-lives. This is because the equilibrium shape now has the extra stability resulting from its spherical configuration, so that the barrier is relatively higher. This situation is experimentally known in the lead region. Hence, also from these considerations, we expect a high stability against fission for neutron-rich heavy nuclei.

It is important to discuss another effect pointed out by Wheeler.[13] The surface energy in the classical mass formula of Weizsäcker can be improved by correcting for the neutron-proton asymmetry. If such a correction is introduced in the liquid-drop theory of fission, it causes the fission parameter Z^2/A to depend on the neutron excess in such a way that the fission half-life decreases with increasing neutron excess. This effect evidently counteracts the general increase discussed in the preceding paragraphs. However, this effect is already included in the present calculations. This is because the variation in fissionability according to the liquid-drop model is determined in the following way: The single-particle effect is calculated for a number of nuclei with known half-lives, and the data are corrected for this effect, as described in Ref. 1. The remaining dependence on the proton and neutron numbers should be a liquid-drop effect. This dependence is then used in the extrapolation to heavier nuclei. Evidently it includes also any symmetry-dependent part of the surface energy.

In the light of the implications of our results, we can now discuss the possibility of producing superheavy nuclei. We first discuss their production by heavy ions, a method which was successfully used for elements 102 and 103 [A typical example is the reaction $Cm^{246}(C^{12}, 4n)102^{254}$]. This method leads to nuclei on the neutron-deficient side of the valley of beta stability. A possible reaction for producing an isotope of element 104 would be $Cf^{252}(C^{13}, 4n)\,104^{261}$. This isotope can be estimated to have a half-life in the millisecond range. In general this method leads to nuclei that fall around the minima in Fig. 2. It might be possible to improve the technique of detection so that some isotopes of elements 104 and 105 could be found. However, it

will certainly be impossible to do any chemistry, so the identification has to rest on their nuclear properties, such as decay modes and reaction yields. In many cases this will require reliable predictions of the nuclear properties in this region.

Next we discuss production of superheavy nuclei by neutron capture on a long time scale. The practical application consists of prolonged irradiation of a sample of some transuranium element in a high-flux reactor. Heavy elements build up via a sequence of neutron captures interrupted by beta decays. If one knows which nuclei are beta stable, it is easy to predict the reaction path. A possible path is shown in Fig. 1. Most of the neutron capture takes place in the even-Z elements, since in general they have many stable isotopes. The even-even nuclei have the shortest spontaneous-fission half-lives, and they will eventually terminate this process. A critical point is reached at Fm^{256}, which has a half-life of 3 hr. This half-life is so short that a very high flux is evidently required to build up an appreciable concentration. With such a high flux the process can easily proceed to Mv. The short half-lives for the isotopes of element 102 will finally set the end point for a reaction of this type.

Another very interesting problem is neutron capture on a short time scale (10 to 100 sec). This process is assumed to account for the production of heavy elements in supernovae explosions. The details of this process can be found in papers by Burbidge et al.,[14] Cameron,[15] and Hoyle and Fowler.[16] As in the process discussed in the preceding paragraph, we have here a sequence of neutron captures and beta decays. The difference is that because of the very high neutron flux the reaction path is located away from the line of beta stability on the neutron-rich side (Fig. 1). The nuclei here have beta half-lives of the order of 0.1 sec. This process continues until spontaneous or neutron-induced fission stops it. It is of great interest to know the position of the end point. Cameron assumes the neutron capture to proceed to the closure of the neutron shell at N = 184. Burbidge et al. estimate the process to stop at A = 260, but this figure was later revised by Hoyle and Fowler to A = 270 to 275. The latter estimate was based on the new spontaneous-fission rates given in Ref. 1, with the effect of a symmetry-dependent surface energy also taken into account. However, in this connection it should be remarked that at A = 270 to 275, the neutron number is probably above the critical value

at which a transition to a spherical equilibrium shape takes place. The increased stability against fission caused by this transition makes it rather improbable that the neutron-capture chain stops here. It seems more likely that the process either stops before the transition point at a mass of about 265 or else proceeds to the closure of the neutron shell at N = 184. In the latter case the process goes on further by alternating neutron captures and beta decays so that the neutron number stays essentially constant while the proton number increases. This leads to a rapid increase in fissionability, and in neutron binding energy, and the reaction chain will probably terminate by neutron-induced fission at a mass of about 290. At present it does not seem feasible to decide which one of these alternatives is actually occurring. This depends very critically on the path of the process, the neutron binding energy, etc.

