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Analysis of Alpha and cluster radioactivity using Q-value dependent relative separation

THAPAR INSTITUTE
OF ENGINEERING & TECHNOLOGY
(Deemed to be University)

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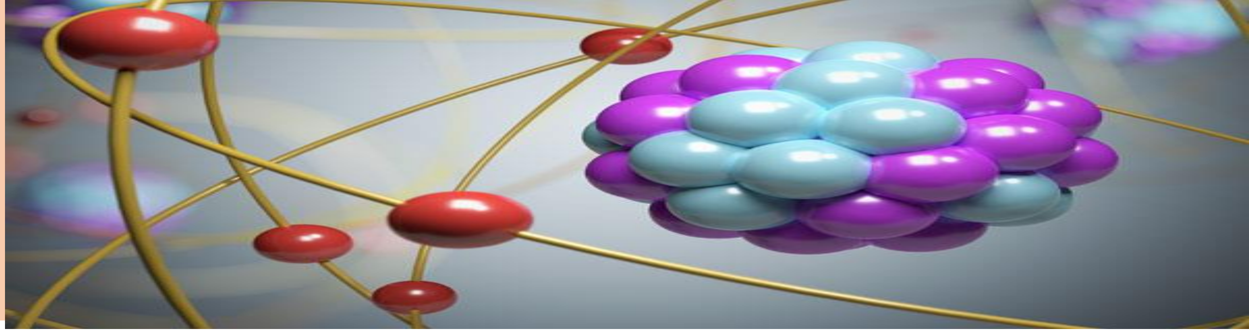
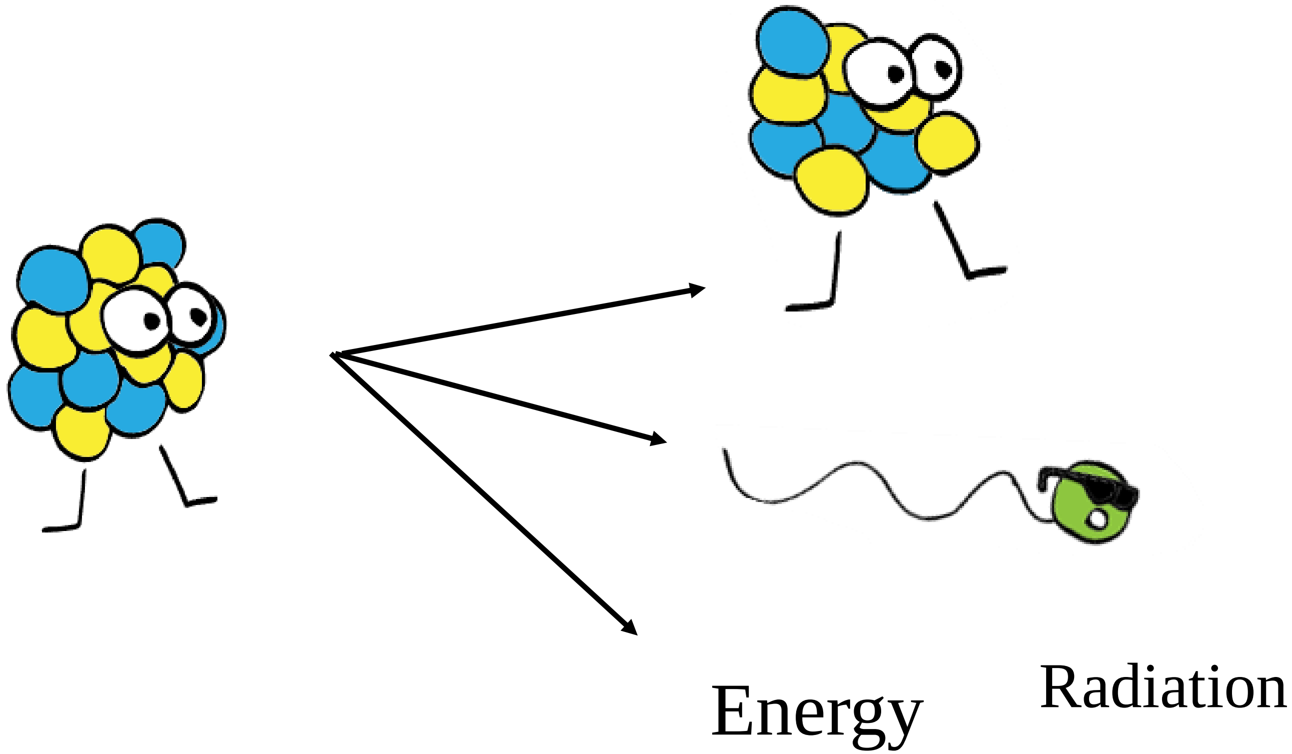
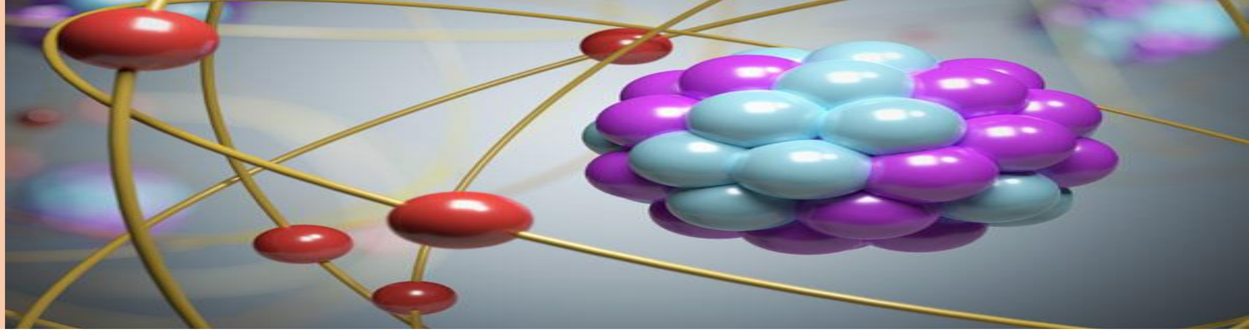
Radioactivity

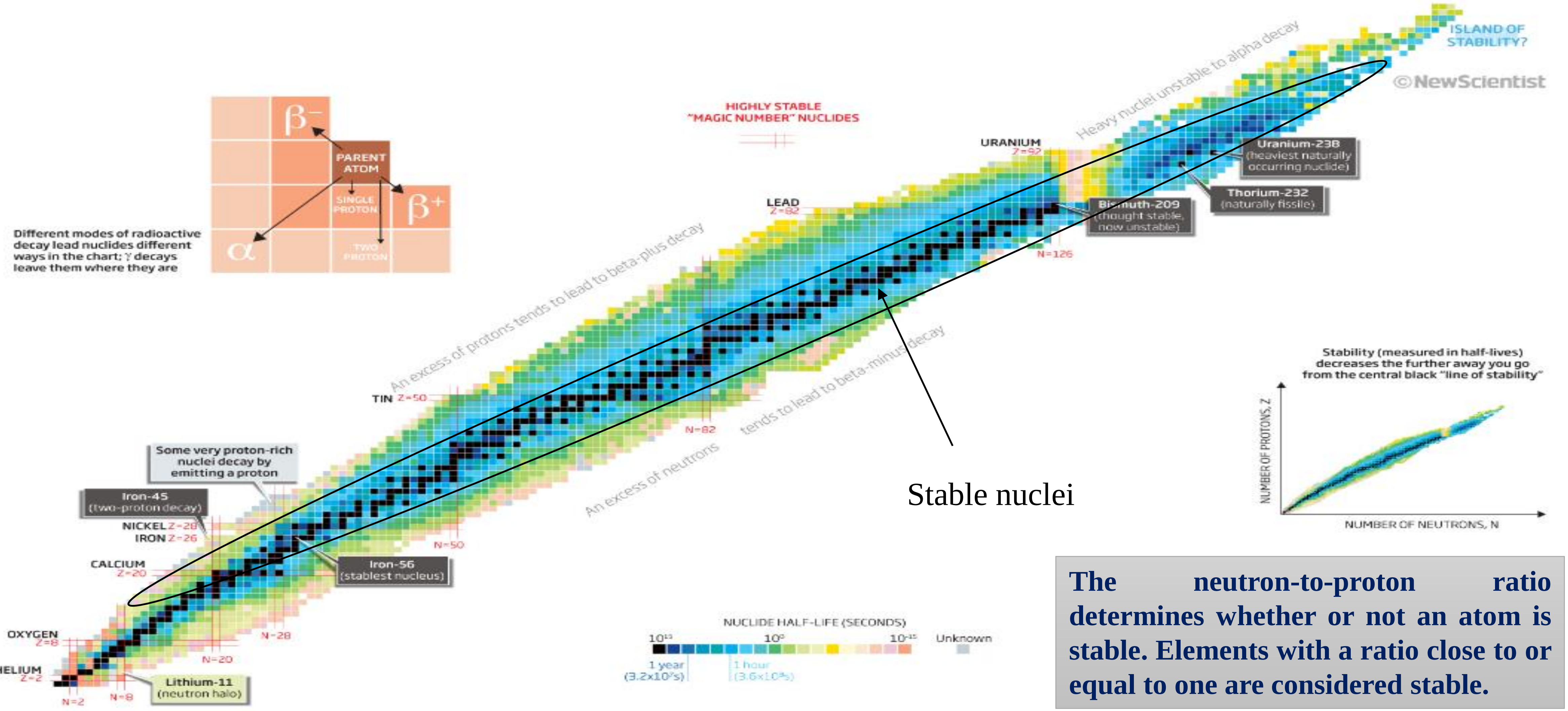




Radioactive decay is the process in which unstable atomic nucleus loses energy and become stable by emitting radiation in the form of particles, clusters or electromagnetic waves.

