International Journal of Modern Physics E
Vol. 12, No. 5 (2003) 661–668

COHERENT DESCRIPTION FOR HITHERTO UNEXPLAINED RADIOACTIVITIES BY SUPER- AND HYPERDEFORMED ISOMERIC STATES

A. MARINOV* and S. GELBERG

The Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel
**marinov@vms.huji.ac.il*

D. KOLB

Department of Physics, University GH Kassel, 34109 Kassel, Germany

R. BRANDT

Kernchemie, Philipps University, 35041 Marburg, Germany

A. PAPE

IReS-UMR7500, IN2P3-CNRS/ULP, BP28, F-67037 Strasbourg Cedex 2, France

Received 9 March 2003

Recently, long-lived high spin super- and hyperdeformed isomeric states with unusual radioactive decay properties have been discovered. Based on these newly observed modes of radioactive decay, consistent interpretations are suggested for previously unexplained phenomena seen in nature. These are the Po halos, the low-energy enhanced 4.5 MeV α-particle group proposed to be due to an isotope of a superheavy element with $Z = 108$, and the giant halos.

Keywords: Superheavy elements; alpha decay; proton decay; isomeric states; superdeformation; hyperdeformation.

PACS Number(s): 23.60.+e, 21.10.Tg, 23.50.+z, 27.90.+b

1. Introduction

Despite the intensive study of nuclear physics and radioactivity for more than a century, there are still several unexplained phenomena seen in nature. In the present paper we consider three such phenomena. The first is that of the Po halos observed in mica,[1,2] where the concentric halos correspond to the α-particle decay chains of ^{210}Po, ^{214}Po and ^{218}Po.[a] Since the lifetimes of these isotopes are short and halos

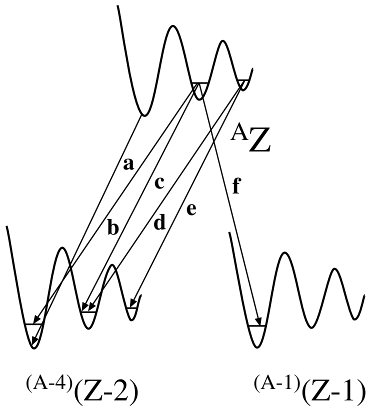
[a]Color pictures of various halos are given in Ref. 3.

belonging to their long-lived precursors from the ^{238}U decay chain are absent, their origin is puzzling. The second unexplained phenomenon is the observation[4–7] in several minerals, using solid state detectors, of a low energy 4.5 MeV α-particle group with an estimated[4] half-life of $(2.5 \pm 0.5) \times 10^8$ years which, based on chemical behavior, has been suggested to be due to the decay of an isotope of Eka-Os ($Z = 108$; Hs). However, 4.5 MeV is a low energy compared to the predicted 9.5–6.7 MeV for β-stable isotopes of Hs,[8–10] and $T_{1/2} = 2.5 \times 10^8$ years is too short by a factor of 10^8, compared to predictions[11,12] from the lifetime versus energy relationship for normal 4.5 MeV α-particles from Hs. Still another unexplained phenomenon is that of the giant halos.[13] Halos, with radii which may correspond to 10 and 13 MeV α-particles, have been seen in mica.[13] Unlike the situation with the Po halos, here it is not absolutely certain that their origin is from such high energy α-particles.[13–15] However, if they are, then their existence is unexplained. For nuclei around the β-stability valley, 10 and 13 MeV α-particles are respectively predicted[8–10] for Z values around 114 and 126. The estimated[12] half-life for 10 MeV α's in $Z = 114$ nuclei is about 1 s, and for 13 MeV α's in $Z = 126$ nuclei, it is about 10^{-4} s. It is not clear how such high-energy α-particles with such short predicted lifetimes can exist in nature.[b] The purpose of this paper is to propose consistent interpretations for the three unexplained phenomena, based on the recently discovered[18–21] high spin long-lived super- and hyperdeformed isomeric states and their unconventional decay properties. Preliminary results have been presented before.[22,23]