One possibility for solving this problem might be to see if the fission-fragment mass distribution shows up as peaks in the abundance curve of the stable nuclei. In the discussion of this problem,[14, 15] it has been assumed that the mass split is asymmetric, as it is for the lighter nuclei with the same value of the fission parameter Z^2/A. However, the assumption neglects the single-particle effects. The present author has shown that these effects have an important influence on the mass distribution.[12] In the present case, an extension of the calculations for the lighter nuclei shows that the nuclei of interest here probably have an asymmetric distribution with a very low peak-to-valley ratio, or perhaps even a broad symmetric distribution. It is unlikely that such a distribution will show up clearly in the abundance curve of the stable nuclei.

Another interesting application of spontaneous-fission systematics to astrophysics lies in the problem of the light curves of Type I supernovae. These curves show a rapid drop during the first few days, but then an exponential tail appears with a half-life of about 55 days. The decay has been observed up to two years. It was suggested by Baade et al.[17] that the spontaneous fission of Cf^{254} supplies the energy during the exponential decline. Even if Cf^{254} has an abundance of only 1% of the heavy nuclei formed in the neutron-capture process, the energy release in fission is so great that a considerable amount of energy is liberated in the debris of the supernovae explosion. A detailed calculation by Hoyle and Fowler[16] shows that the orders of magnitude are right. How the conversion of this energy into visible light

takes place, and especially why the conversion factor is constant, is an unsolved problem.

A problem of interest here is why the light curves appear to have only one single component. In general, one would expect several β-stable nuclei to have spontaneous-fission half-lives in the range of 10 days to 10 years. For a discussion of this problem one must know which nuclei are β-stable in the region of interest. The predictions of Glass, Thompson, and Seaborg[18] show the following β-stable even-even nuclei: Cf^{252}, Cf^{254}, Cf^{256}, Fm^{288}, Fm^{260}, 102^{262}, 102^{264}, 102^{266}, 104^{268}, 104^{270}, etc. (The odd-A nuclei have such a low fission to α branching ratio that they need not be considered here). Elements with $Z < 98$ have such long spontaneous-fission half-lives that they cannot give any noticeable contribution to the light curve. For masses above 270, predictions became too uncertain, but the half-lives are probably comparatively short until the transition to a spherical equilibrium shape takes place, when they should become quite long. An inspection of Fig. 3 shows that for Fm and heavier elements the half-lives of the isotopes in question are shorter than a day. Several of them have half-lives of about 1 day. This might have something to do with the fact that the first, rapid decline of the light curve has a half-life of a few days.

Hence, the exponential tail of the light curves must be attributed to the Cf isotopes with masses 252, 254, and 256. Californium-252 has a half-life of 2 years, and if it is present in considerable amounts it should cause the light curve to flatten out. That this flattening does not seem to occur for some of the known light curves is rather puzzling. Possible explanations for this have been discussed by Cameron.[15] The remaining two isotopes, Cf^{254} and Cf^{256}, should then be responsible for the 55-day exponential decay. It is very interesting to note that the half-life of Cf^{254} recently has been determined to be 61 days.[10] This shows that the curve with the apparent half-life of 55 days is composed of two components. One has a half-life of 61 days and the other should have a slightly shorter half-life. It is very gratifying that the half-life of Cf^{256} is predicted to be about 40 days. If the abundance of Cf^{256} were about 30% of the Cf^{254} abundance, which is quite reasonable, a light curve with an apparent half-life of 55 days would result.

Hence the present systematics seems to give a satisfactory account for supernovae light curves. In this connection it should be pointed out that there

is considerable variation in shape among the light curves of different supernovae. The half-lives of the exponential tail vary between 40 and 60 days. Some curves have a long-lived tail. The more short-lived decays should contain relatively more Cf^{256}. A long-lived tail might indicate the presence of considerable amounts of Cf^{252}. A more detailed study of this problem might make it possible to use light curves to learn something about conditions during the explosion.

Finally, our predictions are obviously rather promising for the production of heavy nuclei in nuclear explosions. The heavier, unknown Cf, E, Fm, and Mv isotopes should be very stable against fission. The α half-life should be long also. The limiting factor would be the β half-life. For the element 102 one has to go to masses above 265 to get fission half-lives of a day or longer. A suitable, β-stable iostope would be 102^{266}. The α-particle half-life should be longer than a year according to the α-systematics. The next element, Lw, is more stable, and for masses of 265 or higher the fission half-lives should be considerably longer than a day. Convenient isotopes one might produce would be Lw^{265} and Lw^{267}. Also for these isotopes the α-particle half-life should be long enough, of the order of one year. Element 104 is more unstable against fission, and not until masses of about 270 are the half-lives long enough for a convenient detection. In this case perhaps only the odd-A isotopes will be detectable. Here the α half-lives should also be long enough for convenient detection. Element 105 is again more stable, and the half-lives of the beta-stable isotopes with masses around 270 should be more than a year. For the element 106 only the odd-A isotopes are expected to have fission half-lives long enough to permit detection. Any further extrapolation of these predictions is too uncertain to be meaningful.

