Branching Ratios for Exotic Decay of ^{14}C from ^{223}Ra

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Exotic decays of light nuclei such as ^{14}C from ^{223}Ra was first observed experimentally by Rose and Jones[1] alongwith alpha decay. The fine structure energy spectrum of this decay by Orsay group [2] has shown preference for populating the excited states. The experimental results reveal that there exists a strong transition with 81% intensity to the first excited and a weaker transition of only 15% to the ground state. These features are strongly indicative of nuclear structure effects which require microscopic dynamical calculations for their description in place of typical theories such as Gamow's alpha decay or super-symmetric nuclear fission. In this paper, our aim is to analyse the fine structure effect within the two step model of 'cluster formation and tunneling through confining Coulomb interaction barrier'. Here, the preformation probability is obtained by solving the time-dependent Schrodinger equation in coupled relative motion co-ordinate R and the mass asymmetry co-ordinate $\eta_A = \frac{A_1-A_2}{A_1+A_2}$ where A_1 and A_2 respectively are the mass numbers of daughter and the emitted cluster. Calculations involving the time dependent Schrodinger equation to obtain the mass distribution yields in heavy ion collisions, such as ^{238}U on ^{238}U, have been carried out by Yamaji et al[3].

I. DYNAMICAL THEORY

This model[4] consists of two step process to describe dynamical coupling of R-η_A motion:

1. Cluster is preformed
2. Tunneling through the Coulomb barrier

Within this coupled motion, the decay constant χ is defined as

$$\chi = \nu(P_{\eta_A}(t))P \qquad (1)$$

where P_{η_A}(t) is the preformation probability and P is tunneling probability through the confining Coulomb interaction barrier. The assault or escape frequency ν is the number of times the cluster hits the boundary of the nucleus and is given by

$$\nu = \frac{v}{R_0} = \sqrt{\frac{2E_2}{\mu}}/R_0 \qquad (2)$$

where velocity v is determined from the kinetic energy of the emitted cluster E$_2$ ($=\frac{A_1}{A_1+A_2}$Q; Q is Q-value of reaction), μ is reduced mass and R_0 is radius of parent nucleus.
The preformation probability at any time t is given by

$$P_{\eta_A}(t) = |\psi(\eta_A, t)|^2 \left[B_{\eta_A\eta_A}(R(t))\right]^{1/2} d\eta_A \qquad (3)$$

and using WKB approximation, the tunneling probability is obtained as

$$P = exp(-2G) \qquad (4)$$

with

$$G = \frac{1}{\hbar}\int_{R_c}^{R_b} \sqrt{2\mu(V_c(r) - Q)}dr \qquad (5)$$

Here $V_c(r) = \frac{Z_1Z_2e^2}{r}$ is the Coulomb potential, R_c and R_b are the inner and outer turning points respectively. The value of r when $V_c(r) = Q$ is $R_b = \frac{Z_1Z_2e^2}{Q}$. The analytical

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TABLE I: Relative preformation probabilities $[P_{\eta_A}(t)]14C/[P_{\eta_A}(t)]_\alpha$ and branching ratios $\chi(^{14}C)/\chi(\alpha)$ for ^{223}Ra.

Decay state	Preformation probability	Branching ratios Experimental	Calculated
$--> {}^{14}C + {}^{209}Pb$ ($\frac{9^+}{2}$,g.s)	1.423×10^{-3}	$(1.0 \pm 0.2) \times 10^{-10}$	6.45×10^{-8}
$--> {}^{14}C + {}^{209}Pb$ ($\frac{11^+}{2}$,0.779 MeV)	2.57×10^{-3}	$(5.7 \pm 0.4) \times 10^{-10}$	9.72×10^{-8}
$--> {}^{14}C + {}^{209}Pb$ ($\frac{15^-}{2}$,1.423 MeV)	2.50×10^{-4}	1.0×10^{-10}	2.0×10^{-9}

solution for G-equation is given by

$$G = \frac{1}{\hbar}\sqrt{(2\mu/Q)}Z_1Z_2e^2\left[\cos^{-1}\sqrt{x} - \sqrt{x(1-x)}\right] \quad (6)$$

with $x = \frac{R_c}{R_b}$

Results and Discussion

Table 1 gives our calculated relative preformation probability of ^{14}C with respect to α-particle for the three observed states. In these calculations, $[P_{\eta_A}(t)]_\alpha$ is assigned a value equal to one. Interestingly, our preformation calculations reveal that the ^{209}Pb ground state is only weakly fed (33.54%) by the corresponding ^{14}C group whereas the first and second excited states at energies of 0.779 and 1.423 MeV, respectively, are populated with 60.67% and 5.89% branching ratios. Thus, the ^{14}C preformation mechanism within $R - \eta_A$ coupling provides an adequate explanation of the observed fine structure effect.

Immediately after preformation, the fragments simply run down th Coulomb barrier. The tunneling probability P is then claculated by using the analytical expression for G in the equation (4).

Finally, we have calculated the branching ratios $\chi(^{14}C)/\chi(\alpha)$ for ^{223}Ra by using equation (1). The results of our calculations along with the experimental data are also shown in Table 1. We find that our calculations are able to reproduce the fine structure effects observed experimentally. However, our results are larger by an order of magnitude 10^2 of the experimental data. It may be well to recollect that first step of the model calculations are carried out only for ^{14}C. We have taken here the preformation probabilities for α-decay equal to one. If the model is extended to α-decay, a good agreement between theory and experiment may be possible; it requires a further study based on cluster formation model[5]. It may also be noticed in our recent calculations that centrifugal barrier contributes significantly in penetration probability. Inclusion of centrifugal effect may further improve the agreement between the theory and experiment.

References

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