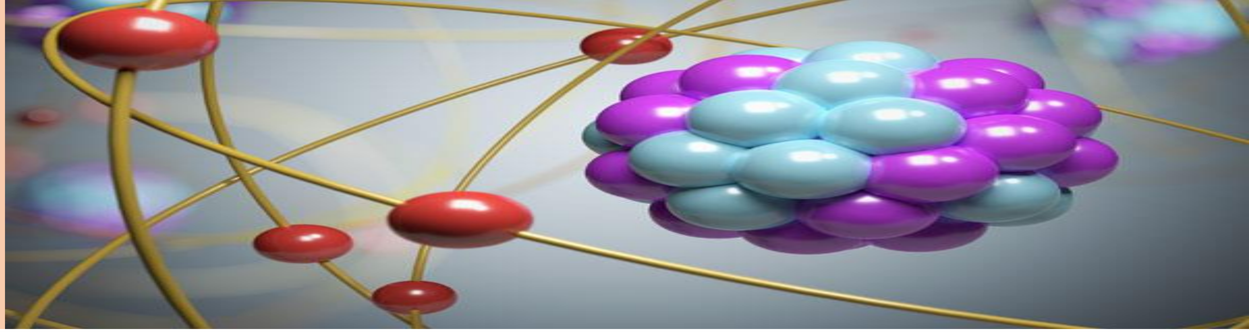
Spontaneous Decay

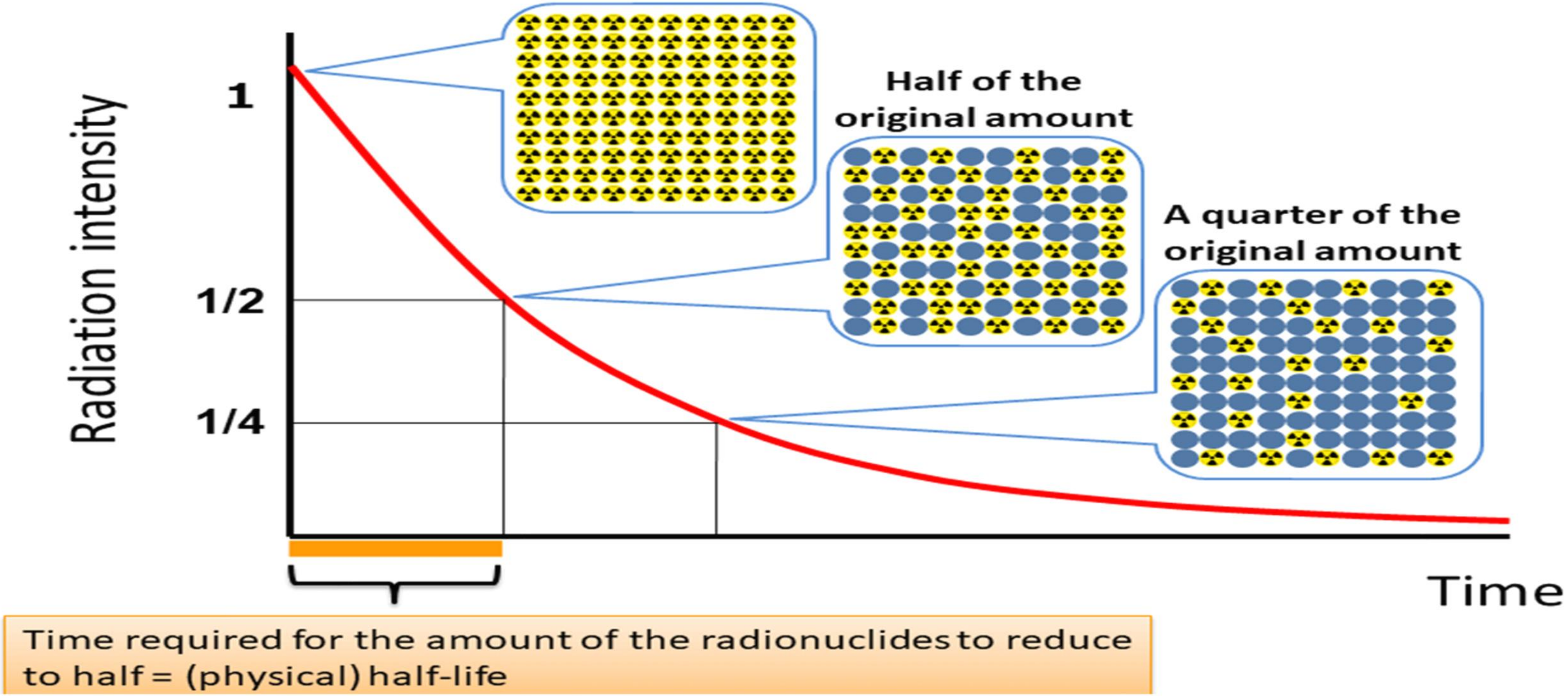




The neutron-to-proton ratio determines whether or not an atom is stable. Elements with a ratio close to or equal to one are considered stable.

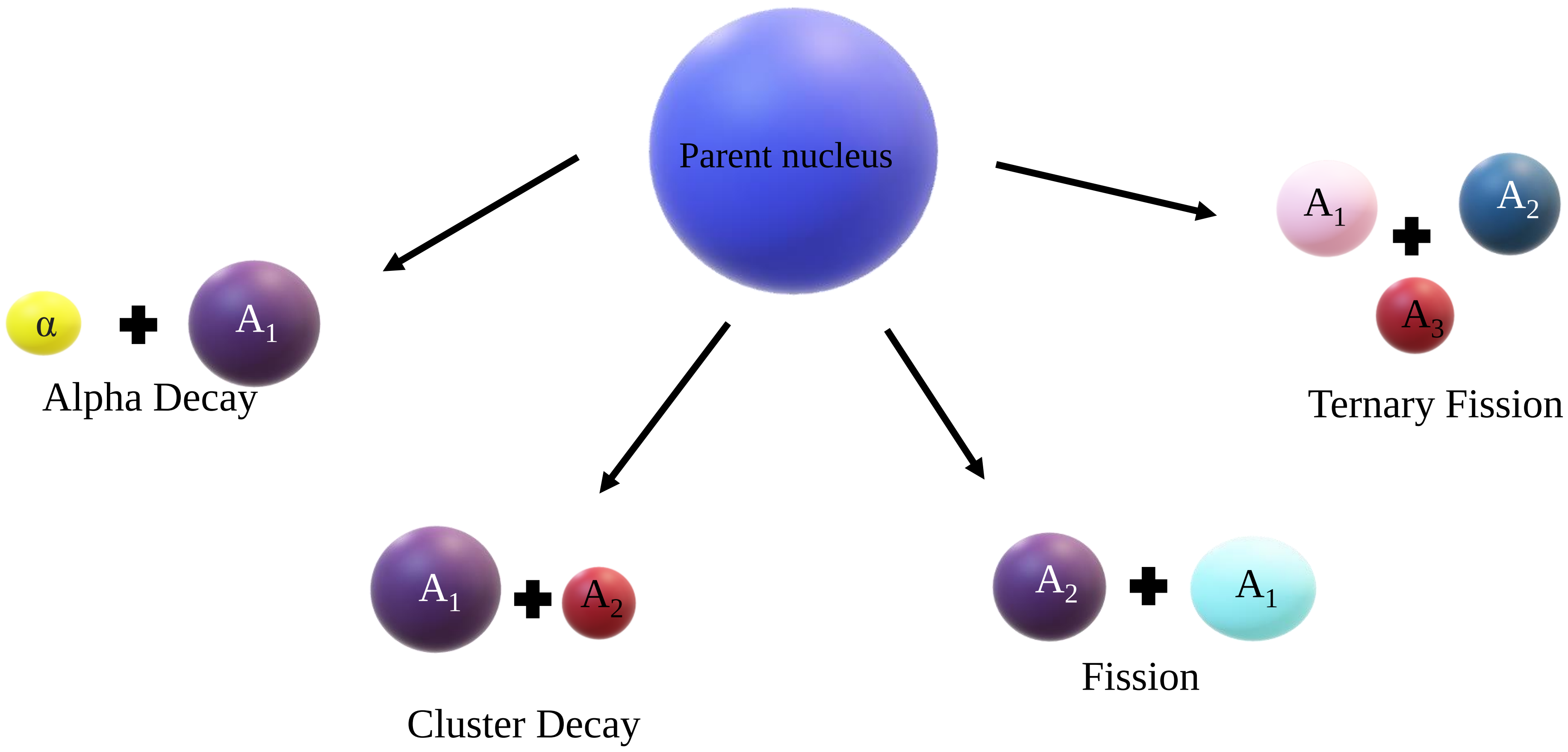
Half life




Radiation intensity
1
1/2
1/4
Half of the original amount
A quarter of the original amount
Time
Time required for the amount of the radionuclides to reduce to half = (physical) half-life

Spontaneous Decay

A_1-Daughter nuclei
A_2-Cluster/particle



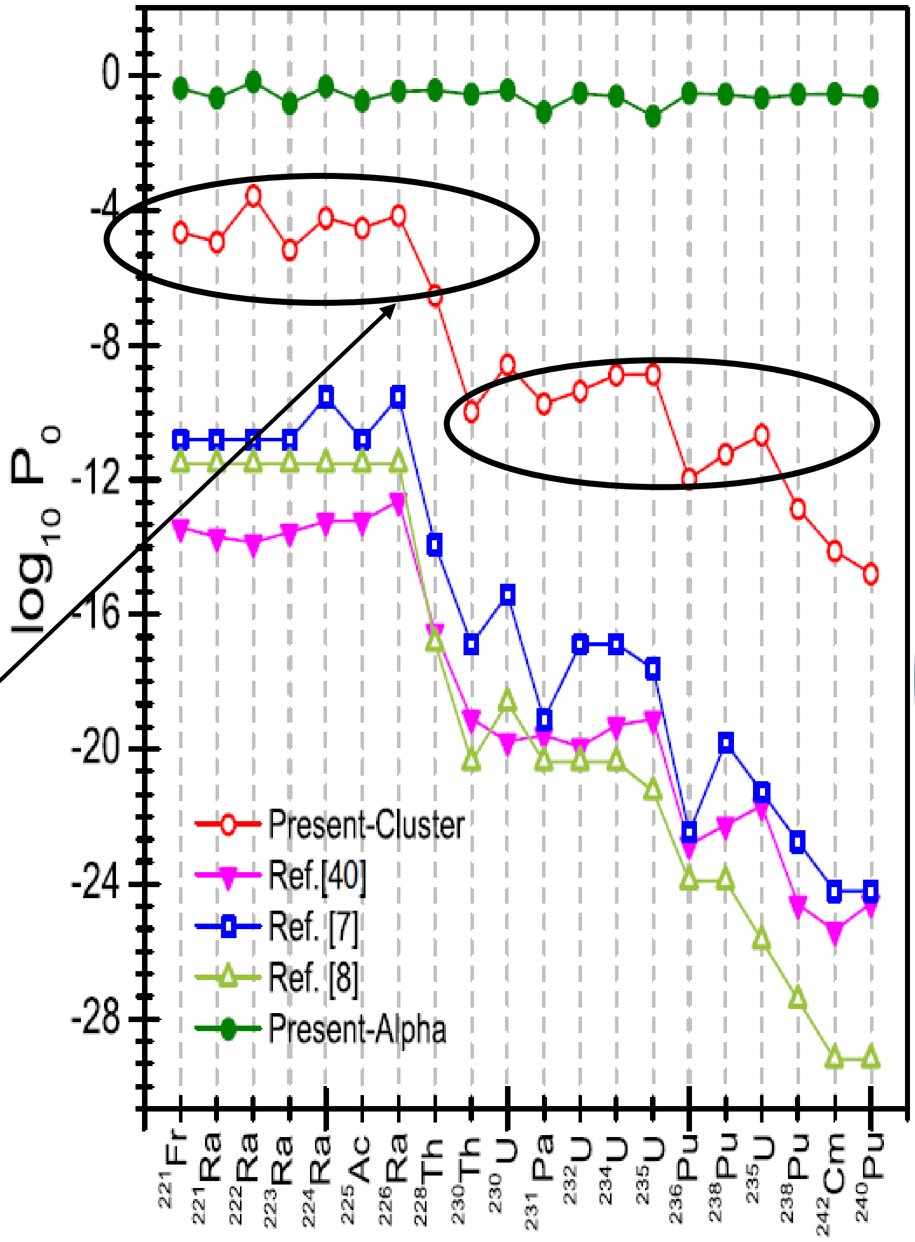
Motivation

Q-Value Effects Preformation Probability

Authors of **Eur. Phys. J. A (2018) 54: 156** introduced a relation between $\log P_0$ with q-value where P_0 is preformation probability.

For Cluster Decay it is as :

$$\log_{10} P_0 = -2.2687 Q^{1/2} + 8.2558.$$



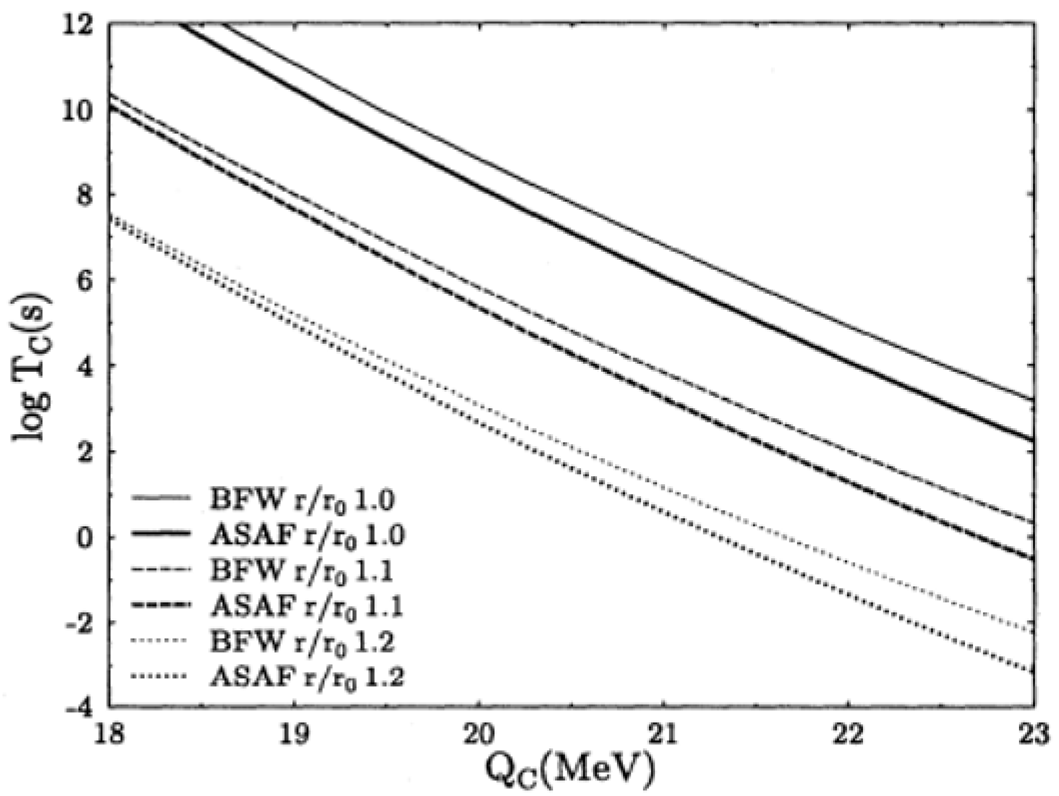
Comparison of this empirical relation with other models is represented

Q-Value Effects $\log T_{1/2}$

5-10% change in the Q-value of the decay channel may change decay half-lives by an order of 2-3.