2. Super- and Hyperdeformed Isomeric States and Abnormal Radioactive Decays

In a study of the ^{16}O + ^{197}Au (Refs. 18 and 19) and ^{28}Si + ^{181}Ta (Ref. 20) reactions at and below the Coulomb barrier, unusually low energy very life-time-enhanced α-particle group[18] on the one hand, and high energy strongly retarded α-particles[20] on the other hand, have been observed in coincidence with superdeformed (SD) γ-ray transitions. In addition, long-lived proton radioactivities[19,20] have been found. These unusual radioactive processes have been explained as due to long-lived high spin super- and hyperdeformed (HD) isomeric state.[c] The situation is summarized schematically in Fig. 1. A SD isomeric state can decay by emitting very enhanced α-particles to a similar state of the daughter nucleus, or by strongly retarded α-particles to a normal deformed state or the ground state (g.s.) of the daughter. It can also decay by retarded proton radioactivity. Similarly, a HD isomeric state can decay by retarded α-particles to SD states, or by enhanced α-particles to HD states of the daughter nucleus. As mentioned above all these unusual radioactive decays have been seen experimentally.[18–21]

[b] On the stability of superheavy elements as predicted in the late sixties of the previous century and on the current situation see Refs. 16 and 17, respectively.
[c] Experimental evidence for hyperdeformed states in U isotopes has been seen in Ref. 24.



(a) $I^{min} \rightarrow I^{min}$. Normal α's.
(b) $II^{min} \rightarrow I^{min}$. Retarded α's (Ref. 20).
(c) $II^{min} \rightarrow II^{min}$. Enhanced α's (Ref. 18).
(d) $III^{min} \rightarrow II^{min}$. Retarded α's (Ref. 20).
(e) $III^{min} \rightarrow III^{min}$. Enhanced α's (Ref. 21).
(f) $II^{min} \rightarrow I^{min}$. Retarded protons (Refs. 19, 20).

Fig. 1. Summary of new types of particle decays seen in different experiments.

These isomeric states have already been used[21] to interpret previously low energy unidentified α-particle groups seen in actinide sources produced by secondary reactions in a CERN W target,[25] and to explain the production,[25] in the same W targets, of a long-lived superheavy element with $Z = 112$, which was based on the observation of fission fragments in separated Hg sources, and on measurements of the masses of the fissioning nuclei.[26]

3. Super- and Hyperdeformed Isomeric States and the Puzzling Phenomena Seen in Nature

As stated above, the discovery of these isomeric states with their unusual decay properties enables one to also explain the previously unexplained phenomena seen in nature.

The Po halos[1,2] may be due to similar isomeric states in nuclei with $Z \approx 84$ which eventually decay by β- or γ-decays to the g.s. of ^{210}Po, ^{214}Po and ^{218}Po.

The observed[4–7] 4.5 MeV α-particle group might be due to an enhanced $III^{min} \rightarrow III^{min}$ (HD $\rightarrow$ HD) transition in a $Z = 108$, $A \approx 270$ nucleus. By using various possible deformation parameters for the third minimum, the predicted[21] half-life for such a transition, as seen in Table 1, is around 10^9 years. This value is in reasonable agreement with the experimental estimate[4] of around 2.5×10^8 years and it differs greatly from the predicted value[11,12] of about 5×10^{16} years for a normal 4.5 MeV α-transition from $Z = 108$.

