Abnormal radioactive decays out of long-lived super- and hyper-deformed isomeric states

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Long-lived high-spin super- and hyper-deformed isomeric states, which exhibit themselves by abnormal radioactive decays, have been observed using the $^{16}$O + $^{197}$Au and $^{28}$Si + $^{181}$Ta reactions. They make it possible to understand the production, via secondary reactions, of the long-lived superheavy element with $Z = 112$ and of the abnormally low energy and very enhanced $\alpha$-particle groups seen in various actinide sources. They might also explain some puzzling phenomena seen in nature.

1. INTRODUCTION

In the past several observations were made which could not be understood under the given knowledge of nuclear physics. First\cite{1,2}, evidence for the production, via secondary reactions in CERN W targets, of a long-lived superheavy isotope $^{272}$Eka-Hg has been obtained. Fission fragments were observed in Hg sources chemically separated from the W targets, and the measured masses undergoing fission (like 308, 315 and 318) were consistently interpreted as due to 5 different common molecules (like -Cl, -N$_3$ and -NO$_2$) of a superheavy isotope with $Z=112$ (Eka-Hg), N~160. There was however no understanding of the long deduced half-life of several weeks and of the large deduced fusion cross section of several mb\cite{2,3}. In a study of actinide fractions from the same W target, long-lived isomeric states were found in the neutron-deficient $^{236}$Am and $^{236}$Bk nuclei with half-lives of 0.6 y and $\geq 30$ d, respectively\textsuperscript{[4]}. Their character was not clear, being far from closed shell nuclei, where high spin isomers are known, and living much longer than the known fission isomers. In addition, several unidentified $\alpha$-particle groups were found in some actinide sources. Thus, 5.14 MeV (t$_{1/2} = 3.8 \pm 1$ y), 5.27 MeV (t$_{1/2} = 625 \pm 84$ d) and 5.53 MeV (t$_{1/2} = 26 \pm 7$ d) groups were respectively found in the Bk, Es and Lr-No sources\textsuperscript{[4,8]} (See fig. 1). Again, one could not understand their relatively low energies (e.g., 5.53 MeV in Lr-No as compared to g.s. to g.s. transitions around 8 MeV, which have about 13 orders of magnitude larger penetrability factors), and very short half-lives ($10^5 - 10^7$ shorter than predicted from the systematics\textsuperscript{[3]}). The deduced evaporation-residue cross sections\textsuperscript{[8]}, in the mb region, are also several orders larger than expected.

A number of unexplained phenomena have also been observed in nature. Po halos,

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produced by α-particles from $^{210}$Po ($t_{1/2} = 138.4$ d), $^{214}$Po ($t_{1/2} = 164$ μs) and $^{218}$Po ($t_{1/2} = 3.0$ m), have been seen in mica [10-12]. Hulubei and Cauchois [13] saw induced Po X-rays in the mineral petzite ($\text{Ag}_3\text{AuTe}_2$). In both cases the precursors Th and U were not present.

Evidence for unidentified α-particles around 4.5 MeV have been seen in several minerals [14-17]. According to the chemistry used they were thought [16] to be due to Eka-Os (element 108). It was also suggested [17] that $^{247}$Cm may be a descendant of this superheavy element. These results were not substantially convincing. The predicted [9] half-life for such low energy α-particles in $Z = 108$ is around $10^{16}$ y, implying the existence of an impossibly large amount of material of about 0.1 g in the studied samples.

In the following a consistent possible interpretation for these phenomena will be given, based on the recently discovered [18-20] long-lived high-spin super- and hyper-deformed isomeric states.

Figure 1. **Left, top:** α-particle spectrum obtained with the Bk source. **Right, top:** α-particle spectrum obtained with the Es source. **Left, center:** Decay curve obtained with the 5.14 MeV group seen with the Bk source (left, top above). (See comment (c) in table 1 regarding the growing half-life of 2.0 y [8]). **Right, center:** Decay curve obtained with the 5.27 MeV group seen with the Es source (right, top above). **Left, bottom:** α-particle spectrum obtained with the Lr-No source. **Right, bottom:** The same as the previous one but taken about 3 months later. From a comparison of the two spectra a half-life of 26±7 d was deduced for the 5.53 MeV group.
2. SUPER- AND HYPER-DEFORMED ISOMERIC STATES
IN THE $^{16}$O + $^{197}$Au AND $^{28}$Si + $^{181}$Ta REACTIONS