It is concluded that, $\log T_{1/2}$ strongly influenced by the Q-Value of the decay channel.

$^{114}Ba \longrightarrow {}^{12}C + {}^{102}Sn$



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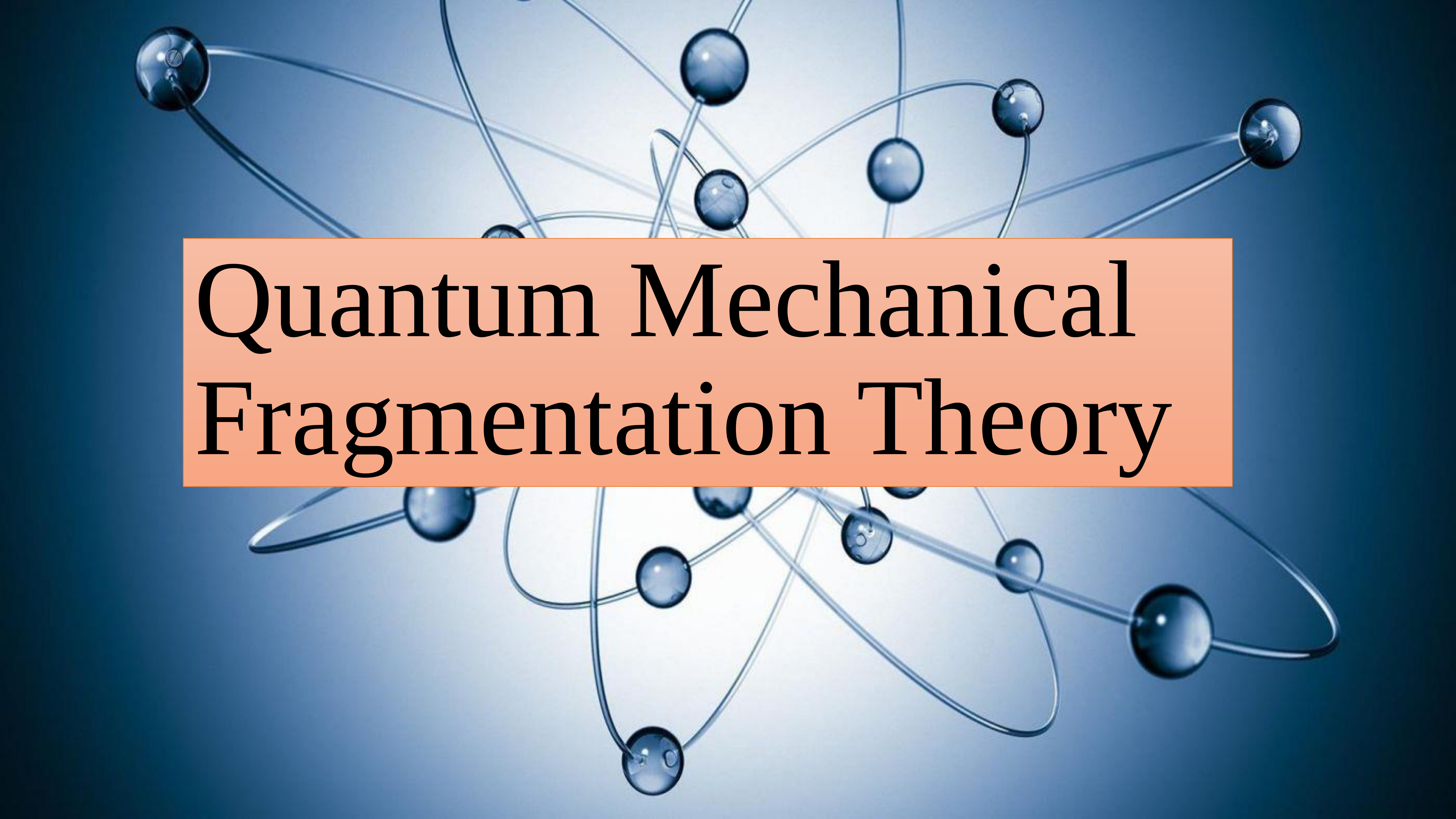
Quantum Mechanical Fragmentation Theory

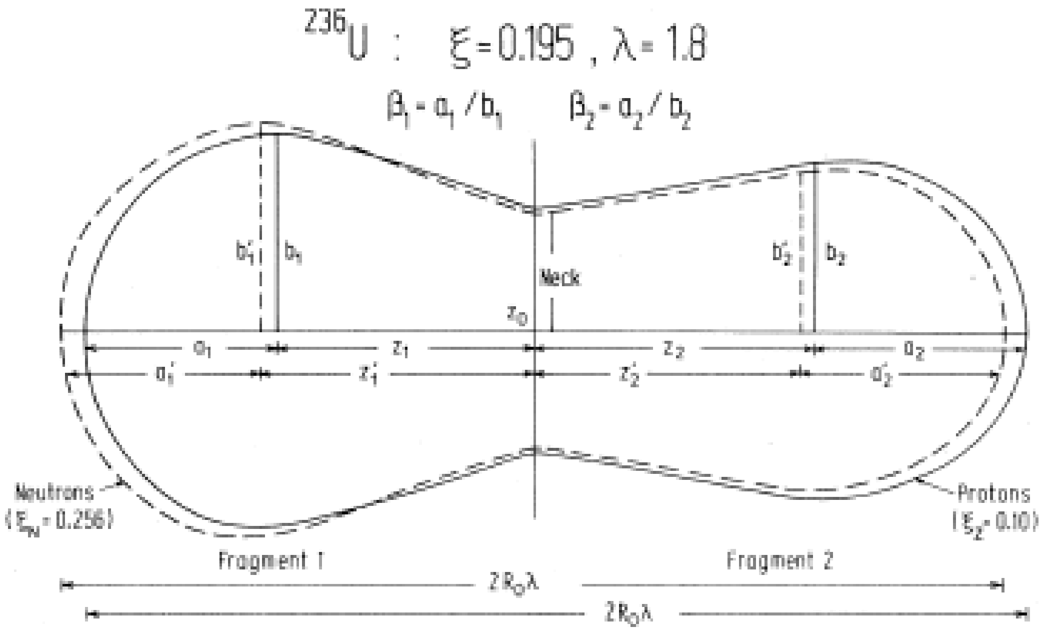


Methodology

Theory of Fission-Mass Distribution

- **Using the concept of mass asymmetry $\xi=(A_1 - A_2)/(A_1 + A_2)$, treated as dynamical collective coordinate, based on ATCSM they calculated the mass distribution of fissioning nuclei ^{226}Ra, ^{236}U & ^{258}Fm.**

The idea was further extended for understanding the charge dispersion in nuclear fission by R K Gupta, W. Scheid and W. Greiner. in PRL Vol. 35, no. 6, (1975).

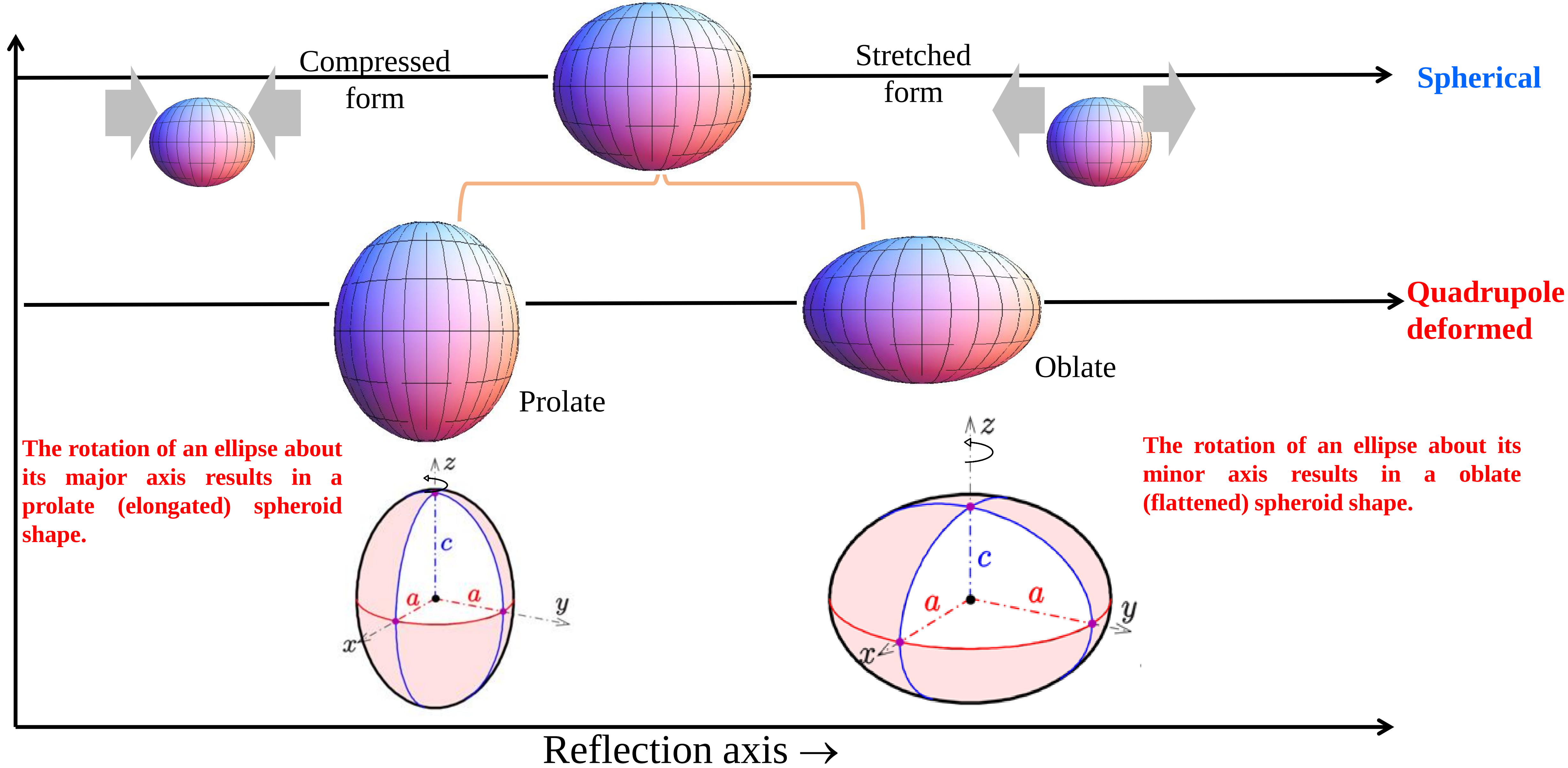


Explanation of the parameters of the asymmetric two-center shell models for the protons and neutrons.