Furthermore, in Fig. 2 deduced α-particle energies for $III^{min} \rightarrow III^{min}$ transitions for some isotopes of Cm and Fm are presented. These energies were obtained from the predicted excitation energies[27] of the third minima in the relevant parent and daughter nuclei and from the known[30] or predicted[10] g.s. to g.s. Q_α values. The Q_α values for $III^{min} \rightarrow III^{min}$ transitions are much lower than the corresponding g.s. to g.s. values (see also Table 1 of Ref. 21), since the excitation energy of the III^{min}

Table 1. Calculated half-lives for hyperdeformed to hyperdeformed α-particle transition of 4.5 MeV from ^{271}Hs assuming various deformation parameters.[21]

β_2	β_3	β_4	$t_{1/2}$ (y)
1.2[a]	0.0[b]	0.0[a]	1.8×10^{11}
1.2[a]	0.19[c]	0.0	4.6×10^{9}
0.85[d]	0.35[d]	0.18[d]	1.3×10^{8}

[a] ϵ_2 and ϵ_4 values for ^{248}Fm were taken from Ref. 27 and converted to β_2 and β_4 values by extrapolation from the curves given in Fig. 2 of Ref. 28.
[b] Assuming $\beta_3 = 0$.
[c] Assuming $\beta_3 = \epsilon_3$ of Ref. 27.
[d] Parameters given in Ref. 29 for ^{232}Th.

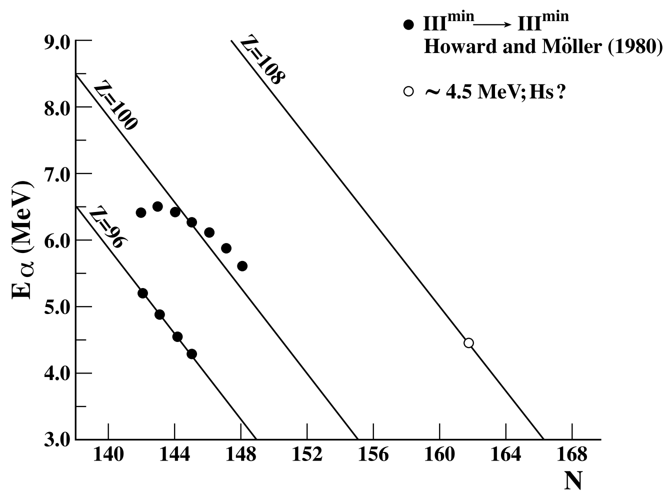


Fig. 2. Predictions,[27] and extrapolations for $\mathrm{III}^{min} \rightarrow \mathrm{III}^{min}$ α-particle energies. The black dots are the predictions for various isotopes of $Z = 96$ and $Z = 100$. The straight lines are extrapolations from these predictions. The open circle shows the position of 4.5 MeV α-particles in $Z = 108$.

in the parent nucleus is predicted to be at a lower value than in the daughter. An extrapolation of the deduced $\mathrm{III}^{min} \rightarrow \mathrm{III}^{min}$ transition energies to $Z = 108$ gives an E_α value of about 4.5 MeV for $N \approx 162$. This is consistent with the suggestion[7] that ^{247}Cm may be a descendent of an element with $Z = 108$ which decays by the 4.5 MeV α-particles, since ^{247}Cm can be obtained from ^{271}Hs ($N = 163$) by six successive α-decays. Another possibility is that the long-lived isotope is ^{267}Hs which decays first by 4.5 MeV α's, and then by two electron capture (EC) or β^+ decays and four α-decays to ^{247}Cm. This scenario allows for a transition from the third minimum to the first minimum because of the total positive Q-value of the

β(EC) decays of about 5 MeV.[8–10] (Transitions from isomeric states to normally deformed states by β(EC) decays have been seen before.[31])[d]

Notwithstanding the uncertainty mentioned above about the origin of the giant halos, let us now suggest a possible interpretation for these halos assuming that they are due to α-particles of around 10 and 13 MeV. It has already been pointed out[14,15] that the giant halos are associated with smaller halos. For instance, in the giant halo seen in Fig. 1 of Ref. 13, where the outer ring corresponds to α-particles of about 10 MeV, one sees also a central black zone which could be due to low-energy α-particles of 4.8 MeV. A good candidate for the sequence of events producing this halo is a long-lived HD isomeric state decaying by a 4.8 MeV $\mathrm{III}^{min} \to \mathrm{III}^{min}$ α-transition, followed by β^+(EC) transitions to a normal state which decays by 10 MeV α-particles. As a specific example, one may consider the following scenario where a HD isomeric state in $^{282}114$ decays by 4.8 MeV α's to a HD isomeric state in $^{278}112$, followed by two β^+(EC) decays to a normal deformed state or to the g.s. of $^{278}110$. This latter nucleus is predicted[8–10] to decay by 10 MeV α-particles. For the deformation parameters given in Table 1, the predicted $T_{1/2}$ value for a 4.8 MeV $\mathrm{III}^{min} \to \mathrm{III}^{min}$ α-transition from $^{282}114$ is 10^8–10^{11} years, and the sum of the two Q_β of above 6 MeV (Refs. 8–10) makes the transition from the isomeric state in the third minimum to a normal state in one of the daughter nuclei possible.