The $^{16}$O + $^{197}$Au and $^{28}$Si + $^{181}$Ta reactions have been studied using beams from the Pelletron accelerator in Rehovot, catcher foil technique and long-period off-line measurements in Jerusalem. In the first reaction at $E_{Lab} = 80$ MeV [18,19], long-lived high-spin super-deformed isomeric states have been found. They exhibited themselves by decaying with relatively low energy (5.2 MeV) and very enhanced ($t_{1/2} \sim 90$ m, $3 \times 10^5$ enhancement) $\alpha$-particles in coincidence with $\gamma$-rays of a superdeformed band (SDB), and also by long-lived proton decays with half-lives of about 6 and 70 h. In the $^{28}$Si + $^{181}$Ta reaction at $E_{Lab} = 125$ MeV [7,20], about 10% below the Coulomb barrier, a high energy (7.8 - 8.6 MeV) and long-lived ($40 \text{ d} \leq t_{1/2} \leq 2.1$ y) $\alpha$-particle group was found in coincidence with SDB $\gamma$-rays (fig. 2), and consistently interpreted as due to production of a high-spin long-lived hyper-deformed isomeric state in $^{195}$Hg, which decays by a factor of $10^{13}$ retarded $\alpha$-particles to SDB states in $^{191}$Pt. ($^{195}$Hg may be produced via 1p1n evaporation reaction and 3 consecutive $\alpha$-decays. The probability that almost all the measured $\gamma$-ray energies will accidentally fit the predicted energies of a SDB transitions is $4.1 \times 10^{-8}$. (The background is zero). The high energy $\gamma$-rays are most probably sum events rather than single photo-peak events. Therefore the number of Compton events is relatively low [20]).

Figure 2. **Left:** $\alpha$ - $\gamma$ coincidence plot from one measurement of the $^{28}$Si + $^{181}$Ta reaction. $E_{Lab} = 125$ MeV, with 200 $\mu$g/cm$^2$ C catcher foil, taken for 76.8 d, starting 77.4 d after the end of irradiation. The $\gamma$ - ray energies of the encircled events fit with SDB transitions. The squared events fit with known characteristic X - rays and the events in triangles are identified with known $\gamma$ - ray transitions (see ref. [20]). **Right:** $E_\gamma$ versus $J(J+1)-(J-1)J$ for the $\gamma$ - rays seen in coincidence with 7.8 - 8.6 MeV $\alpha$ - particles. (The encircled events in the left figure plus similar events obtained in a second measurement [20]).

3. SUPER- AND HYPER-DEFORMED ISOMERIC STATES
IN THE ACTINIDES

Based on these results and on the predicted [21] excitation energies of the second and third minima in various actinide nuclei, the unidentified $\alpha$-particle groups from the
actinide fractions (Section 1) can be consistently interpreted [7,8], both from the low energy and the enhanced lifetime points of view, as due to $\Pi_{\text{min}}^{\text{II}} \rightarrow \Pi_{\text{min}}^{\text{II}}$ or $\Pi_{\text{min}}^{\text{III}} \rightarrow \Pi_{\text{min}}^{\text{III}}$ transitions (see table 1). The 5.14 MeV group in Bk grew at the beginning (fig. 1, left, center). It therefore may be due to a $\Pi_{\text{min}}^{\text{II}} \rightarrow \Pi_{\text{min}}^{\text{II}}$ transition from $^{238}\text{Am}$ or a $\Pi_{\text{min}}^{\text{III}} \rightarrow \Pi_{\text{min}}^{\text{III}}$ transition from $^{238}\text{Cm}$, which were produced from $^{238}\text{Bk}$ by the EC/$\beta^+$ process [8,4]. (Fig. 6 of ref. [8] indicates that the first case, where a rather deep second minimum is predicted [21], is more likely). The 5.27 and 5.53 MeV groups in the Es and Lr-No sources are consistent with $\Pi_{\text{min}}^{\text{III}} \rightarrow \Pi_{\text{min}}^{\text{III}}$ transitions from $^{247}\text{Es}$ and $^{252}\text{No}$, respectively.

Table 1
Predicted $\alpha$-particle energies [21] and half-lives for various transitions between super-deformed and hyper-deformed minima in Am-No nuclei. The values in bold are consistent with the experimental results mentioned in Section 1.

| Mother Isotope | $E_{\alpha}$ (MeV) | $E_{\alpha}$ (MeV) | $E_{\alpha}$ (MeV) | $t_{1/2}$ | $t_{1/2}^{\exp}$ |
|----------------|-----------------|-----------------|-----------------|-----------|-----------------|
| $^{238}\text{Am}^{\text{c}}$ | 5.94 | $5.13$ | 4.53 | 10.8 y (0.71; 0.0; 0.09) | 3.8±1 y |
| $^{238}\text{Cm}^{\text{c}}$ | 6.51 | 5.90 | $5.24$ | 0.5 y (1.05; 0.17; 0.0) | 3.8±1 y |
| $^{247}\text{Es}$ | 7.37 | 7.47 | $5.27$ | 382 d (1.05; 0.19; 0.0) | 625±84 d |
| $^{252}\text{No}$ | 8.42 | ~7.8 | ~5.6 | 81 d (1.20; 0.19; 0.0) | 26±7 d |

$^a$ Deduced from ref. [21].
$^b$ Calculated according to formulas given in refs. [8,18]. $\beta_2$ and $\beta_4$ values were deduced from the $\epsilon_2$ and $\epsilon_4$ values given in ref. [21] using fig. 2 from W. Nazarewicz and I. Ragnarsson, Handbook of Nuclear Properties. eds. D. Poenaru and W. Greiner (Clarendon Press, Oxford, 1996) p. 80. The value of $\beta_3$ was taken equal to $\epsilon_3$.

