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α-Decay: A distinct type of spontaneous fission

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Abstract. With the help of a plot of logarithmic experimental α-decay half-life of even-even α-emitters versus the fissility parameter, it is demonstrated that α-decay is a distinct type of spontaneous fission. A simple empirical relation between experimental α-decay half-life and the fissility parameter is also given. A close examination of the nature of dependence of α-decay half-life on fissility parameter reveals that Coulomb repulsive energy accelerates the process of α-decay rather than retard it.

Keywords. α-Decay; spontaneous fission

1. Introduction

Though much has been known of the α-decay phenomenon, probably much more still remains to be known. According to Bethe (1937) and Frenkel (1946) an α-particle is constituted as a separate entity in the process of emission rather than pre-existing in the original nucleus as in the Gamow picture of α-decay. This idea of α-formation and -emission has found its logical conclusion in the 'α-decay without tunnelling' picture due to the present author (Basu 1974). Frenkel further maintains that α-decay is a distinct type of spontaneous fission. Unfortunately this suggested fission character of α-decay phenomenon has not received as much attention of workers in this field as it deserves. This is probably less due to the complexity of the problem and more due to one's eagerness to preserve this phenomenon as a class by itself contrary to the spirit of a unified approach to all physical phenomena physics is trying hard to achieve. Of course, Kramish (1952) and Studier and Huizenga (1954) have made, on the basis of Frenkel's comment, some comparative studies of α-decay and spontaneous fission as two competing modes of spontaneous fission and have drawn important conclusions about the behavioural trend of the α-decay and fission life-times of even-even isotopes with respect to the fissility parameter. But no separate study of α-decay phenomenon has, as yet, been undertaken to establish its distinct fission character. With the possibility of α-decay over the Coulomb-barrier being well-established (Basu 1974, Basu and Sen 1975) and with spontaneous fission being the only disintegration process capable of taking place over the top of the barrier (Feld 1953) Frenkel's remark has acquired added importance and relevance and calls for a serious investigation into the fission-character of α-decay.

The present study is devoted to this almost ignored aspect of the α-decay phenomenon and is purported to demonstrate that α-decay is purely a highly asymmetric type of spontaneous fission. An attempt is also made to express the α-decay half-life of members of even-even isotopic series in terms of the fissility parameter.

2. Theory

The first thorough theoretical treatment of the fission process was carried out by Bohr and Wheeler (1939). They likened a nucleus to a charged liquid drop. According to them, the nuclear shape is determined by a balance between the short-range attractive forces represented by them by the surface tension of a liquid and the Coulomb repulsive forces of the protons in the nucleus. Total surface tension effect and total Coulomb effect were then denoted by the corresponding terms in the empirical mass formula. Bohr and Wheeler then obtained the condition for fission for the case of symmetric binary fission of a nucleus and showed that the fissility of a nucleus should depend on the term Z^2/A to be called the fissility parameter of the nucleus. A nucleus to be spontaneously fissile must have its value of Z^2/A in the critical range of 18-48. The theory of fission mechanism as given by Bohr and Wheeler has become part of text-book material and therefore, needs no repetition. It must, nevertheless, be pointed out here that the fissility parameter Z^2/A is obviously proportional to the ratio of the total Coulomb repulsive energy ($\propto Z^2/A^{1/3}$) and to the total surface tension energy ($\propto A^{2/3}$) of the nucleus; and as such spontaneous fission of a nucleus is the result of a competition between the Coulomb repulsive energy trying to disrupt the nucleus and the attractive surface tension effect trying to oppose this disruption, the former winning over the latter ultimately. Though derived in consideration of symmetric fission only, Z^2/A is applied indiscriminately to the study of fission-rate, irrespective of the type of fission, symmetric or asymmetric.