$$\xi_Z = \frac{Z_1 - Z_2}{Z_1 + Z_2}, \quad \xi_N = \frac{N_1 - N_2}{N_1 + N_2}.$$

$$\xi = \frac{A_1 - A_2}{A_1 + A_2} = \frac{Z}{A}\xi_Z + \frac{N}{A}\xi_N$$

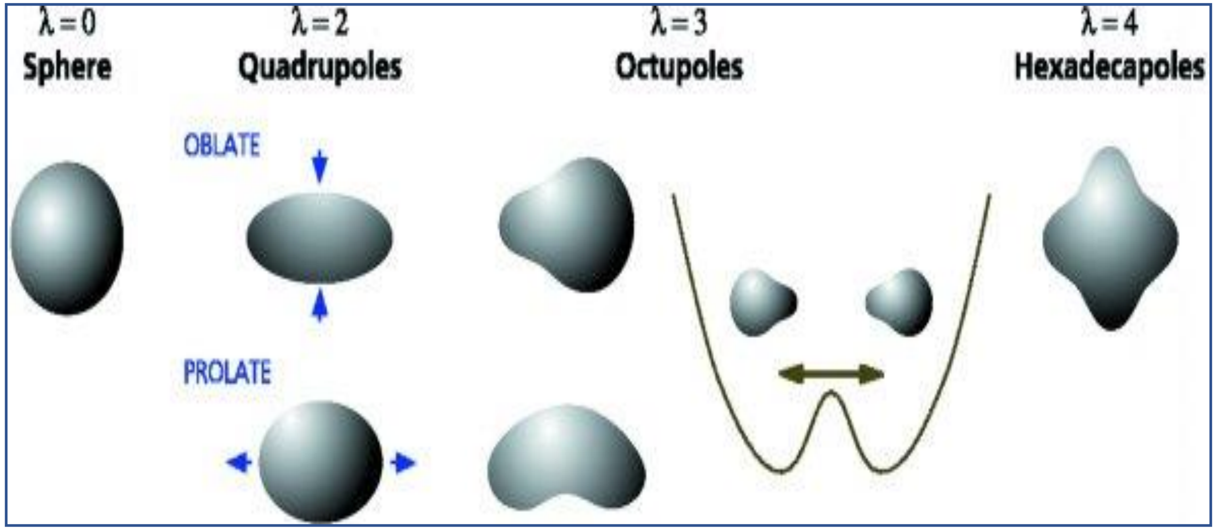
Nuclear Shapes

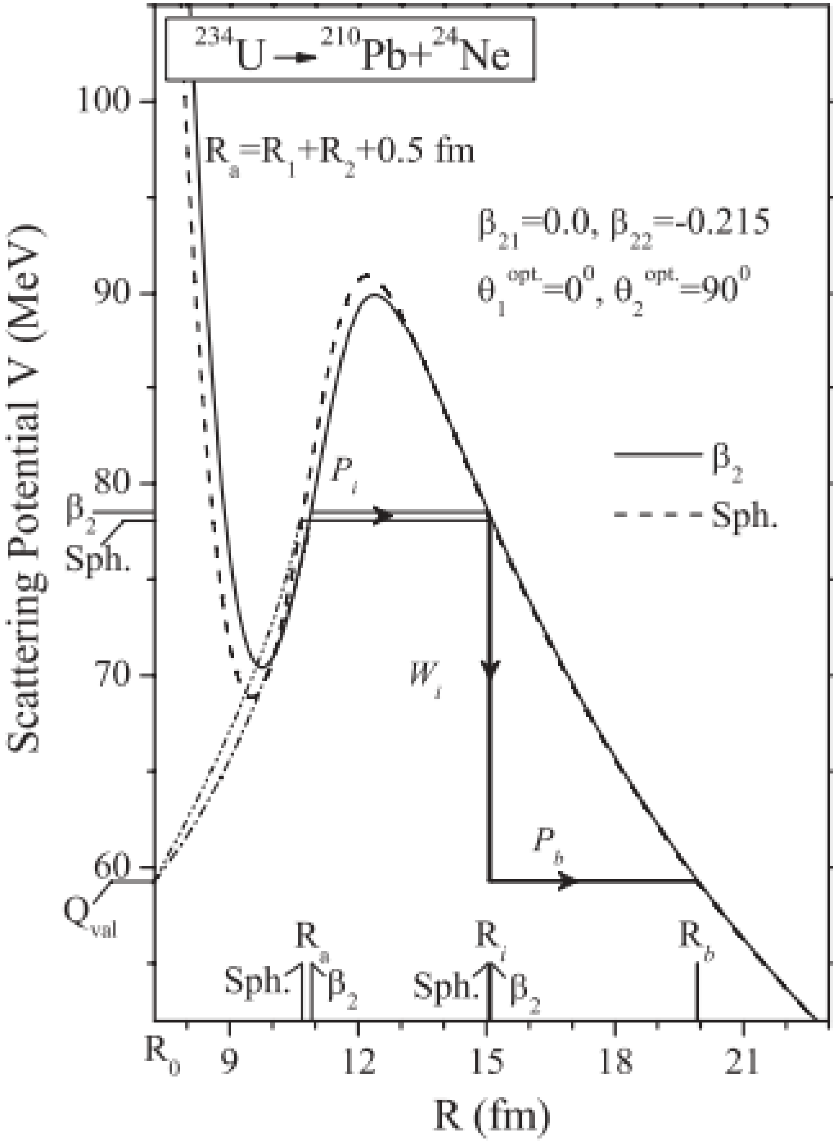


Deformation Effects

$$R_i(\alpha_i) = R_{0i}\left[1 + \sum_{\lambda} \beta_{\lambda i} Y_{\lambda}^{(0)}(\alpha_i)\right]$$

The deformation and orientation effects the barrier height.





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Methodology

The collective potential V(η, R) can be calculated as

$$V(\eta,\eta_Z,R) = -\sum_{i=1}^{2} B_i(A_i,Z_i,\beta_{\lambda i}) + V_C(R,Z_i,\beta_{\lambda i},\theta_i,\phi) + V_N(R,A_i,\beta_{\lambda i},\theta_i,\phi) + V_\ell(R,A_i,\beta_{\lambda i},\theta_i,\phi)$$

The binding energy contains both the macroscopic (liquid drop model) and microscopic (shell-correction) part.

$$\sum_{i=1}^{2} V_{LDM} + \sum_{i=1}^{2} \delta U \exp\left(-\frac{T^2}{T_0^2}\right)$$

Methodology

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$$V(\eta,\eta_Z,R) = -\sum_{i=1}^{2} B_i(A_i,Z_i,\beta_{\lambda i}) + V_C(R,Z_i,\beta_{\lambda i},\theta_i,\phi) + V_N(R,A_i,\beta_{\lambda i},\theta_i,\phi) + V_\ell(R,A_i,\beta_{\lambda i},\theta_i,\phi)$$

$$V_C(Z_i,\beta_{\lambda i},\theta_i,\alpha_i,T) = \frac{Z_1Z_2e^2}{R(T)} + 3Z_1Z_2e^2 \sum_{\lambda,i=1,2} \frac{1}{2\lambda+1}\frac{R_i^\lambda(\alpha_i,T)}{R(T)^{\lambda+1}} Y_\lambda^{(0)}(\theta_i)\left[\beta_{\lambda i} + \frac{4}{7}\beta_{\lambda i}^2(\theta_i)\right]$$

Deformation dependent coulomb potential

Methodology

The collective potential V(η, R) can be calculated as

$$V(\eta,\eta_Z,R) = -\sum_{i=1}^{2} B_i(A_i,Z_i,\beta_{\lambda i}) + V_C(R,Z_i,\beta_{\lambda i},\theta_i,\phi) + V_N(R,A_i,\beta_{\lambda i},\theta_i,\phi) + V_\ell(R,A_i,\beta_{\lambda i},\theta_i,\phi)$$

Proximity potential

$$V_N(s_0) = f(sh., geo.)\Phi(s_0) = 4\pi\bar{R}\gamma b\Phi(s_0).$$

$$\Phi(s_0) = \begin{cases} \frac{-1}{2}(s_0-2.25)^2 - 0.0852(s_0-2.54)^3 \\ -3.437exp\left(\frac{-s_0}{0.75}\right) \end{cases}$$

$$\gamma = \gamma_0\left[1 - k_s\left(\frac{N-Z}{A}\right)^2\right]$$

Methodology

The collective potential V(η, R) can be calculated as

$$V(\eta,\eta_Z,R) = -\sum_{i=1}^{2} B_i(A_i,Z_i,\beta_{\lambda i}) + V_C(R,Z_i,\beta_{\lambda i},\theta_i,\phi) + V_N(R,A_i,\beta_{\lambda i},\theta_i,\phi) + V_\ell(R,A_i,\beta_{\lambda i},\theta_i,\phi)$$

$$V_\ell = \frac{\hbar^2 \ell(\ell+1)}{2I(T)}$$

Moment of inertia

For ground state decays l is taken to be Zero

Methodology

The collective potential V(η, R) can be calculated as

$$V(\eta,\eta_Z,R) = -\sum_{i=1}^{2} B_i(A_i,Z_i,\beta_{\lambda i}) + V_C(R,Z_i,\beta_{\lambda i},\theta_i,\phi) + V_N(R,A_i,\beta_{\lambda i},\theta_i,\phi) + V_\ell(R,A_i,\beta_{\lambda i},\theta_i,\phi)$$

Schrodinger wave equation separated for η-coordinates

$$\left[-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta} + V(\eta)\right]\psi^\nu(\eta) = E_\eta^\nu \psi^\nu(\eta)$$

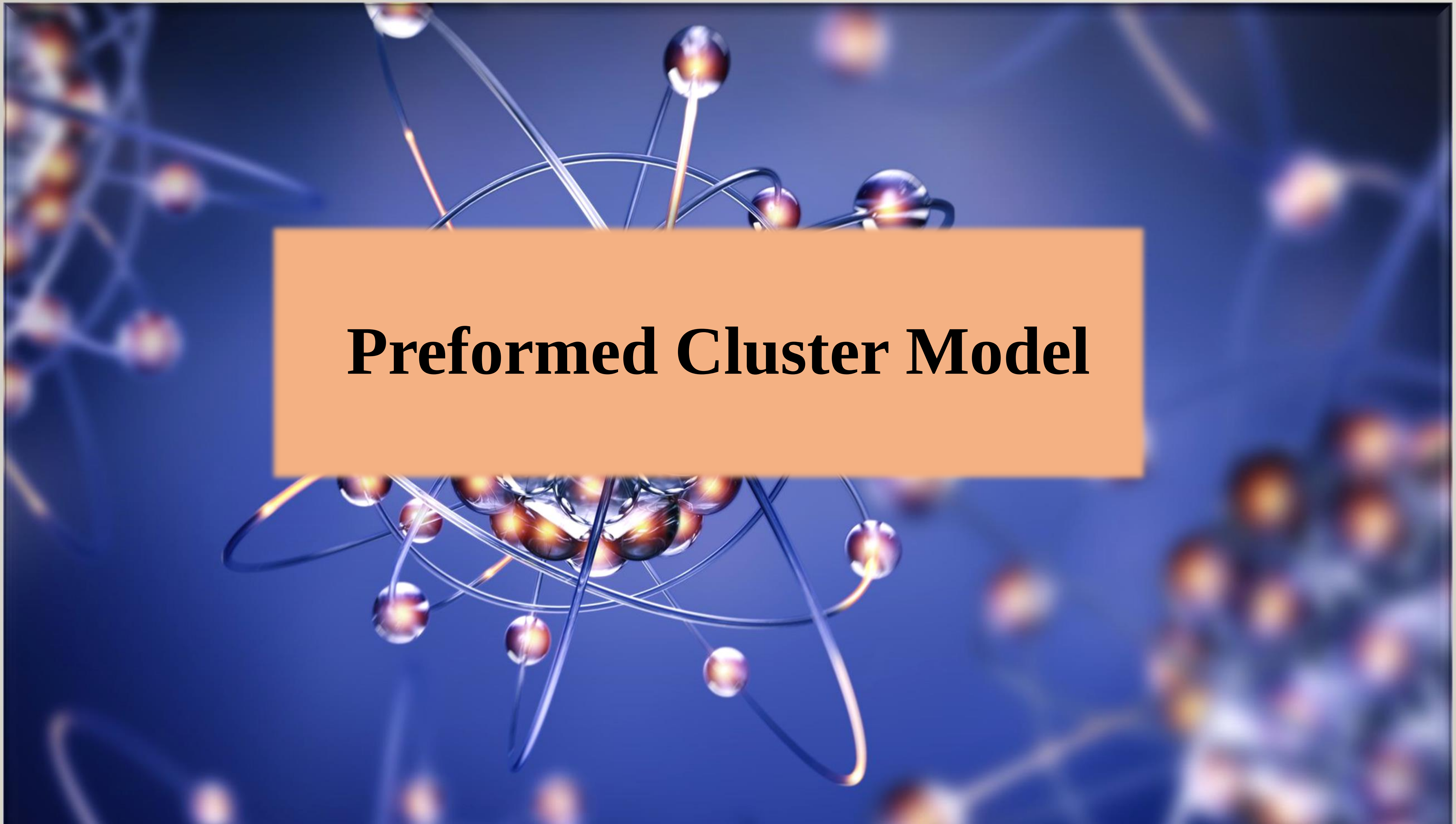
- For ground state decay, ν = 0
- For excited state decay, ν = 1, 2, 3,……

The preformation probability, P_0, which imparts the structure information of the decaying nucleus, is obtained by solving the stationary Schrodinger equation in η

$$P_0 = \sqrt{\beta_{\eta\mu}}\,|\psi(\eta(A_i))|^2 (2/A_{CN})$$

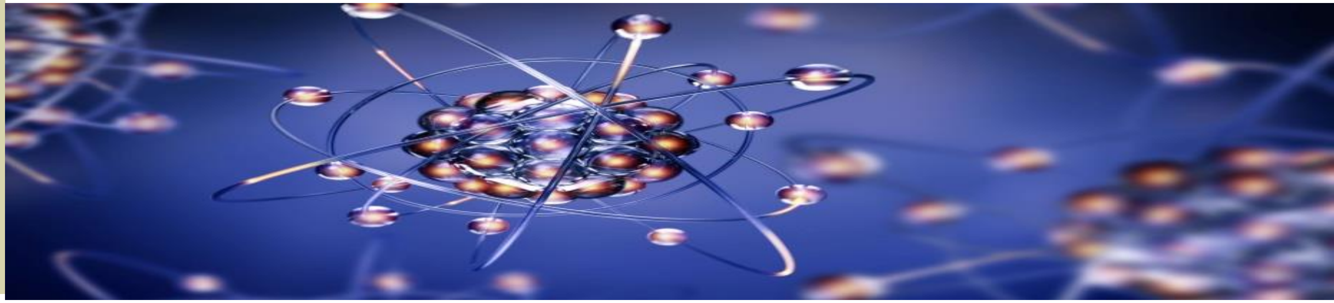
The penetrability P is calculated under WKB approximation, solved analytically as follows

$$P = \exp\left[-\frac{2}{\hbar}\int_{R_a}^{R_b}\{2\mu[V(R)-Q_{eff}]\}^{1/2}dR\right]$$



Preformed Cluster Model

Preformed Cluster Model



The preformed cluster model (PCM) is based on Quantum Mechanical Fragmentation Theory (QMFT).

