Quasi-fission and fission timescales: Zeptosecond versus attosecond

A.Ray[1] , A. K. Sikdar[1], A. De[2]

[1]Variable Energy Cyclotron Centre,*1/AF Bidhan nagar, Kolkata-700064, INDIA.*
[2]*Raniganj Girls' College, Raniganj, West Bengal, INDIA.*
** email: ray@vecc.gov.in*

Introduction

Although both the fission and quasi-fission processes have been known for a long time [1], recently a controversy has developed [2] regarding a basic question about the time scales of these nuclear processes. The theories of these processes predict fission and quasi-fission time scales of the order of 10^{-20} sec to 10^{-21} sec for the highly excited trans-uranium or uranium-like complexes. Model-dependent nuclear measurements of fission timescales based on prescission neutron emission and the giant dipole resonance agreed with the calculations within an order of magnitude, but always got somewhat higher mean values for the timescales. This discrepancy has been explained as the effect of the viscosity of the nuclear matter slowing down the fission process. However recent measurements of the timescales of the fission and quasi-fission processes by model-independent crystal blocking technique [3] and atomic X-ray technique [4] obtained values of the order of attosecond (10^{-18} sec) for the timescales of both fission and quasi-fission processes of the highly excited trans-uranium or uranium-like complexes. These results have remained unexplained so far and seem to be beyond the capabilities of current nuclear theories. Recently R. du Rietz et al. [2] measured mass-angle distributions of ^{64}Ni (310-341 MeV)+W, ^{48}Ti (220-260 MeV)+W and ^{34}S (310-341 MeV)+W reactions. They also performed simulations of the mass-angle distributions by parametrizing the nuclear sticking time distributions with half Gaussians followed by exponential decay and converted sticking time to the observed scattering angle using calculated angular momentum and moment of inertia of the system. Comparing the simulation with the corresponding experimental mass-angle distribution, they obtained that the timescales for ^{64}Ni+W and ^{48}Ti+W quasi-fission reactions were 5×10^{-21} sec and 10×10^{-21} sec respectively, whereas the timescale of ^{34}S+W fission reaction was found to be greater than 10^{-20} sec. These results are in good agreement with the theoretical calculations. Andersen et al. [3] measured the timescales of quasi-fission reactions ^{74}Ge (390 MeV)+W, ^{58}Ni (330-375 MeV)+W, ^{48}Ti(240-255 MeV)+W and fission reaction ^{32}S(180 MeV)+W by model-independent crystal blocking technique and obtained about one attosecond (10^{-18} sec) for the timescales of all those quasi-fission and fission processes. These results contradict both the theoretical results and R. du Rietz et al.'s results [2] by more than two orders of magnitude.

Of course, questions can be raised regarding the results obtained from Andersen et al.'s crystal blocking experiment [3]. However all measurements based on crystal blocking and atomic X-ray techniques have obtained about an attosecond lifetime for fission and quasifission processes irrespective of the energy region and projectile-target combinations chosen. So one cannot ignore those results and the controversy should be addressed.

Exponetial decay of dinuclear system

It is known [1] that the angular distribution of quasi-fission processes show forward focusing according to the formula $\frac{d\sigma}{d\theta} \propto e^{-(\frac{\theta}{\gamma})}$, where θ is the scattering angle in the center of mass frame and γ indicates damping. For the fission process as $\gamma \to \infty$, the angular distribution becomes symmetric and $\frac{d\sigma}{d\theta} = const.$ In order to derive this exponential angular distribution, we assume the formation of ensembles of excited dinuclear states in the exit channel undergoing exponential decays with different lifetimes depending on the ratio (M_R) of the masses of the ejectile and (projectile+target) system. Considering the exponential decay of an ensemble of quasi-bound states having a specific value of M_R and Ex with decay constant λ, we obtain $\frac{dN}{dt} = -\lambda N_0 exp(-\lambda t)$, where N_0 is the initial number of quasi-bound dinuclear states. Let L be the orbital angular momentum of the dinuclear state. Since L is very large ($\geq 40\ \hbar$) in our case, we can treat this rotation classically and consider that the dinuclear system rotates through an angle θ_{rot} in time t. Then following Toke et al. [5], if I be the moment of inertia of the dinuclear system, we obtain