Finally, let us consider the giant halo presented in Fig. 3 of Ref. 13 which would correspond to 13.1 MeV α-particles. Here too, in addition to the large halo, one sees a small dark ring with an inner radius which, if caused by α-particles, correspond to a low energy of about 5.1 MeV.[e] Similarly to the situation above, one can propose as a scenario for this halo a HD isomeric state in $^{316}126$ which decays by a $\mathrm{III}^{min} \to \mathrm{III}^{min}$ low-energy α-transition to $^{312}124$, followed by two β^+(EC) transitions, leading to the g.s. of $^{312}122$. The $^{312}122$ nucleus is predicted[8,9] to decay by α-particles of around 13 MeV. For a 5.1 MeV HD to HD α-transition from $^{316}126$ the predicted[21] half-life, using the parameters of Ref. 29 (Table 1, last line) is 3×10^{11} years. (Longer lifetimes are obtained for the other sets of parameters in Table 1, whereas larger deformation parameters, and consequently shorter lifetimes, may exist in the nucleus $^{316}126$ compared to ^{232}Th for which the parameters in Ref. 29 were predicted.) Thus, a consistent picture for the giant halo is possible if 5.1 MeV α-particles are the origin of the small halo within the larger one.[f]

[d] It should, however, be mentioned that in principle the above 4.5 MeV α-particles may also be due to a strongly retarded $\mathrm{II}^{min} \to \mathrm{I}^{min}$ or $\mathrm{III}^{min} \to \mathrm{II}^{min}$ transition in the region of Os itself. Such transitions have been seen in the Os–Ir–Hg region[20] though with half-lives of several months. (For normal 4.5 MeV α-particles in Os the expected[11,12] half-life is about 1 year. Such short-lived nuclides cannot exist in nature).

[e] The widening of this ring is probably due to an overexposure effect. Compare for instance Figs. 1l and 1i of Ref. [32] where the halo from the 6.0-MeV α-group in Fig. 1l is quite wide.

[f] Overexposure and blurring effects might be the reasons why inner ring structure due to successive disintegrations after the high energy α-decays are not seen in Figs. 1 and 3 of Ref. 13, since: "Also in the Th-U halos, where about 10^5 of them have been studied,[32] most have centers > 20 microns diameter, which generally produces halos without distinct inner ring structure, whereas

It should, however, be mentioned that the existence of low energy α-particle groups is not a necessary initial step for observed giant halos. HD isomeric states which decay by EC(β) finally to the g.s. of superheavy nuclei, can explain such giant halos as well.

Let us finally touch on the problem why these SD and HD isomeric states which were used by us to explain the above phenomena do not decay by fission. Their long lifetimes in the region of 10^9 years, also against fission, are probably due to the combined effect of the potential barrier and the high spin of the state. As a matter of fact, back in 1969[33] a new type of fission isomeric state was predicted for nuclei with $N \approx 144$–150. A specialization energy[34] in excess of 4 MeV for the second barrier was predicted for a $[505]\frac{11}{2}^-$ state, which is associated with a factor of about 10^{15} increase in the half-life of a normal fission shape isomer.