Decay Constant

$$\lambda_{PCM} = \upsilon_0 P P_0 \quad , T_{1/2} = \frac{\ln 2}{\lambda}$$

Half life

Assault Frequency

Preformation Probability

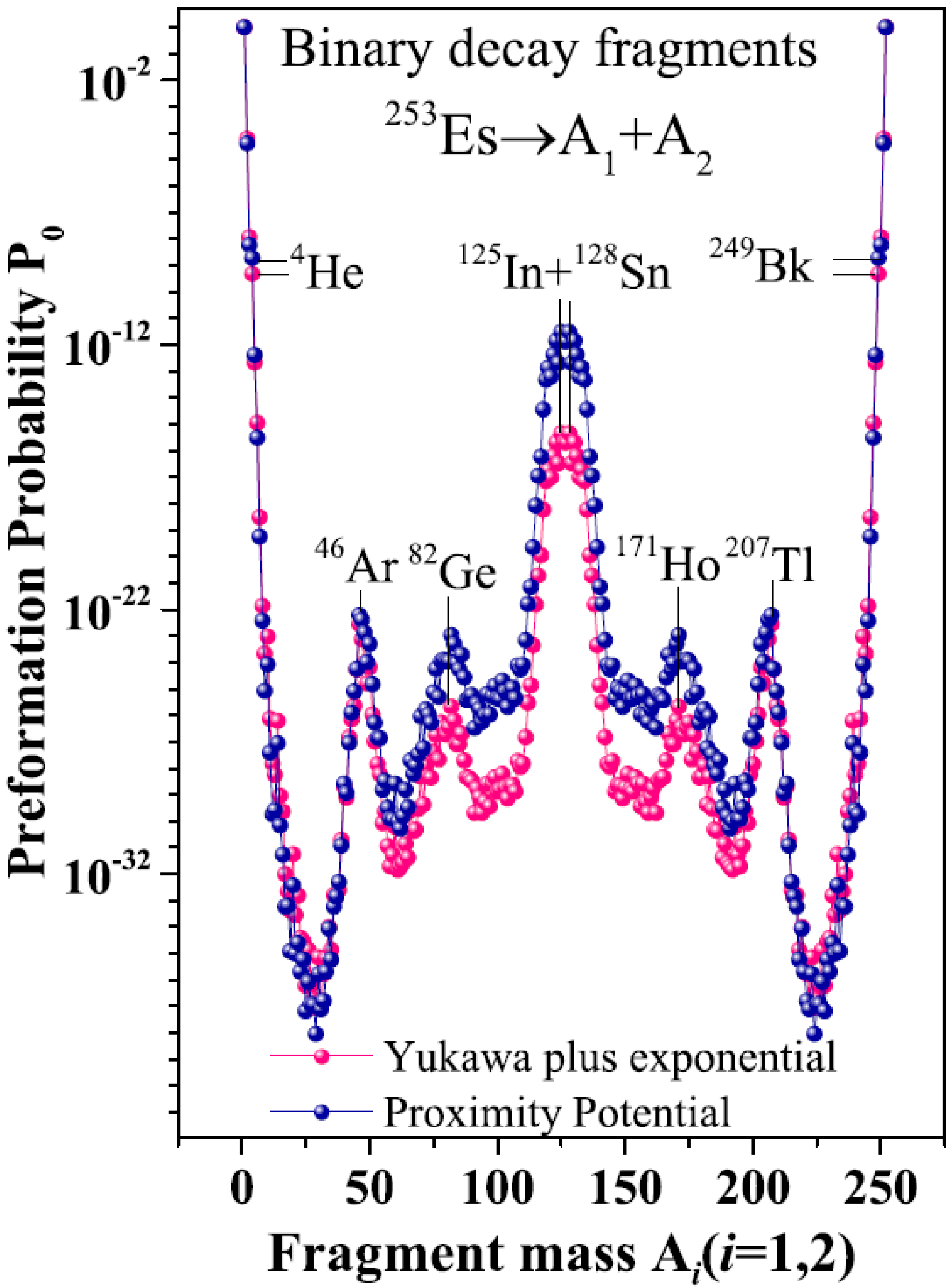
Penetration Probability

Preformed Cluster Model

Preformation Probability

The preformation probability, P_0, which imparts the structure information of the decaying nucleus, is obtained by solving the stationary Schrodinger equation in η

$$P_0 = \sqrt{B_{\eta\eta}}\,|\psi(\eta(A_i))|^2\left(\frac{2}{A_{CN}}\right)$$



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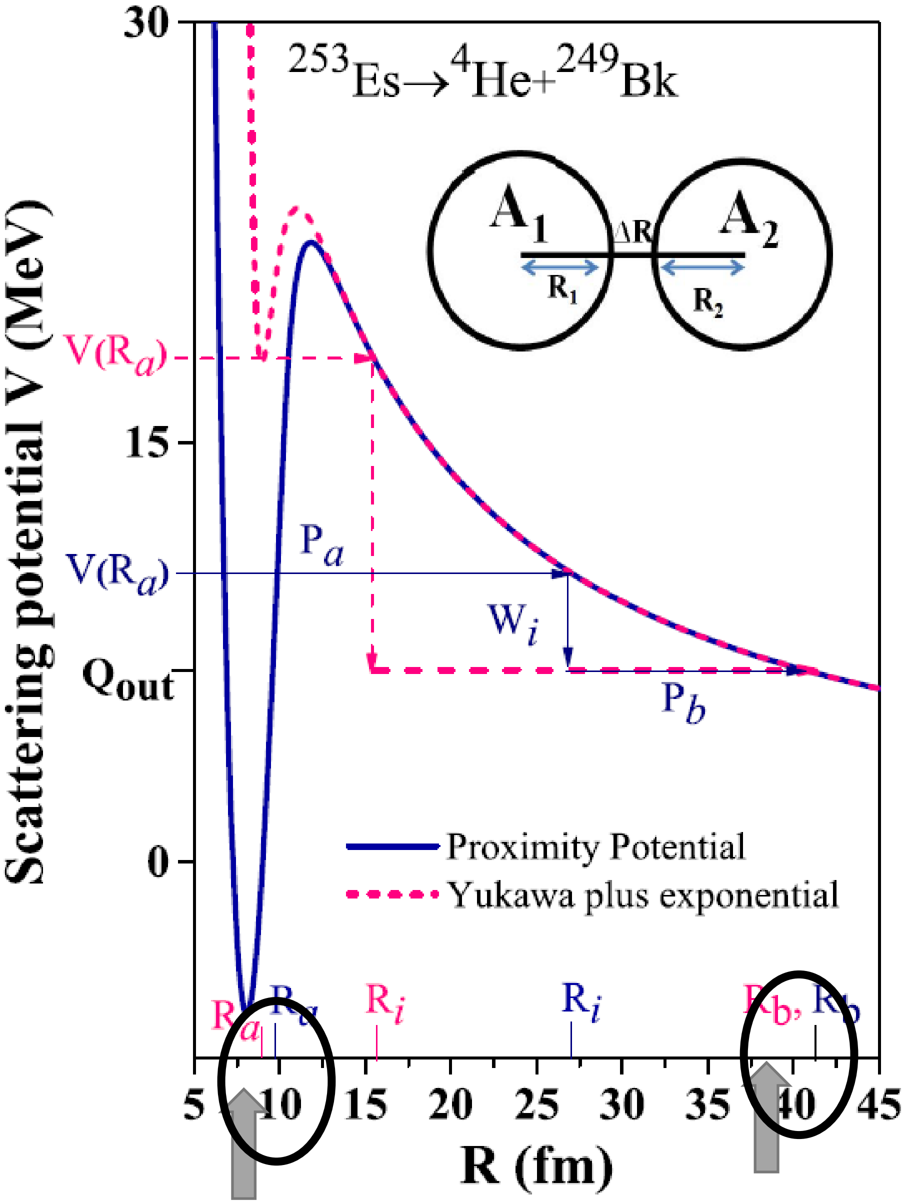
Preformed Cluster Model

Penetration Probability

Three step process:

$$P_a = exp[-\frac{2}{\hbar}\int_{R_a}^{R_i}\{2\mu[V(R)-V(R_i)]\}^{1/2}dR],$$

$$P_b = exp[-\frac{2}{\hbar}\int_{R_i}^{R_b}\{2\mu[V(R)-Q]\}^{1/2}dR],$$



First Turning Point

Second Turning Point

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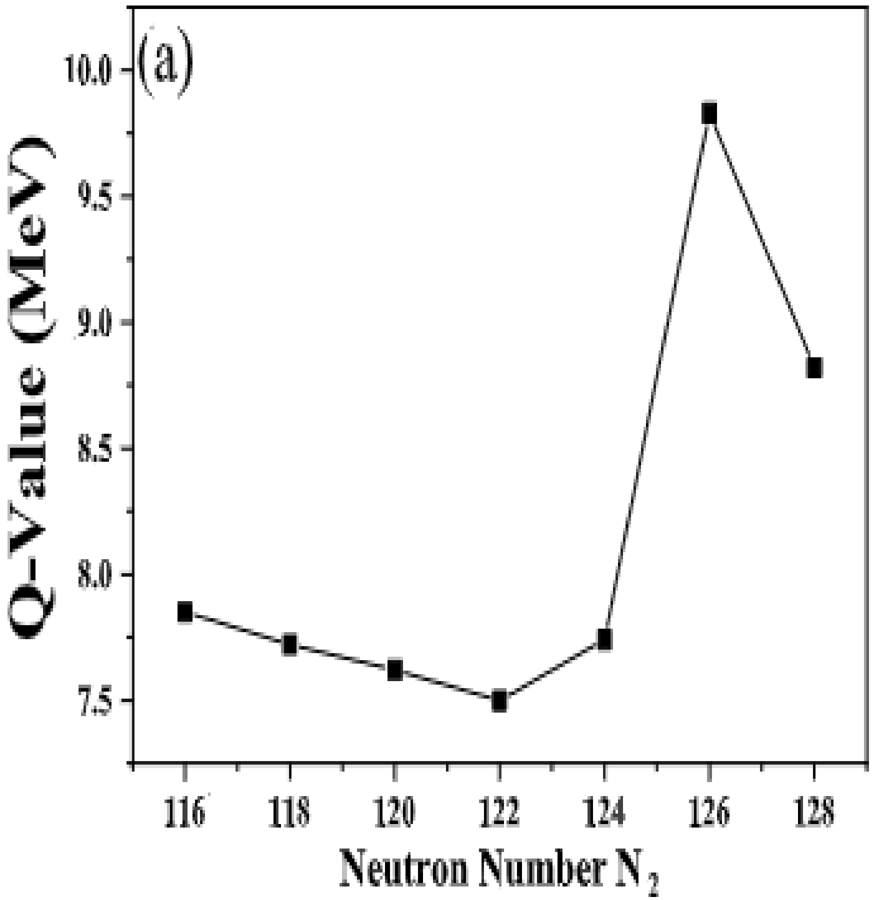
Present Work

Present work is mainly focused on alpha decay and cluster radioactivity of the nuclei belongs to actinide region.

