Spectroscopic factors in diproton radioactivity

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Introduction

To form a stable nucleus, an appreciable balance should be maintained between protons and neutrons. In the case of light nuclei, this balance is obtained when the number of protons equals the neutron number. Beyond A = 40, more number of neutrons are present to counter balance the Coulombic repulsion due to the charged protons. The number of neutrons with respect to the number of protons increases until the neutron number reaches N = 126 and the proton number approaches Z = 82 for lead. Nuclei which do not keep up this balance are unstable and undergo decay by radioactive processes. For a small disequilibrium, a beta decay occurs ie a neutron is transformed into a proton or vice versa which involves a proton transformation into a neutron, positron and neutrino. If this imbalance is too large, the nuclear forces can no longer bind all the nucleons and the nucleus becomes particle unstable. Thus the limits of nuclear stability are reached and the unstable nucleus gives out the excess nucleons. The emission of two-protons and two neutrons namely alpha radioactivity was first observed. This is usually observed in the Z = 82-92 case. For heavier nuclei, spontaneous fission was found to occur. Theoretical predictions by Goldanskii in 1960s showed that for medium mass nuclei with A = 50 to 100, other type of decay would occur. For very proton rich odd nuclei, one proton radioactivity ie emission of one proton should be observed. For even nuclei with a large proton excess, two-proton radioactivity i.e. emission of two-protons would occur. These one proton or two-proton emitters are although particle unbound, they may have appreciable half-life due to the coulomb barrier the protons have to tunnel through. Later it was realized that two-proton emission could decay via different mechanisms. Depending on the position of the intermediate one proton daughter state, the two-proton emission might be a sequential process where one-proton emission populates a well defined energy state in the one-proton daughter, before a second one-proton emission occurs to a two-proton daughter state. However, the nuclear pairing force, which couples two nucleons of the same type to gain energy, is responsible for the fact that the masses of even-Z nuclei are smaller than the one of the one-proton daughter, thus rendering one-proton emission impossible. In such a case, the two-protons have to be emitted simultaneously for energy conservation. The *simultaneous* two-proton decay can be described by two cases (i) the two-protons have no angular or energy correlation and the decay mechanism is dictated by phase space. This decay is commonly referred to as democratic decay. (ii) the decay proceeds via the He^2 resonance and as in alpha decay, a preformed cluster is emitted, decaying into two-protons as the two-proton system is not bound. This decay is called as He^2 emission.

Theoretical formalism

Shanmugam-Kamalaharan cluster model [1] has been modified for 1p radioactivity is now extended to 2p radioactivity with necessary modifications. The total amount of energy available to the two-protons is given by Q_{2p}. A fraction of this energy ε, is converted into the mass of the He^2. The remainder, $E_{2p} = Q_{2p} - \varepsilon$, is the energy available for the diproton to tunnel through the barrier [2]. When the pair penetrates the barrier it breaks up into two-protons with ε converted into the relative energy of the proton-proton pair. The post scission potential is the sum of the Coulomb potential and the centrifugal potential

$$V(r) = V_c(r) + V_l(r)$$

and the Coulomb potential is given by

$$V_c(r) = \frac{zZe^2}{4\pi\varepsilon_0 r}$$

where z and Z are the charge of the diproton (z=2) and daughter nucleus respectively. For low ε the He^2 has less mass and hence the diproton has more kinetic energy and is more likely to tunnel through the barrier. The probability of penetration becomes less likely as the kinetic energy decreases ie as ε increases.

Results and discussion

The figure 1 shows the variation of Log T and mass number. The half-life values are found to be higher near the medium mass region. If the decaying states are broad, it will result in short half-life as it is acted upon by low Coulomb and low centrifugal barrier.

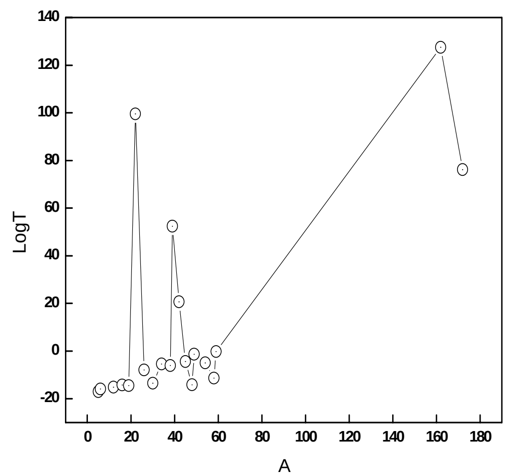

Fig. 1 Variation of calculated half-lives with diproton emitters mass number

The figure 2 shows the variation of Q values of the two-proton emission. The Q value increases in the medium mass region. This shows that the emission is effective in this region. It shows a wide gap in the 50< Z > 80 region, which is well known for 1p emission.

The identification of this decay is hampered by the stringent energetic requirements $S_p > 0$ and $S_{2p} < 0$. The table shows that sum of the diproton emitters have $S_{1p} < 0$ and $S_{2p} < 0$ exhibiting the possibility to decay by sequential emission. Rest of the nuclei have $S_{1p} > 0$ and $S_{2p} < 0$ indicating the possibility to decay by simultaneous emission. The diproton coming out of the parent nucleus unpair at a radial distance of the order of 10^{-22} m.

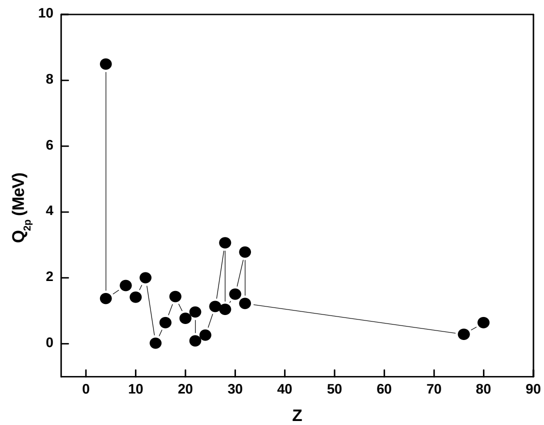

Fig. 2 Q_{2p} values with atomic number

Table: Single proton and diproton separation energy values of proton emitters

Nucleus	S_{1p} (MeV)	S_{2p} (MeV)
Be^5	-5.391	-3.0991
O^{12}	-0.459	-1.312
Mg^{19}	-1.561	-0.441
Ni^{48}	-0.411	-2.651
Ni^{49}	-0.071	-0.971
Ge^{58}	-0.241	-2.541
Be^6	0.593	-1.966
Ne^{16}	0.072	-1.483
Si^{22}	13.32	-7.3
S^{26}	0.188	-0.826
Ar^{30}	0.348	-1.78
Ca^{34}	0.898	-1.672
Ti^{38}	1.028	-1.99
Cr^{42}	1.088	-1.35
Fe^{45}	0.108	-1.24
Zn^{54}	0.398	-1.90
Ge^{59}	0.298	-1.5
Os^{162}	1.038	-1.3
Hg^{172}	0.813	-1.452
Hg^{173}	0.573	-0.901

References

[1] G. Shanmugam, and B. Kamalaharan, Phys. Rev. C **41**, No.2 (1990) 1742.

[2] A.A.H.Mahmud, et al, Eur. Phys. J.A. **15**, 85 (2002).