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A Theoretical Review & Structure of Exotic Nuclei

Nidhi Sharma*

M.Sc. Physics, B.Ed., #449, Sector-13, Urban Estate, Kurukshetra, Haryana, India

Abstract – The exotic decay can be treated as a case of strong asymmetric fission or an exotic process of cluster formation and tunneling through the barrier making many assaults on the barrier similar to a decay. So all theoretical attempts made so far originate either from Garnow theory of alpha decay or nuclear fission. Exotic decay was first predicted by Sandulescu et. al., in 1980 based on the quantum mechanical fragmentation theory (QMFT). In paper we gave a brief description of QMFT and details of some theoretical models. In paper an improved model incorporating ground state deformation of both parent and daughter, treating emitted cluster as sphere is given and the effect of deformation on half life time is studied in the case of experimentally observed decay modes. We studied fine structure (decay to various excited states of the daughter) for some decay modes and calculated the hindrance factor for the decay of 223~bay emitting 14cc luster to various excited states of the daughter.

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INTRODUCTION

The spontaneous decay of radioactive nuclei with the emission of clusters heavier than alpha particle, without being accompanied by neutron emission, is termed as exotic decay or cluster radioactivity. This rare, cold process is intermediate between alpha decay and spontaneous fission. The rare nature of this process stems from the fact that this process is masked by a large number of a decay events. In exotic decay the energy released as Q value is completely consumed by the kinetic energy alone of the two fragments. Exotic decay of superdeformed 76~r1,8 sr and 80~writ h the estimated qudrapole deformations P = 0.35 to 0.44 in the ground state and decay of these nuclei produced as an excited compound system in heavy ion reaction are presented in Paper Exotic decay of 11 heavy nuclei with *Z* ***2*** 100 are studied with a view to look for some measurable modes of decay which in turn can lead to the production of some other new heavy or super heavy nuclei as daughter. Paper gives the details of this study. The exotic decay can be treated as a case of strong asymmetric fission or an exotic process of cluster formation and tunneling through the barrier making many assaults on the barrier similar to *a* decay. So all theoretical attempts made so far originate either from Garnow theory of alpha decay or nuclear fission. Exotic decay was first predicted by Sandulescu et. al., in 1980 based on the quantum mechanical fragmentation theory (QMFT). In Paper 2 we gave a brief description of QMFT and details of some theoretical models. In the present study, we have developed a model to explain the exotic decay taking the Coulomb and proximity potential **as** the interacting barrier, the details of which are given in Paper 2 as the present model. The main objective in this study includes verification of the model by reproducing the available experimental data and the comparison of the present model with other models. As a part of this we have also studied the transition fiom cluster mode to fission mode. A brief description of the experimental methods usually used in exotic decay studies and a short review of the experimentally observed modes of decay are given in Paper **3.** In Paper 4, the present model is applied to experimentally observed decay modes and also to proton rich Xe to Gd parents in the trans-tin region emitting clusters ranging fiom *a* particle to sulphur. This region far from the P stability line can be produced in heavy ion induced reactions. These studies are extended to neutron rich Ba to Gd parents to examine the role of doubly magic 132~dnau ghter in these decays.

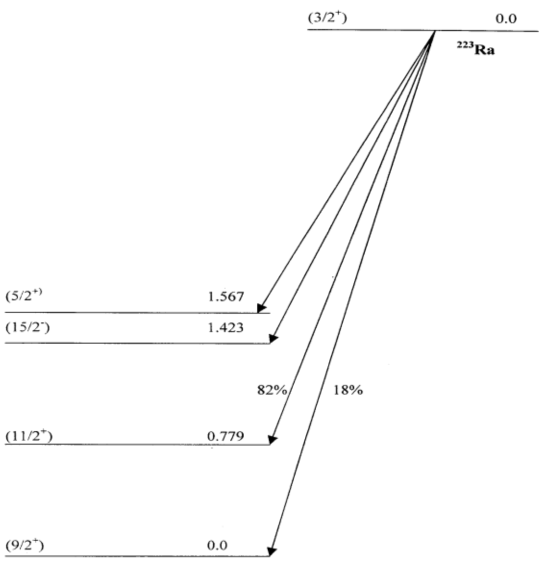
STRUCTURE OF EXOTIC NUCLEI

Logarithm of half life time and other characteristics for "C fine structure from 221~2r,2 5a~re~ given in Table 6.2 and Table 6.3 respectively. Tables 6.4 and 6.5 show 24~fiene structure from 231~2a3, 3r~es pectively. Hindrance factor pattern observed in 14c decay of 223~isa s imilar to hindrance factor pattern observed in alpha decay of 227~hw,h ere both the parents have reflection asymmetric deformed shape [I 101. This pattern results because ground state of the parent is parity mixed state, very different from the ground state (912') of daughter but very similar to the parity mixed excited state (1 1/2'state) of daughter. There are different definitions for Hindrance factor (HF), some of them are related to model dependent parameter (eg. reduced width) [68,106,107] In analogy to the barrier penetration theory of alpha decay, all transitions other than ground state to ground state transition of even-even nuclei are observed to be slower than the theoretical predictions and are said to be hindered. This odd-even effect of parent nuclei is denoted by a quantity called hindrance factor (HF), simply a ratio between calculated (theoretical)