Alpha Decay

Alpha decay of different isotopes of Actinium nuclei i.e. ^{207}Ac, ^{209}Ac, ^{211}Ac, ^{213}Ac, ^{215}Ac, ^{217}Ac, ^{221}Ac were studied by taking spherical choice of fragments.

The Q-value of alpha decay channel for Ac nuclei is calculated and plotted w.r.t neutron number of daughter nucleus



Alpha Decay

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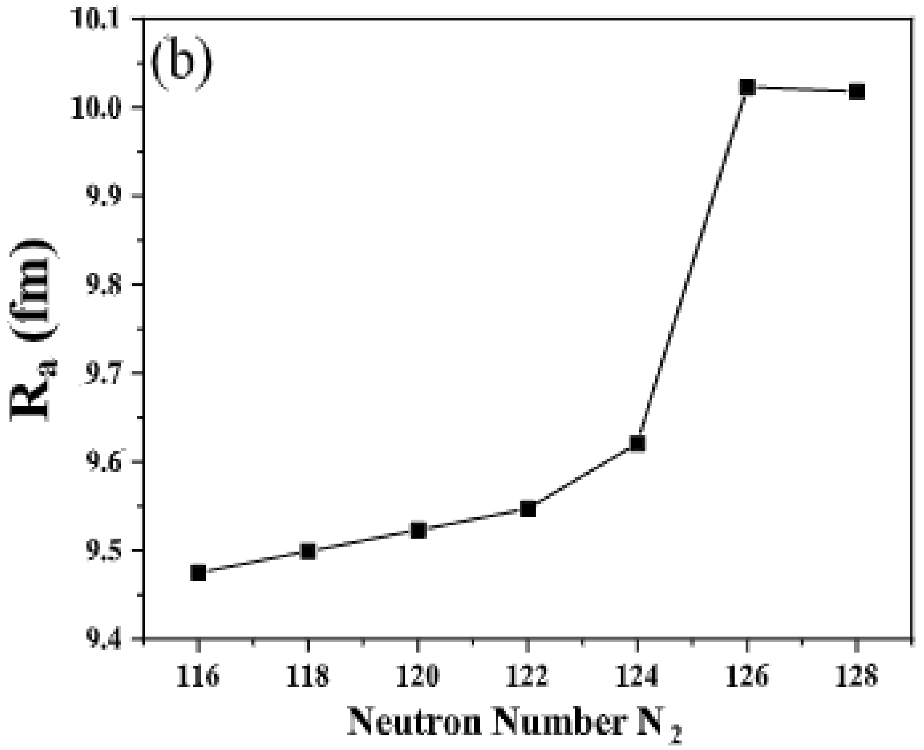
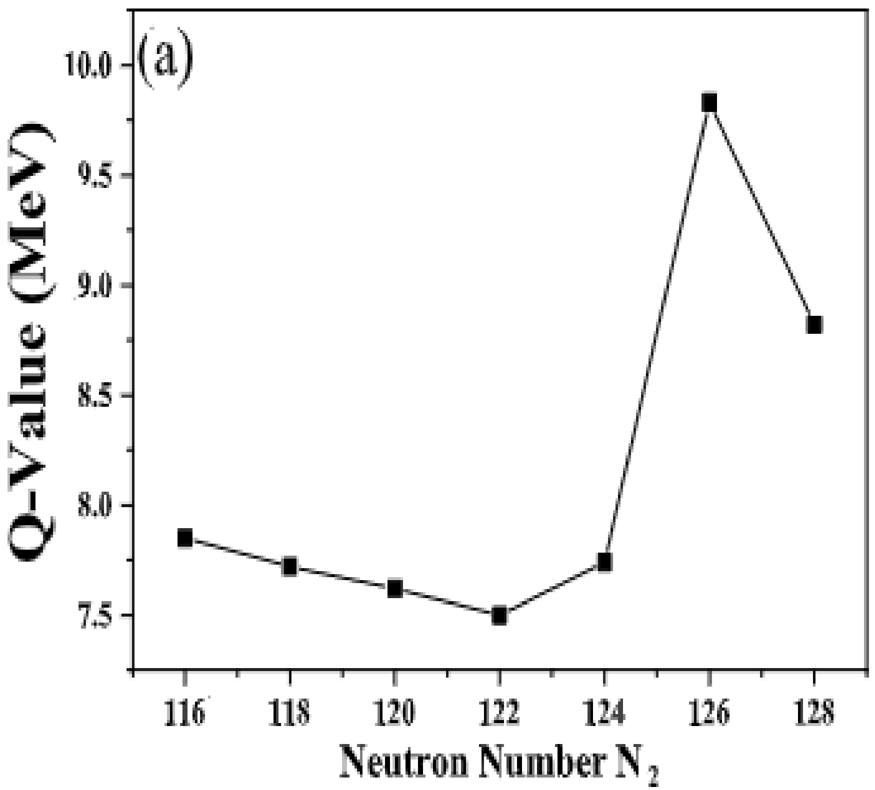
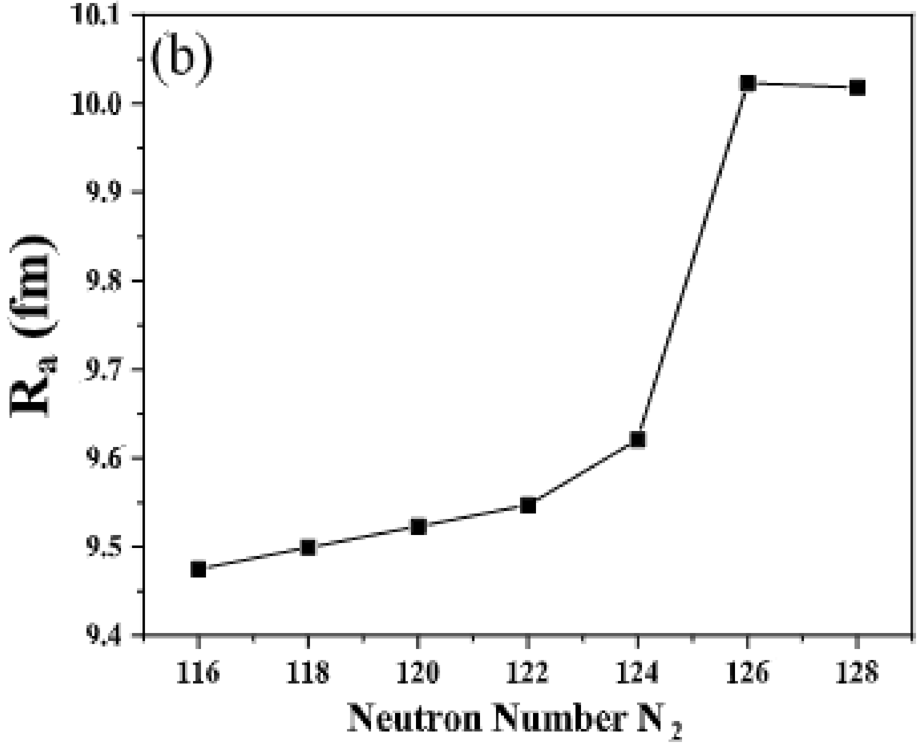


Further variation of First Turning Point (R_a) is analyzed and shell effects are clearly visible at N=126 (neutron closed shell)

Alpha Decay

Alph
nucle
^{217}Ac
choic

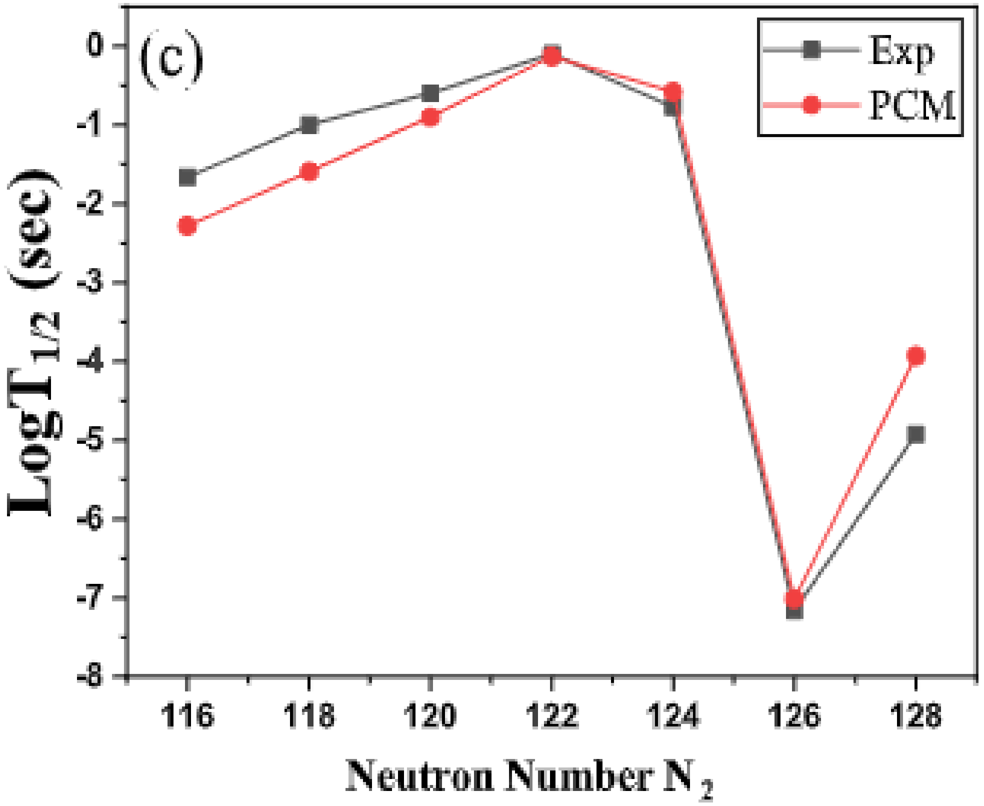




Furthe
analyz
N=126 (neutron closed shell)

Alpha Decay

Alpha decay of different isotopes of Actinium nuclei i.e. ^{207}Ac, ^{209}Ac, ^{211}Ac, ^{213}Ac, ^{215}Ac, ^{217}Ac, ^{221}Ac were studied by taking spherical choice of fragments.



Experimental $LogT_{1/2}$ are compared with calculated values and shows a good agreement.

Alpha Decay

$$\frac{R_a}{R_t} = 1.17857 + 0.01311 * Q - 0.000931599 * Q^2$$

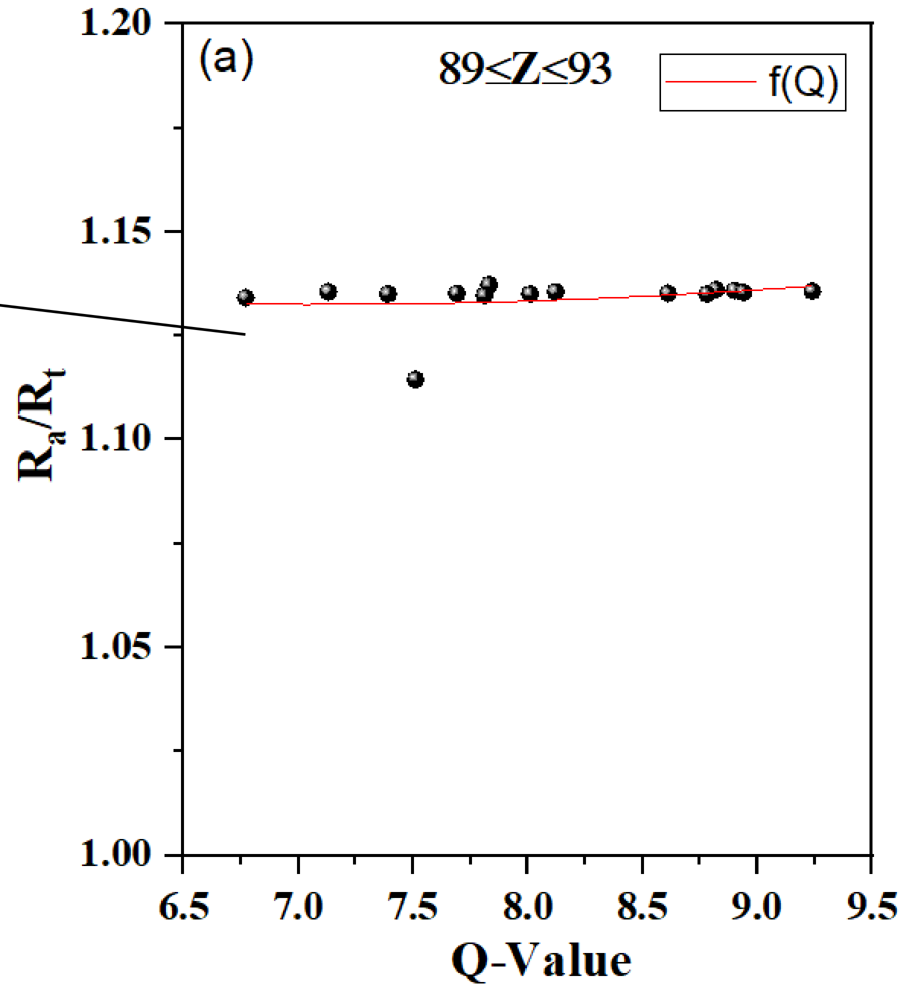
$\Delta R = (0.90\text{-}1.20)\text{fm}$

