3. Fission through Vibrational Resonance Populated by Monochromatic Photons

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I propose an experiment to investigate the possibility of minor actinide transmutation by using a new fission decay mechanism. The decay proceeds by populating the vibrational levels created on the hyper deformation. Monochromatic photons generated by the Compton backscattering of laser light on the relativistic electrons allow this study.

Keywords: Fission, Fission barrier, Vibrational level, Hyper Deformation, Nuclear transmutation

1 Introduction

Steady generation of electric power using nuclear reactor is important. The main concern, however, is the treatment of minor actinide (MA) having long life, which is accumulated in the reactor. In order to transmute the MA, an accelerator driven reactor is proposed. In this method, the minor actinides are fissioned by fast neutrons and transmuted to fission fragments ranging from about 70 to 160 u.

In this report, I propose an experiment to investigate the possibility of MA transmutation by using new fission decay mechanism. In this method the nucleus is excited in the vibrational level formed on the potential minimum corresponding to hyper deformation (HD). A theory suggests that the system excited in this level experiences the vibrational motion with an unique shape. I expect that, when this level is populated by monoenergetic photons, only nuclei having limited mass number are generated. If this nucleus is easily treated and the life is short enough, this reaction opens a way to transmute MA to the non-hazardous nuclei.

2 Fission barriers

A nucleus disintegrates into two fragments when the system overcomes or penetrates the fission barrier. This barrier arises from the interplay between the surface tension of a liquid drop-like nucleus and the Coulomb repulsion of its charge [1]. This can explain the gross shape of fission cross section as a function of the excitation energy delivered to a heavy nucleus, namely the sharp rise in the sub-”threshold” region and a rather “flat” plateau above the barrier. The classical fission barrier is drastically changed by incorporating an energy correction originating from the single particle motion of a nucleon, i.e. shell correction energy [2]. The shell corrected fission barrier shows so-called “double humped” shape. This structure could successfully explain important experimental aspects. Firstly, the second minimum created between the two barriers forms a quasi-stable nucleus, explaining the existence of fission isomers [3]. Specht et al. [4] observed rotational bands on the second minimum and determined the moment of inertia. This is a strong evidence of this state being super-deformation (SD). The double humped fission barrier can explain the cross section in the sub-threshold region, which shows fine structures (or peaks) and does not follow the smooth curve predicted by the classical tunneling of single barrier (Hill-Wheeler [1] ). The vibrational levels formed in the second minimum enhances the tunneling probability (resonance tunneling), when the excitation energy of the system matches this level, making fine structures below the fission barrier [3].

Recent large scale calculation of the potential energy surface including multi-dimensional deformation parameter (5 dimensions or more) suggests third minimum located around the hyper deformation (HD) region [5][6]. The HD minimum is created only when the mass asymmetric...
The deformation parameter has non-zero value. The shape of the HD state is very much elongated and the neck grows large. The shape looks like two nuclei being in contact. The calculation demonstrates that the double magic nucleus $^{132}$Sn has a strong influence on the shape of HD state (Figure 1) with its shape being spherical.

![Equilibrium shapes of $^{232}$Th at the ground state (top), fission isomer (middle) and third minimum.](image)

Figure 1. Equilibrium shapes of $^{232}$Th at the ground state (top), fission isomer (middle) and third minimum. (taken from Ref.[6] )

Figure 2 (a) shows schematic representation of the "triple humped fission barrier", and the associated barrier penetrability (Fig.2 (b)). The barrier structure assumed here creates three vibrational levels in each minimum. The fission probability sharply increases when the excitation energy of the compound nucleus matches the vibrational levels. It is noted that levels appearing near the barrier top give broader fission width. In order to determine which of the states (HD or SD) is responsible for the specific peak, we need to investigate the moment of inertia. This can also be accomplished by observing the rotational band built on the vibrational level, which should appear in the fission cross section (note that Figure 2 (b) does not show the fine peaks in the fission probability associated with the rotational bands). Since the level spacing of rotational band is very small, precise measurement is required to isolate the levels. However, a recent investigation succeeded in extracting the moment inertia of the HD state from the experimental data by using the fitting procedure [7][8].