3. Results and Discussion

Figure 1 is a plot of the logarithmic α-decay half-life versus the fissility parameter which evidently yields a set of perfect straight lines, each line being characteristic of an even-even isotopic series of α-emitters. Clearly enough from this plot, α-decay, half-life is a fast decreasing function of Z^2/A. Studier and Huizenga (1954) also came to the same conclusion from their study of the comparative half-life of the nuclei vis-a-vis the fissility parameter. Hyde and Seaborg (1957) plotted logarithmic spontaneous fission half-life against Z^2/A of even-even nuclei and obtained a set of more or less irregular curves contrary to the perfect straight lines obtained in figure 1. A straight line envelope to these curve may be drawn to demonstrate an exponential dependence of fission half-life on the fissility parameter which will naturally be very approximate and crude compared to the perfect exponential dependence of α-decay half-life on Z^2/A indicated in figure 1. All these observations clearly point to the fact that Z^2/A is a very faithful fissility parameter of a nucleus in the case of extremely asymmetric spontaneous fission rather than in the case of symmetric or less asymmetric fission. This is again very surprising in view of the fact that consideration of pure symmetric fission was the basis for the derivation of the parameter Z^2/A. Happily an explanation of this unexpected behaviour of Z^2/A lies hidden in the very nature of the parameter itself. As pointed out already, Z^2/A is proportional to the

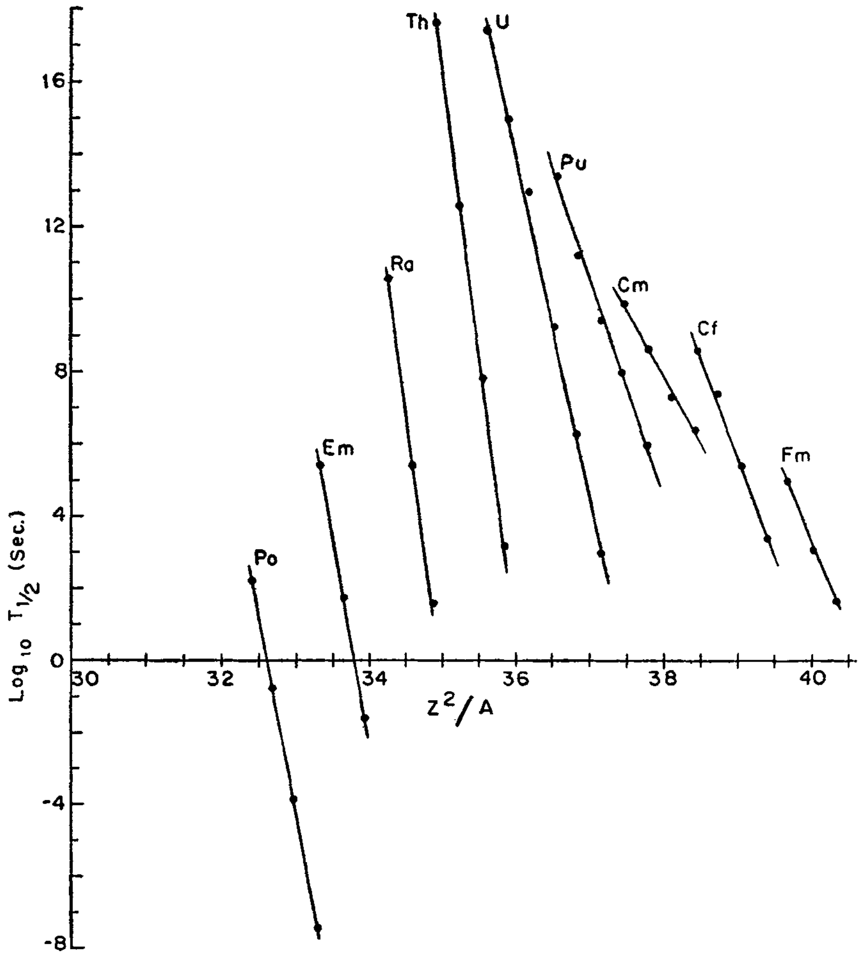

Figure 1. Plot of logarithmic experimental α-decay half-life of even even α-emitters versus Z^2/A.