$89 \leq Z \leq 93$

$$R_a = R_t(f(Q))$$

First Turning Point

Q-dependent polynomial



Alpha Decay

$$\frac{R_a}{R_t} = 1.17857 + 0.01311 * Q - 0.000931599 * Q^2$$

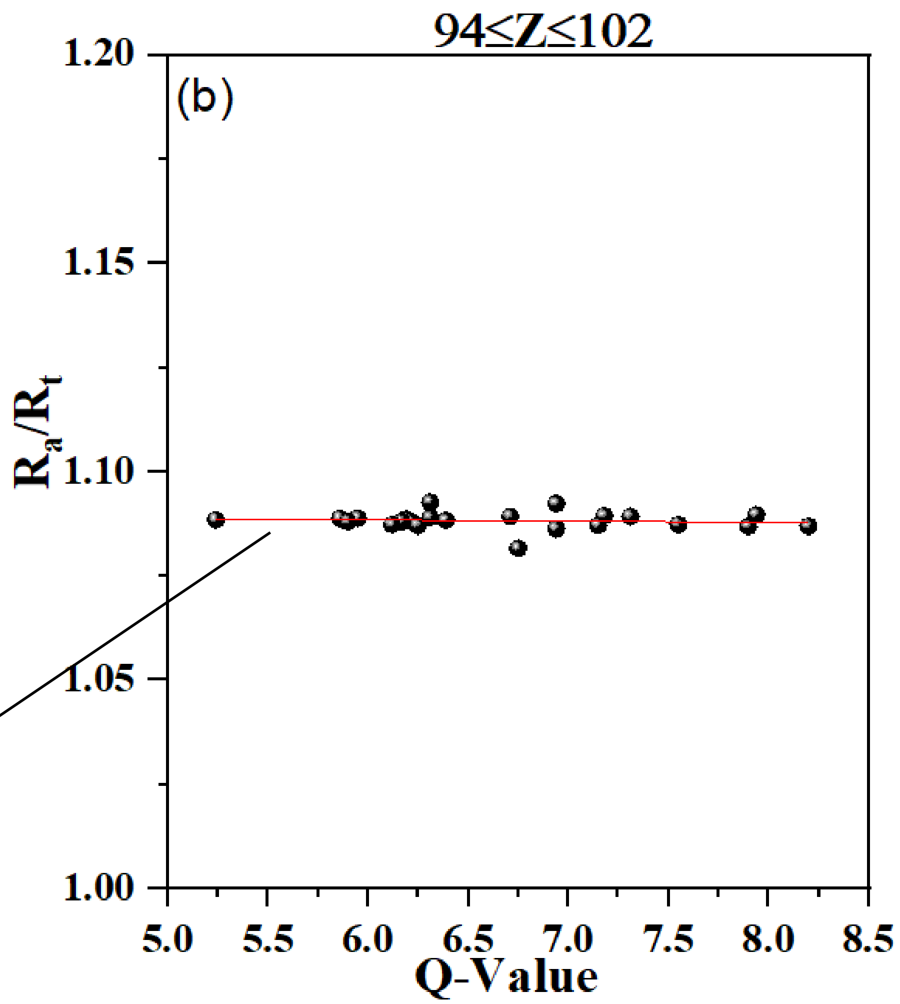
$\Delta R = (0.90\text{-}1.20)\text{fm}$

89 ≤ Z ≤ 93

$$\frac{R_a}{R_t} = 1.08702 - 0.000657 * Q - 0.00007184 * Q^2$$

$\Delta R = (0.50\text{-}0.80)\text{fm}$

94 ≤ Z ≤ 102



Alpha Decay

Standard Deviation

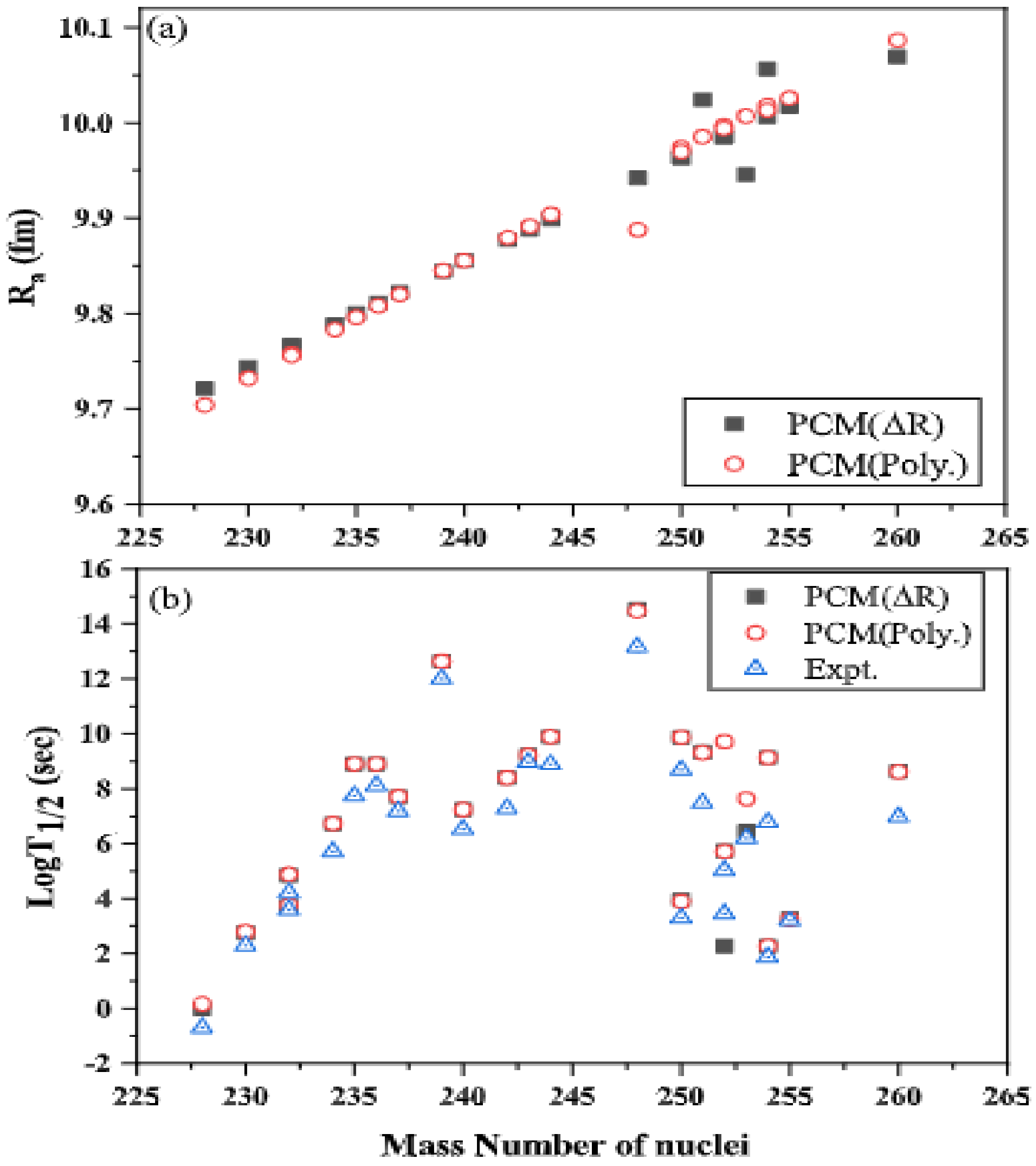
$$\sigma = \left[\sum_{i=1}^{n} [\log_{10}(T_i / T_{\text{Expt.}})]^2 / (n-1) \right]^{1/2}.$$

σ = 1.14 and 1.15.

Using given Polynomial

By varying ΔR = (0.50-0.80)fm

$89 \leq Z \leq 93$



Alpha Decay

Standard Deviation

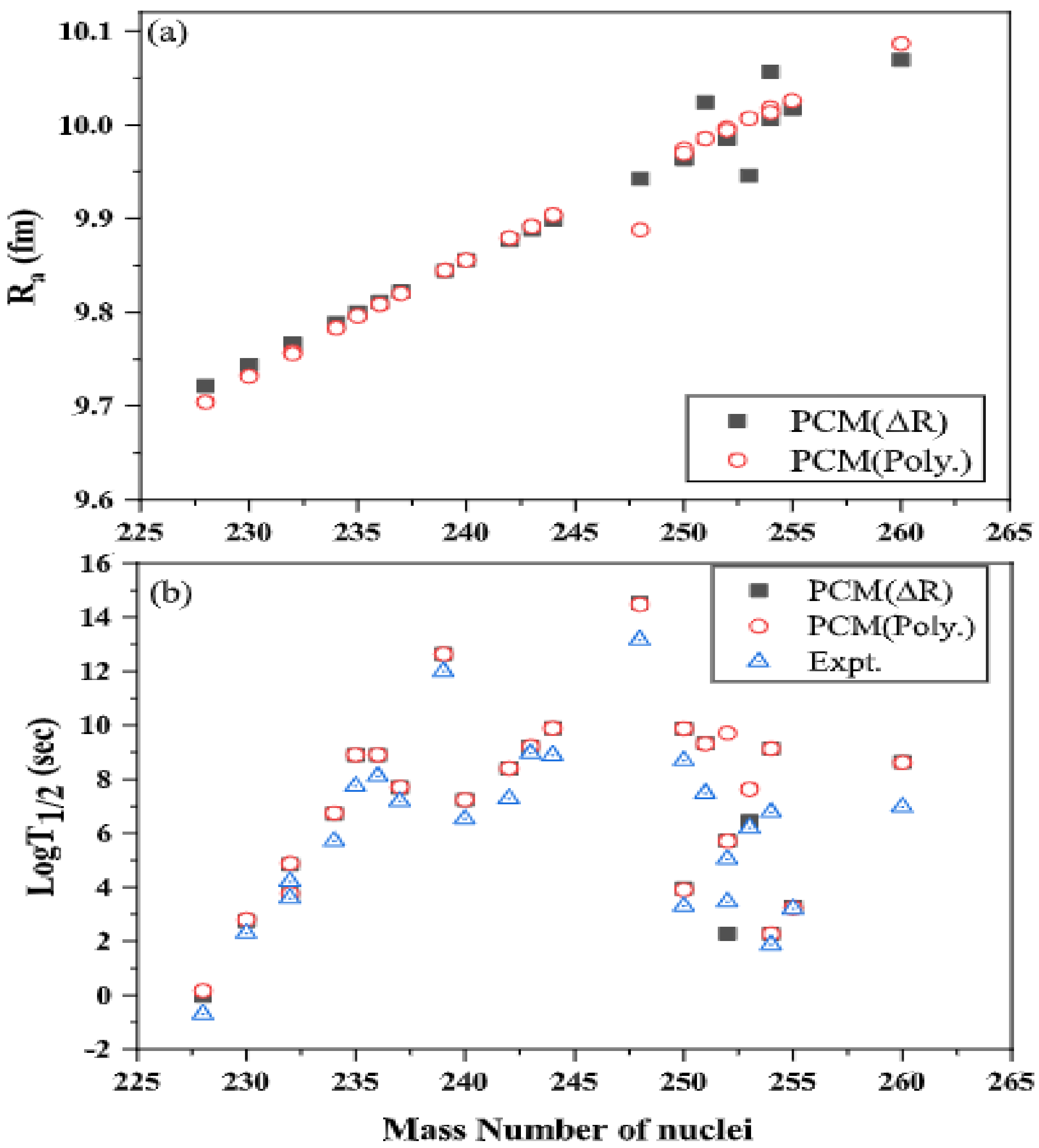
$$\sigma = \left[\sum_{i=1}^{n} [\log_{10}(T_i / T_{\text{Expt.}})]^2 / (n-1) \right]^{1/2}.$$

σ = 1.76 and 1.07.