4. Possible Scenarios for Production of Superheavy Elements in Nature

It is worthwhile mentioning that a natural way to produce HD high spin isomeric states is by heavy ion reactions. First, high spin states are produced by these reactions, and secondly, as seen in Fig. 8 of Ref. 21, for suitable projectile-target combinations, the shape of the compound nucleus in the third minimum fits with the shape of the projectile and target nuclei at the touching point, and very small penetration and dissipation energies are involved in the reaction. The above isotopes $^{267}108$, $^{282}114$ and $^{316}126$ could presumably be produced by the following cold fusion reactions:

(i) $^{208}\text{Pb} + {}^{60}\text{Fe} \rightarrow {}^{267}\text{Hs} + \text{n}$ ($Q_{\text{value}} = -214$ MeV; C.B. = 223 MeV)
(ii) $^{208}\text{Pb} + {}^{74}\text{Ge} \rightarrow {}^{282}114$ ($Q_{\text{value}} = -262$ MeV; C.B. = 267 MeV)
(iii) $^{232}\text{Th} + {}^{84}\text{Kr} \rightarrow {}^{316}126$ ($Q_{\text{value}} = -319$ MeV; C.B. = 317 MeV)
(iv) $^{238}\text{U} + {}^{78}\text{Se} \rightarrow {}^{316}126$ ($Q_{\text{value}} = -302$ MeV; C.B. = 307 MeV),

where the projectile and target nuclei are stable or quasi-stable isotopes. (C.B. is the Coulomb barrier between the projectile and the target nucleus for a radius parameter $R_0 = 1.4$ fm).

5. Summary

In summary, it has been shown that the newly discovered long-lived super- and hyperdeformed isomeric states and their unusual radioactive decay properties enable one to understand certain previously puzzling phenomena seen in nature. Thus, the Po halos can be understood as being due to the existence of such isomeric states in nuclei around ^{210}Po, ^{214}Po and ^{218}Po which undergo β- and γ-decays to the ground states of these isotopes. Likewise, the low-energy enhanced 4.5 MeV α-particle

only relatively few possess the tiny, micron-size centers necessary to produce halos with distinct rings." (Private communication from R. V. Gentry).

group[4–7] can be quantitatively understood as a hyperdeformed to hyperdeformed transition from an isotope with $Z = 108$, $A \approx 270$. Finally, it has been shown that the giant halos can be consistently interpreted as being due to 10 and 13 MeV α-particles following low energy $\mathrm{III}^{min} \rightarrow \mathrm{III}^{min}$ transitions in superheavy nuclei around $Z = 114$ and $Z = 126$, respectively, which eventually decay to normal states emitting such high-energy α-particles. The existence in both cases of halos with small radii, which might be related to hyperdeformed to hyperdeformed transitions, along with the large halos, lends support to this scenario. It has, however, been pointed out that the existence of low energy α-particle groups as an initial step is not a necessary condition for the interpretation of giant halos. III^{min} isomeric states which decay by EC(β) and γ-rays finally to the ground states of superheavy nuclei would lead to giant halos as well.

Based on the above it seems to us that the search for superheavy elements in nature should be pursued.

Acknowledgments

We appreciate valuable discussions with R. V. Gentry, J. L. Weil and N. Zeldes. D. Kolb acknowledges financial support from the DFG.