and measured decay constant or ratio between experimental half life time and theoretical half life time [72]. Conventionally a transition is favoured if hindrance factor is low close to 1 and is hindered if it is greater than 5.

HF= *-R=c-o* , ***TSTt*** *R,, T:*

For fine structure studies we included centrifugal term V, = ti2e(e + 1) in the *2pr2* interacting potential barrier. The angular momentum ***I*** is determined from the spin and parity conservation



In a recent experiment, with maximum resolution of "C ion [9O KeV full width at half maximum (FWHM)] and with no alpha particle background done in l995 by Hourani et a1 [68], a total number of 899 C events were recorded, 130 events for transition to ground state of 209~b76, 8 events leading to lSt excited state and a solitary event at the location of **4th** excited state. No event was detected at the location of 2"d and 3rd excited states.

Hindrance Factor

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RESULT & DISCUSSION

When deformation effects are included, half life time value is found to decrease slightly. When logarithm of predicted half life time obtained treating parent and fragments as spherical are compared ~itthha t for deformed parent and daugh -ter it is found that deviation (change) in half life time value increases with increase in mass of the parent and also with increase in mass of the cluster. When deformation of parent alone is taken there is appreciably no deviation in half life time value. This is because parent deformation affects relatively small pre scission part of the barrier but it will not affect the barrier corresponding to separated fragments. In asymmetric disintegration most of the barrier corresponding to separated fragments.

Table 5.1. Comparison of calculated values of logarithm of half life time for the case with out deformation (a), with parent and daughter deformation (b), with daughter deformation (c), with parent deformation (d), with experimental values.

Parent nuclei	Daughter nuclei	Emitted cluster	Q value (MeV)	Deformation Parent β_2	daughter β_4	β_2	$\log_{10}(T_{1/2})$ (a)	(b)	(c)	(d)	Expt.
^{221}Fr	^{207}Tl	^{14}C	31.28	0.098	-0.060	0.003	13.90	13.73	13.79	13.85	14.52
^{221}Ra	^{207}Pb		32.39	0.098	-0.060	0.003	12.58	12.41	12.46	12.52	13.39
^{222}Ra	^{208}Pb		33.05	0.104	-0.060	0.003	11.07	10.90	10.96	11.01	11.01
^{223}Ra	^{209}Pb		31.85	0.138	-0.075	0.003	13.69	13.45	13.58	13.56	15.04
^{224}Ra	^{210}Pb		30.53	0.144	-0.075	0.003	16.74	16.45	16.62	16.55	15.68
^{225}Ac	^{211}Bi		30.48	0.151	-0.080	0.003	18.03	17.72	17.92	17.83	17.16
^{226}Ra	^{212}Pb		28.21	0.151	-0.080	0.003	22.55	22.21	22.44	22.31	21.34
^{230}Th	^{206}Hg	^{24}Ne	57.78	0.185	-0.075	-0.003	26.00	25.34	26.19	25.17	24.61
^{231}Pa	^{207}Tl		60.42	0.185	-0.080	0.003	22.56	21.70	22.36	21.87	22.88
^{232}U	^{208}Pb		62.31	0.192	-0.080	0.003	20.72	19.83	20.52	20.01	20.40
^{233}U	^{209}Pb		60.50	0.192	-0.080	0.003	24.15	23.16	23.95	23.34	24.84
^{234}U	^{210}Pb		58.84	0.198	-0.075	0.003	27.39	26.16	27.20	26.33	25.92
^{232}Th	^{206}Hg	^{26}Ne	55.97	0.192	-0.070	-0.003	29.54	28.81	29.74	28.63	>29.2
^{234}U	^{208}Pb		59.47	0.196	-0.075	0.003	25.88	24.87	25.67	25.05	25.88
^{234}U	^{206}Hg	^{28}Mg	74.13	0.198	-0.075	-0.003	27.55	26.47	27.78	26.27	27.54
^{238}Pu	^{210}Pb		75.93	0.205	-0.060	0.003	28.31	26.32	28.07	26.58	25.70
^{237}Np	^{207}Tl	^{30}Mg	75.02	0.198	-0.070	0.003	27.34	25.92	27.09	26.14	>26.9
^{238}Pu	^{208}Pb		77.03	0.025	-0.060	0.003	25.70	24.07	25.45	24.29	25.70
^{238}Pu	^{206}Hg	^{32}Si	91.21	0.205	-0.060	-0.003	28.65	26.82	28.94	26.58	25.27
^{241}Am	^{207}Tl	^{34}Si	93.84	0.212	-0.050	0.003	25.40	23.16	25.10	23.41	>25.3