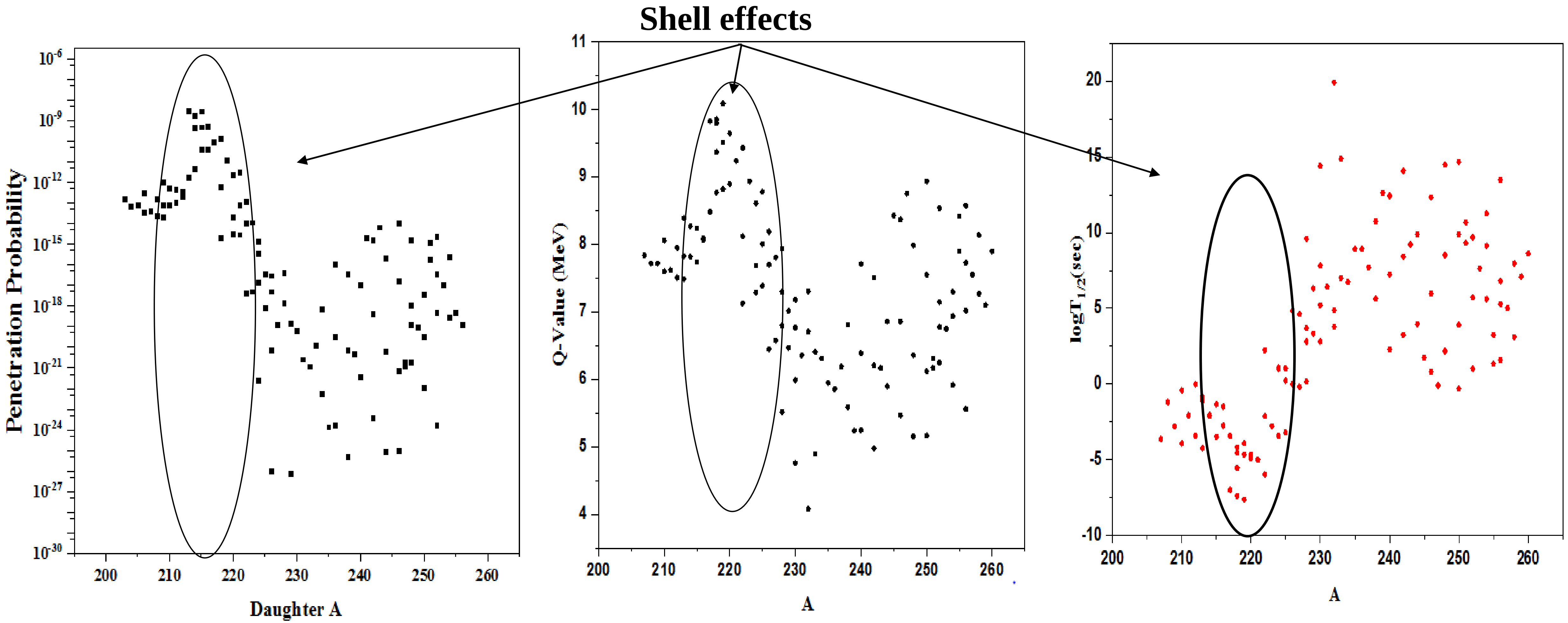
Using given Polynomial

By varying ΔR = (0.90-1.20)fm

94 ≤ Z ≤ 102

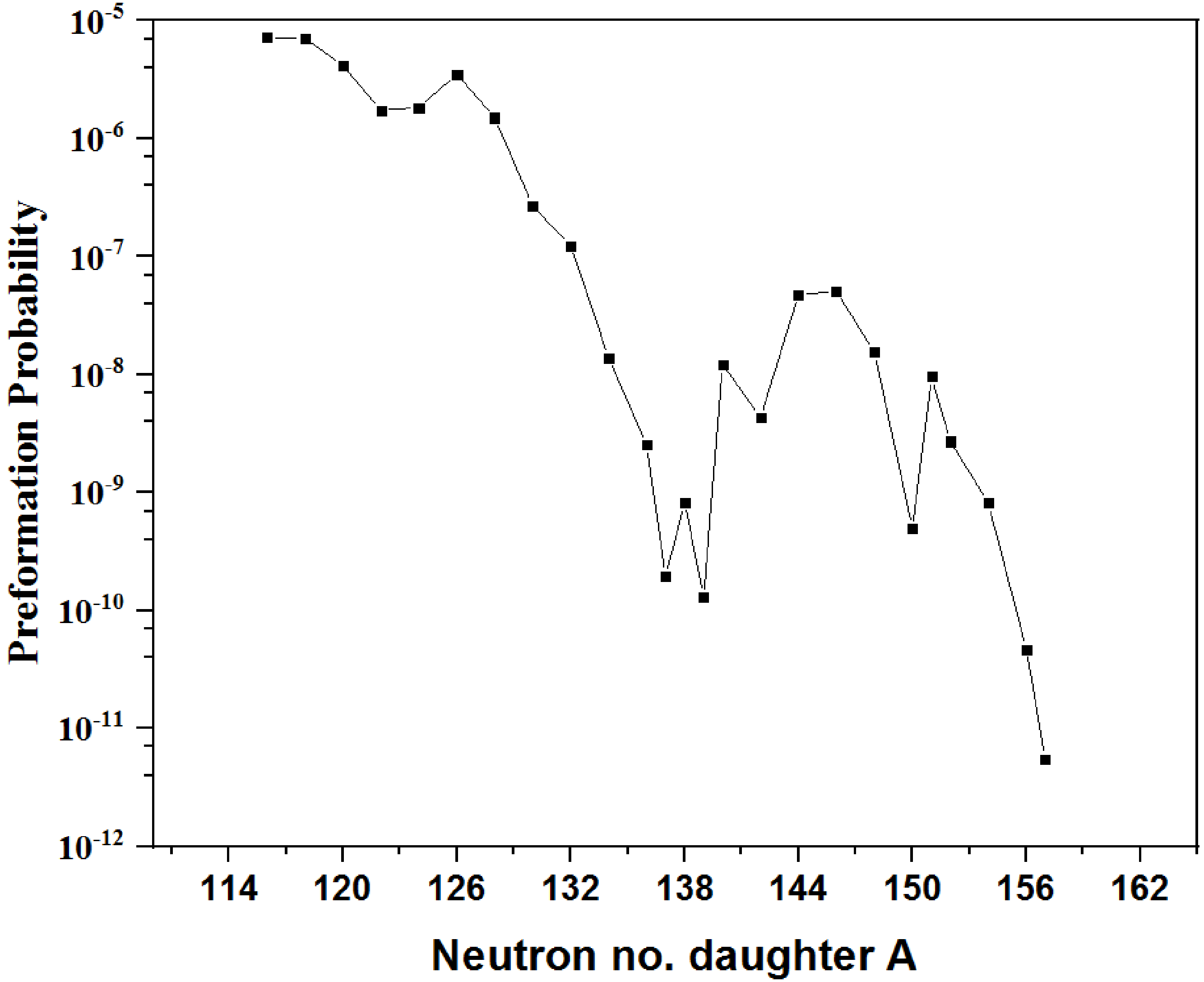


Penetration Probability and Q-Value of Alpha decay

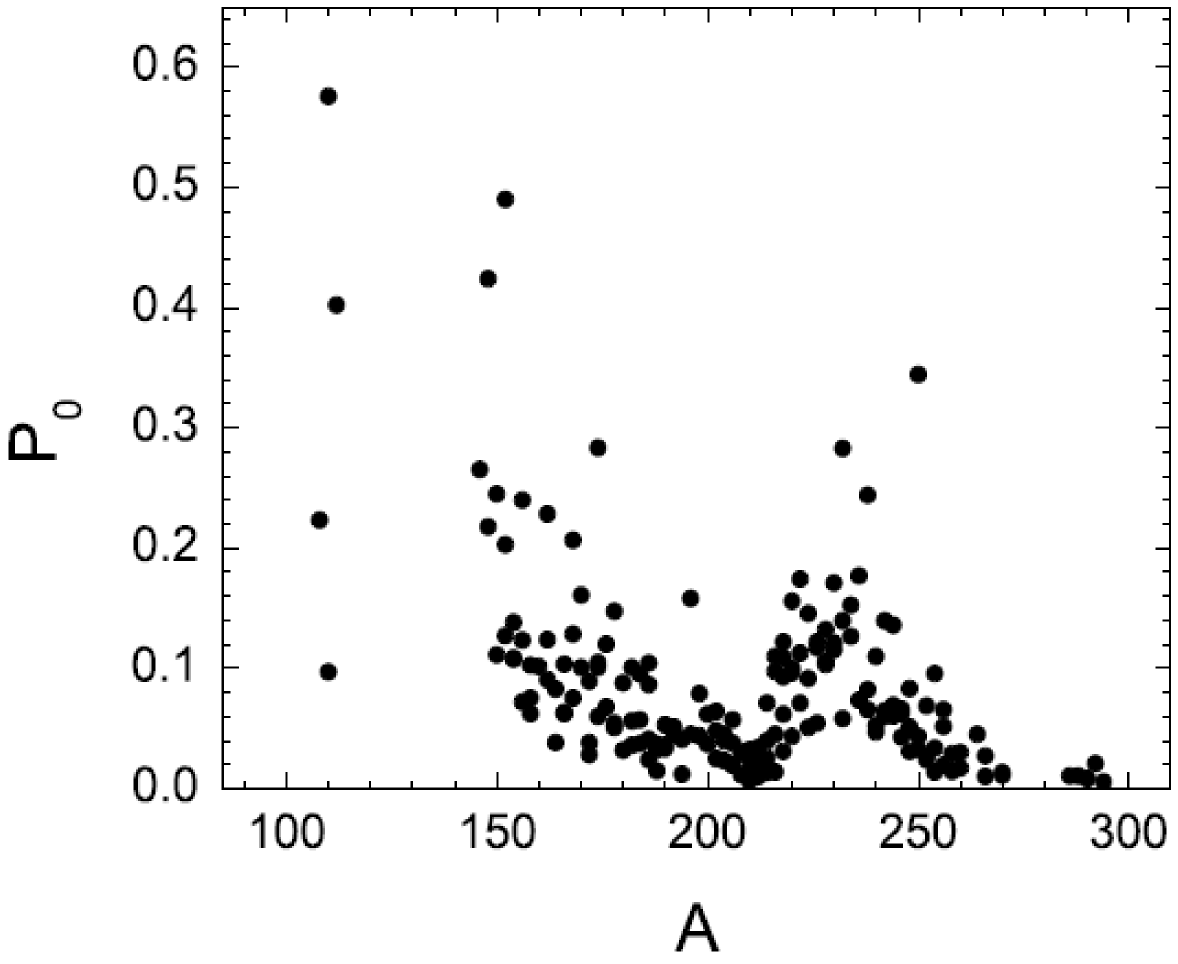


$89 \leq Z \leq 102$

Half life of Alpha Decay



Preformation of alpha decay first decreases and then increases suddenly and further starts decreasing due to shell effects at N=126.



This observation is similar as shown by PHYSICAL REVIEW C **77**, 054318 (2008)

Cluster Decay

For Spherical Fragments

$$\frac{R_a}{R_t} = 1.05502 - 0.000117016 * Q + 0.0000003424 * Q^2$$

$\sigma = 4.20$

For Deformed Fragments

$$\frac{R_a}{R_t} = 1.05706 - 0.0001977 * Q + 0.000007926 * Q^2$$

$\sigma = 2.73$

Deformed choice of fragments shows a good approximation

Summary

- Nuclei ranging **$89 \leq Z \leq 102$** are studied for Alpha and cluster decay.

- Alpha decay of different Ac nuclei were studied. Analysis of q-Value and First turning point R_a with neutron number of daughter nuclei is done.

- A relationship between Q-Value of these decays with first turning point (R_a) is introduced.

- To check the validity of the polynomial standard deviation is calculated and it shows a good approximation.

- Further Cluster Radioactivity is studied for the same range and polynomial is introduced for the same.

- Preformation probability, penetration probability and $\log T_{1/2}$ of alpha decay for the given range is studied and it shows shell effects plays a very important role.

thank you