ratio of the disruptive effect of the total Coulomb energy to the stabilizing effect of the total surface tension (due to the surface nucleons). As such, Z^2/A will be a reliable fissility parameter only for that type of fission in which one of the two fragments is composed of the surface nucleons only. α-Decay is one such extremely asymmetric fission in which the emitted α-particle—one of the two fission fragments, is entirely constituted of the surface nucleons (Basu 1974). Hence it is no wonder that Z^2/A turns out to be a very reliable fissility parameter for α-decay half-life. Z^2/A is again not reliably representative of less asymmetric and symmetric fission obviously because both the fission fragments, being heavy in this case, are composed not only of surface nucleons, but also of inner nucleons. Consequently, besides the surface tension effect due to the surface nucleons, other forces due to the inner nucleons also come into play in this type of symmetric or less asymmetric fission. Hence the fissility parameter for this type of fission will not be as simple as that for extremely asymmetric fission like α-decay. The more or less irregular behaviour of symmetric or less asymmetric fission half-life against Z^2/A is, therefore, expected.

As is clear from figure 1, perfect linearity of relationship between logarithmic α-decay half-life and Z^2/A demonstrates conclusively that α-decay rate of an α-emitter depends solely on Z^2/A i.e. the excess of Coulomb disruptive energy over the attractive surface energy of the nucleus. The stiff negative slope of each straight line shows, on the other hand, that α-decay rate is extremely sensitive to changes in the value of the fissility parameter. Clearly enough from the figure, α-decay half-life in any isotopic series decreases very fast with increasing value of the fissility parameter i.e. with increasing excess of Coulomb repulsive energy over the attractive surface energy in the case of isotopes with decreasing mass-number. The fact that α-decay half-life decreases with increasing Coulomb energy in the α-emitter goes to show that Coulomb repulsive energy is rather the cause of α-decay than a barrier to it. Such a simple relationship between α-decay half-life and the fissility parameter is to be traced to the fact that α-decay is a surface phenomenon (Basu 1974) and that the fissility parameter in its present form is most appropriate, as pointed out already, to this type of fission with its centre in the surface region of the nucleus. Figure 1, in short, demonstrates conclusively that α-decay is, as pointed out by Frenkel (1946), a distinct type of spontaneous fission.

Each straight line in figure 1 representative of an even-even isotopic series of α-emitters admits of an easy representation by the following equation:

$$\log_{10} T_{1/2}\,(\text{sec}) = -\,mZ^2/A + C \tag{1}$$

wherefrom one gets the following expression for the α-decay half-life of an α-emitter in terms of its fissility parameter.

$$T_{1/2} = 10^{C} \times 10^{-mZ^2/A} \tag{2}$$

m and C are characteristic constants of each isotopic series and can be easily evaluated from figure 1 and eq. (1), respectively.

Experimental fission half-life and the fissility parameter of spontaneously fissile nuclei do not admit of any such simple relationship between them as eq. (1). Seaborg (1952) has, however, given a relation between spontaneous fission half-life and the fissility parameter similar to eq. (2). But this relation is very rough and approximate, being based on the straight line envelope to the experimental curves in the plot of logarithmic spontaneous fission half-life versus Z^2/A.

The empirical relation (2) is very significant in that it clearly brings out, for the first time, the dynamic role played by Coulomb repulsive energy in the determination of α-decay rate of an α-emitter. The one-body expression for α-decay half-life in Gamow picture of α-decay is, in contrast, marked by a static and obstructive background role of Coulomb disruptive energy. It should not be difficult to appreciate from the nature of eq. (2) that Coulomb repulsive energy plays a significantly constructive role in the intra-nuclear dymamics of α-formation and α-emission. Such a conclusion is also apparent from the role of Coulomb energy in fission-mechanism. As shown elsewhere (Basu 1976), this is also exactly the conclusion of an ‘ α-decay without tunnelling ’ analysis of α-decay mechanism.

4. Conclusion

The present investigation conclusively demonstrates that α-decay is a distinct type of spontaneous fission. This finding again lends added support to the ' α-decay without tunnelling ' picture (Basu 1974) which, it should not be difficult to appreciate now, represents another version of highly asymmetric spontaneous fission-mechanism. It is in the fitness of natural scheme of things that α-decay which is not more than spontaneous binary fragmentation of a heavy nucleus turns out to be a pure case of spontaneous fission and not a separate phenomenon by itself.

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