$^c$ Since the intensity of the 5.14 MeV group in Bk grew at the beginning (fig. 1, left, center), it may be due to a decay of an isotope of Cm or Am which is produced from Bk by the EC/$\beta^+$ process. (Similarly to the $^{236}\text{Bk}$ and $^{236}\text{Am}$ cases which decay to $^{236}\text{Pu}$ [4]).

Figure 3. Summary of abnormal particle decays seen in various experiments.
The long-lived isomeric states in the $^{236}\text{Am}$ and $^{236}\text{Bk}$ nuclei can be interpreted as due to the existence of super- or hyper-deformed isomers in these nuclei which decay by the EC or $\beta^+$ processes eventually to the normal states in $^{236}\text{Pu}$ [4].

Fig. 3 summarizes the various new and abnormal particle decays which were observed in different experiments. It should be mentioned that a high-spin long-lived super-deformed isomeric state has been predicted back in 1969 [22].

4. THE LONG-LIVED SUPERHEAVY ELEMENT WITH Z = 112

The experiments [1,2] concerning element 112 can now be understood as due to its production in a long-lived super- or hyper-deformed isomeric state, rather than in the ground state. The large deduced fusion cross section is due to two effects. a) Very little extra-push energy is needed in order to produce the compound nucleus in such a state. b) The fusion probability in the secondary reactions, where the projectile is itself a deformed fragment produced just within $2\times10^{-14}$ s before interacting with another W nucleus in the target, is much larger as compared to fusion with a normal projectile, due to the much reduced Coulomb repulsion [23].

5. ISOMERIC STATES AND SUPERHEAVY ELEMENTS IN NATURE?

The discovered high spin super- and hyper-deformed isomeric states may be the source for the Po halos [10–12] (either in the $^{210}\text{Po}$, $^{214}\text{Po}$ and $^{218}\text{Po}$ isotopes which decay by $\gamma$’s to the ground states, or in the appropriate Pb or Bi nuclides which decay by $\beta^-$ to the corresponding Po isotopes), and also for the observed Po induced X-rays in petzite [13].

![Figure 4](image_url)

Figure 4. Predictions [21], and extrapolations from these predictions, of the $\text{III}^{\text{min}} \rightarrow \text{III}^{\text{min}}$ $\alpha$-particle energies. The black dots are the predictions for various isotopes of Z=96 and Z=100. The straight lines are extrapolations from these predictions for Z=108 and Z=112. The open triangle shows the position of the 6.73 MeV $\alpha$-particles seen with the Hg sources from the CERN W targets [4]. The open circle shows the position of 4.5 MeV $\alpha$-particles in Z=108.

The low energy $\alpha$-particles around 4.5 MeV [14,17] may consistently be interpreted as due to a very enhanced $\text{III}^{\text{min}} \rightarrow \text{III}^{\text{min}}$ transition in Z~108 and A~271. The predicted
The half-life in this case is around $10^9$ y, which implies an amount of material of about 10 ng. This resolves the main difficulty in understanding these data where an impossible amount of 0.1 g was deduced assuming a normal $\alpha$-transition (see the Introduction). In addition, an extrapolation of the predictions of $\alpha$-energies of $\text{III}^{\text{min}} \rightarrow \text{II}^{\text{min}}$ transitions (see fig. 4), shows that for $Z=108$, $E_{\alpha}$ of about 4.5 MeV corresponds to $N \sim 162$. This is consistent with the suggestion that $^{247}\text{Cm}$ may be a descendent of the superheavy element with $Z=108$ which decays by the 4.5 MeV $\alpha$-particles, since $^{247}\text{Cm}$ can be obtained from $^{271}$Hs$_{163}$ by successive 6 $\alpha$-decays. It should however be mentioned that in principle the above 4.5 MeV $\alpha$-particles may also be due to a very retarded $\text{II}^{\text{min}} \rightarrow \text{I}^{\text{min}}$ or $\text{III}^{\text{min}} \rightarrow \text{II}^{\text{min}}$ transition in the region of Os itself. (For normal 4.5 MeV $\alpha$-particles in Os the expected half-life is about 1 y. Such short-lived nuclide can not exist in nature).

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