$\frac{d\sigma}{d\theta}\ \alpha\ \frac{L}{I\gamma^2}\exp\left(-\frac{\theta_{rot}}{\gamma}\right)$, where $\gamma = \frac{I}{\lambda L}$. If $\theta_{c.m.}$ be the scattering angle and θ_C be the total Coulomb deflection angle, then we get

$$\frac{d\sigma}{d\theta}\ \alpha\ \frac{L}{I\gamma^2}\exp\left(\frac{\theta_C}{\gamma}\right)\exp\left(-\frac{\theta_{c.m.}}{\gamma}\right)\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

We have analyzed available mass-angle distribution data and obtained angular distributions for different values of M_R. These angular distributions have been fitted with eq. (1). Reasonably good exponential fits have been obtained and from those fits, the parameter γ has been extracted for different values of M_R. We obtained the lifetime of the process ($1/\lambda$) from the value of the corresponding γ and found that the timescales of ^{64}Ni+W reaction was 2.3×10^{-21} sec for M_R=0.37 and 5.5×10^{-21} sec for M_R=0.45. For ^{48}Ti+W reaction, we obtained timescale $=3.2\times10^{-21}$ sec for M_R=0.35 and 9.1×10^{-21} sec for M_R=0.45. These results are in good agreement with the timescales obtained from ref [2]. From our analysis of the angular distribution of various ejectiles from ^{58}Ni(280 MeV)+^{40}Ar reaction [1], we obtain that for the emission of ^{24}Mg, the timescale is 3.3×10^{-21} sec and for the emission of ^{12}C, the timescale is 10×10^{-21} sec. So clearly, all the extracted timescales are of the order of Zeptosecond (10^{-21} sec).

Possible nonexponetial decay in early time

If we treat the unstable dinuclear states quantum mechanically, then the unitary reversible quantum mechanical time evolution of unstable states cannot by itself lead to irreversible exponential decay. Quantum mechanics predicts [6] much slower nonexponential decay of an unstable state due to the quantum mechanical probability of regenerating the initial state from the decay products leading to an approximately flat initial survival probability (close to unity) for some time. Classical descriptions of quasi-fission/fission processes do not include any such quantum mechanical delay and assume irreversible exponential decay immediately after the formation of unstable dinuclear states. However any direct measurement of fission or quasi-fission process should measure a longer timescale because of this inherent quantum mechanical delay. So the question is how long this nonexponential decay timescale (leading to an effective quantum mechanical delay) could be? Clearly any type of measurement process will destroy the quantum coherence of the wave function and lead to an irreversible exponential decay. The wave function of any unstable state is unavoidably subjected [6] to such natural measurement processes because of the interaction of the decaying state with the environment. In the case of the experimental study of fission and quasi-fission processes, probably the first such natural measurement process is the interaction of the decaying state with the electronic K-orbital of the corresponding atomic complex and the emitted K-X-ray photon from the combined complex should carry information whether a fission/quasi-fission event took place. Since the timescale for K-X-ray emission from uranium-like atoms is $\sim10^{-18}$ sec and if we consider X-ray emission as the first measurement process destroying the quantum coherence of the wave function, then the nonexponential decay timescale or the effective quantum mechanical delay time should be $\sim10^{-18}$ sec. Hence any direct measurement (such as crystal-blocking technique) of fission/quasi-fission process involving uranium-like atomic complex should see quantum mechanical delay $\sim10^{-18}$ sec in addition to the nuclear decay time of $\sim10^{-21}$ sec.

Conclusion

The recent controversy regarding the timescale of quasi-fission/fission process is an important unsolved problem of nuclear physics. We have analyzed the angular distribution of quasi-fission processes assuming exponential decay of ensembles of dinuclear states in the exit channel and obtained quasi-fission timescales in good agreement with the analysis of ref [2]. Considering the initial slow nonexponential decay of an unstable quantum mechanical state, it has been proposed that any direct measurement should see the additional inherent quantum mechanical delay of the decay process and this delay could be $\sim10^{-18}$ sec for the cases studied.

References

[1] *Treatise on Heavy-Ion Science*, Vol 2, ed. D. A. Bromley, Plenum Publishing, N. Y., 1984.

[2] R. du Rietz et. al. Phys. Rev Lett. **106** , 05271 (2011).

[3] J. U. Andersen et al., Phys. Rev C**78**, 064609 (2008).

[4] M. O. Fregeau et al., Phys. Rev. Lett. **108**, 122701 (2012).

[5] J. Toke et al., Nucl. Phys. A**440**, 327 (1985).

[6] L. Fonda et al., Rep. Prog. Phys. **41**, 587 (1978).