For the elements 105 and 106 the α-particle half-lives become short (or the order of days or hours) if one uses a straightforward extension of the known α-particle systematics. It is therefore necessary to treat this problem in greater detail. A mass formula for deformed nuclei has been developed[19] that can be used to predict the α energies of the nuclei in question. The details of this work will be published elsewhere. It is sufficient in this connection to remark that the α energies seem to be slightly lower than an extension of the α systematics indicate, and consequently the half-lives are longer. Hence

the α decay does not seem to present any difficulty for the production and detection of these heavy nuclei.

Hence, as far as stability against spontaneous fission and α-decay is concerned, it should be possible to produce several new elements and several new isotopes of the known elements. The decisive factor is the neutron flux. Dorn's calculations[6] show that an increase of the flux by a factor of four extends the mass range by about seven units. Comparison with the experimental yield curve of the "Mike" experiment indicates that it might be possible to reach masses high enough to produce new elements.

As pointed out earlier, there is considerable uncertainty in these predictions. The actual situation might be less favorable for production of heavy nuclei than indicated here. The spontaneous-fission rates depend very critically on nuclear properties that are difficult to calculate accurately. In any case, a search for new isotopes and elements in the debris of nuclear explosions should give very important information about the spontaneous-fission systematics.

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REFERENCES

1. Sven A. E. Johansson, Nucl. Phys. 12, 449 (1959).
2. H. Diamond, P. R. Fields, C. S. Stevens, M. H. Studier, S. M. Fried, M. G. Inghram, D. C. Hess, G. L. Pyle, J. F. Mech, W. M. Manning, A. Ghiorso, S. G. Thompson, G. H. Higgins, G. T. Seaborg, C. I. Brown, H. L. Smith, and R. W. Spence, Phys. Rev. 119, 2000 (1960).
3. B. Foreman and G. T. Seaborg, J. Inorg. Nucl. Chem. 7, 305 (1958).
4. D. W. Dorn, Phys. Rev. 121, 1740 (1961).
5. W. J. Swiatecki, Phys. Rev. 100, 937 (1955).
6. D. W. Dorn, Phys. Rev. 126, 693 (1962).
7. P. A. Seeger, Nucl. Phys. 25, 1 (1961).
8. A. Ghiorso and T. Sikkeland (Lawrence Radiation Laboratory, Berkeley), private communication.
9. F. Asaro (Lawrence Radiation Laboratory, Berkeley), private communication.
10. L. Phillips, R. C. Gatti, R. Brandt, and S. G. Thompson, Lawrence Radiation Laboratory Report UCRL-10464, Sept. 1962 (unpublished).
11. R. C. Gatti, R. Brandt, L. Phillips, and S. G. Thompson, Lawrence Radiation Laboratory Report UCRL-10456, Sept. 1962 (unpublished).
12. Sven A. E. Johansson, Nucl. Phys. 22, 529 (1961).
13. R. Brandt, F. G. Werner, M. Wakano, R. Fuller, and J. A. Wheeler, Proceedings of the Conference on Nuclidic Masses (University of Toronto Press, Toronto, 1960).
14. E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Rev. Mod. Phys. 29, 547 (1957).
15. A. G. W. Cameron, Stellar Evolution, Nuclear Astrophysics, and Nucleongenesis, Chalk River Report CRL-41, Chalk River, Ontario, Canada, Atomic Energy Commission of Canada, AECL No. 454, June 1957.
16. F. Hoyle and W. A. Fowler, Astrophys. J. 132, 565 (1962).
17. W. Baade, E. M. Burbidge, F. Hoyle, G. R. Burbidge, R. F. Christy, and W. A. Fowler, Publ. Astron. Soc. Pacific 68, 296 (1956).
18. R. A. Glass, S. G. Thompson, and G. T. Seaborg, J. Inorg. and Nucl. Chem. 1, 3 (1955).
19. Sven A. E. Johansson, preprint manuscript (unpublished).

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