Table.5.l gives hindrance factor values for **"C** transition from 312' ground state of 223~toa v arious final states of 209~blt. is found that the transition to ground state 912' (HF=125, for ***t*** = 0) is strongly hindered, while the one to the first excited state 1112'=(HF=0.43, for **l** = 0) is favoured. The transition to 2nd and 3rd excited state 1512- and 512' (HF>11 and HF>5 respectively, for **e** = 0) &e also hindered [108]. Same is the case when centrifugal term (angular momentum) is included in the interacting potential. These findings are in good agreement with experiments done by Hourani et a1 [68]. Hindrance factor pattern observed in **14c** decay of 223~isa s imilar to hindrance factor pattern observed in alpha decay of 227~ hw,h ere both the parents have reflection asymmetric deformed shape [l 101. This pattern results because ground state of the parent is **parity** mixed state, very different from the ground state (912') of daughter but very similar to the parity mixed excited state (1 1/2'state) of daughter. 223~Nail sson deformed wave function contains large components arising from the spherical i1 1/2 neutron shell 209 model orbit but none from the g912 state, the ground state configuration of Pb. The fine structure from '23~a**gi ves direct** evidence on **the** presence of spherical component in the deformed parent nucleus 081.

CONCLUSION

The present paper is an attempt to understand more on the exotic decay, the rare mode of decay intermediate between a emission and spontaneous fission. The common feature of this decay is that one of the nuclei always refers to spherically closed or nearly closed shell nucleus. The so far observed daughter nuclei in the exotic decay of naturally occurring radioactive nuclei are spherically closed shell *08pb or neighboring nuclei. The only other nucleus experimentally searched for is 'OOsn daughter, in the exotic decay of "'~a produced in heavy ion reaction. Details of the present model are also given in this Paper, which is based on the potential barrier consisting of the Coulomb potential and the proximity potential. It is found that inclusion of proximity potential reduces the height of the barrier, which closely agrees with the experiments. The present model is applied to different cases of experimentally observed decay modes. It is found that the present model is able to reproduce the experimental half lives and branching ratios reasonably well. In Paper 4 the exotic decay of neutron deficient Xe to Gd parents in trans-tin region emitting 4~toe 3 2w~a s studied. Most of the decay half lives are well within the present upper limit for measurements. *T,,,* value is minimum for those decays leading to 'OOsn daughter which stress the role of doubly magic 'OOsn daughter in these decays. It is found that neutron excess in the parent nuclei slow down the exotic decay process. Geiger-Nuttall plots for all clusters from these parents are studied and are found to be linear. It is found that inclusion of proximity potential will not produce any deviation to the linear nature of these plots. Nuclear structure effects and shell effects are evident from the observed Exotic decay of neutron rich Ba to Gd parents emitting various clusters are also studied. In this case also it is found that *T,,,* has minimum value for those decays leading to doubly magic "'~n daughter compared with the neighboring ones. This finding also reveals the role of doubly magic daughter in exotic decay. It is found that neutron proton asymmetry in parent and daughter is responsible for the reduced decay rate of these nuclei compared with their neutron deficient counterparts. The preference of non *a* like structures in the decay leading to "'sn and *a* like structure in the decay leading to 'OOsn point out the importance of asymmetry and symmetry of proton and neutron in the two cases respectively. We have modified the present model and made an attempt to study the effect of deformation ***P,*** and ***P,*** of parent and daughter on half life time, treating emitted cluster as spherical. When deformation effects are included half life time value is found to decrease and it is found that parent deformation alone will not produce any appreciable change. These findings are in gross agreement with the experiments. We studied the fine structure (decay to the excited state of daughter) for some modes of decay and calculated the hindrance factor for 14 c transition from 223~toa various excited states of 09~b. The details are described in Paper 6. It is found that the transition to ground state is strongly hindered, while the one to first excited state is favoured. The transitions to second and third excited states are also hindered. Our findings are in good agreement with the experimental data. The fine structure from 223Ra gives direct evidence on the presence of spherical component in the deformed parent nucleus.

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Corresponding Author

Nidhi Sharma*

M.Sc. Physics, B.Ed., #449, Sector-13, Urban Estate, Kurukshetra, Haryana, India

E-Mail –