References

1. G. H. Henderson and F. W. Sparks, *Proc. Roy. Soc. Lond.* **A173**, 238 (1939).
2. R. V. Gentry, *Science* **160**, 1228 (1968).
3. R. V. Gentry, *Creation's Tiny Mystery* (Earth Science Associates, Knoxville, Tennessee, 1992).
4. V. V. Cherdyntsev and V. F. Mikhailov, *Geochemistry* No. 1, 1 (1963).
5. R. D. Chery, K. A. Richardson and J. A. S. Adams, *Nature* **202**, 639 (1964).
6. V. V. Cherdyntsev, V. L. Zverev, V. M. Kuptsov and G. I. Kislitsina, *Geochemistry* No. 4, 355 (1968).
7. H. Meier *et al.*, *Z. Naturforsch.* **25**, 79 (1970).
8. P. Möller, J. R. Nix and K.-L. Kratz, *At. Data Nucl. Data Tables* **66**, 131 (1997).
9. H. Koura, M. Uno, T. Tachibana and M. Yamada, *Nucl. Phys.* **A674**, 47 (2000); RIKEN-AF-NP-394 (April 2001).
10. S. Liran, A. Marinov and N. Zeldes, *Phys. Rev.* **C62**, 047301 (2000); arXiv:nucl-th/0102055.
11. V. E. Viola, Jr. and G. T. Seaborg, *J. Inorg. Nucl. Chem.* **28**, 741 (1966).
12. G. Royer, *J. Phys. G: Nucl. Part. Phys.* **26**, 1149 (2000).
13. R. V. Gentry, *Science* **169**, 670 (1970).
14. R. Brandt, *Proc. Int. Symp. on Superheavy Elements*, ed. M. A. K. Lodhi, Lubbock, Texas (1978) p. 103.
15. D. Molzahn, R. Brandt, R. Helmbold, H. Jungclas and P. Vater, *Nuclear Tracks* **4**, 4 (1980).
16. U. Mosel and W. Greiner, *Z. Phys.* **222**, 261 (1969).
17. W. Greiner, *J. Nucl. and Radiochemical Sci.* **3**(1), 159 (2002).
18. A. Marinov, S. Gelberg and D. Kolb, *Mod. Phys. Lett.* **A11**, 861 (1996).
19. A. Marinov, S. Gelberg and D. Kolb, *Mod. Phys. Lett.* **A11**, 949 (1996).

20. A. Marinov, S. Gelberg and D. Kolb, *Int. J. Mod. Phys.* **E10**, 185 (2001).
21. A. Marinov, S. Gelberg, D. Kolb and J. L. Weil, *Int. J. Mod. Phys.* **E10**, 209 (2001).
22. A. Marinov, S. Gelberg, D. Kolb, R. Brandt and A. Pape, *Proc. 3rd Int. Conf. on Exotic Nuclei and Atomic Masses ENAM 2001*, eds. J. Äystö *et al.*, Hämeenlinna, Finland, 2–7 July, 2001 p. 380 (Springer).
23. A. Marinov, S. Gelberg, D. Kolb, R. Brandt and A. Pape, *Phys. At. Nucl.* **66**, 1137 (2003); *Yad. Fiz.* **66**, 1173 (2003); a paper presented at *VII Int. School-Seminar on Heavy Ion Physics*, May 27–June 1, 2002, Dubna, Russia.
24. A. Krasznahorkay *et al.*, *Phys. Rev. Lett.* **80**, 2073 (1998).
25. A. Marinov, C. J. Batty, A. I. Kilvington, G. W. A. Newton, V. J. Robinson and J. D. Hemingway, *Nature* **229**, 464 (1971).
26. A. Marinov, S. Eshhar, J. L. Weil and D. Kolb, *Phys. Rev. Lett.* **52**, 2209 (1984); (E) **53**, 1120 (1984).
27. W. M. Howard and P. Möller, *At. Data and Nucl. Data Tables* **25**, 219 (1980).
28. W. Nazarewicz and I. Ragnarsson, *Handbook of Nuclear Properties*, eds. D. N. Poenaru and W. Greiner (Clarendon Press, Oxford, 1996) p. 80.
29. S. Ćwiok, W. Nazarewicz, J. X. Saladin, W. Plóciennik and A. Johnson, *Phys. Lett.* **B322**, 304 (1994).
30. G. Audi and A. H. Wapstra, *Nucl. Phys.* **A565**, 66 (1993).
31. A Marinov, S. Eshhar and D. Kolb, *Phys. Lett.* **B191**, 36 (1987).
32. R. V. Gentry, *Science* **184**, 62 (1974).
33. S. G. Nilsson, G. Ohlén, C. Gustafson and P. Möller, *Phys. Lett.* **30B**, 437 (1969).
34. J. A. Wheeler, *Physica* **22**, 1103 (1956).