Fission through the SD or HD resonance is the event that the system surely experiences the deformation of this state, so that events creating this peak may have much chance to produce "specific" fragments, especially for the HD vibration. This regular collective motion may effectively drive the nascent fragments at HD to appear at the scission point. For the HD resonance fission, the most probable fragment should be a nucleus around $^{129}$Sn (and its partner) in light of theoretical calculation. Investigation of the mass yield probability for the resonance fission, especially for the HD resonance, must be a challenging work.

3 Resonance fission experiment

Historically, the fission cross section for the sub-threshold region has been investigated using transfer reaction such as (d,p), (t,p) [9]. The excitation energy of the compound nucleus formed by the transfer reactions is widely distributed. We need to determine it by measuring kinetic energy of outgoing light particles such as protons. Light particles are usually detected by using silicon detector or magnet spectrograph. Neutron induced fission is the other method to investigate resonance fission [10]. This is, however, only applicable to the reaction through which the excitation energy of the system after neutron capture lies below the fission barrier. The excitation energy of the compound nucleus is scaled with the kinetic energy of neutron. The energy spectrum of neutron source available has a distribution, so that we usually apply time-of-flight technique to determine neutron energy. There has been no measurement on the
mass yield curve investigated for the specific resonance arising from the HD state as well as SD state.

These two kinds of reactions, transfer reaction and neutron capture, produce compound nucleus whose excitation energy is widely distributed. On the contrary, monochromatic photons generated by a laser beam interacted with relativistic electrons populate excited state in the limited energy span, so that we can choose fission events associated with the resonance. This would give a practical method of MA transmutation, if the resonance fission showed unique mass breaking as stated before. In the next section, I describe an experiment in more detail using monochromatic photon generated by Compton backscattering of laser light.

![Fig.2](a) Schematic representation of triple-humped fission barrier. Vibrational levels are calculated. Rotational levels formed on the vibrational level are also shown. (b) Fission probability.

4 Resonance fission using monochromatic photons

Figure 3 (a) shows the relationship between electron energy and backscattered photons. According to the energy (or wave length) of the laser light, three curves are shown. To generate γ-rays of 4 ~ 6 MeV, which is the energy range interesting in this study, we are free in choosing electron energy and wave length of laser. The choice of these quantities must be made with consideration of energy resolution. Fission width of the vibrational resonance has value of about a few keV, meaning that monochromatic γ-rays with high resolution is needed to accomplish this experiment. In Fig.3 (b), energy spread of backscattered photon is shown from the reference of Ohgaki et al. [11]. Although the energy spread of the monochromatic photon is somewhat system dependent, the discussion below seems to give general trends.

![Fig.3](a) Backscattered photon energy as a function of electron energy. (b) Energy spread of backscattered photon [11].
The photon energy spread is approximately written as \cite{11,12}
\begin{align}
\Delta E_v / E_v &= \left( \frac{2 \Delta E/E_e}{\gamma} + \left( \gamma \Delta \theta \right)^4 \right)^{1/2} \\
\Delta \theta &= \left( \theta_e^2 + \theta_c^2 \right)^{1/2} \\
\gamma &= E_e / m_e
\end{align}
\tag{1-3}
where \(\Delta E_v\) is the energy spread of the electron beam with energy \(E_e\), \(m_e\) is the mass of electron, \(\theta_e\) is the electron beam divergence and \(\theta_c\) is a collimation half angle. Figure 3 (b) shows the energy spread of photon calculated by Eqs. (1)-(3). The parameters used here are the data of TERAS \cite{12}.

Collimation angle is set at \(\theta_c = 0.056\) [mrad]. The energy spread increases with electron energy \(E_e\). Especially, factor \(\gamma\) entering in Eq.(3) controls the spread predominantly for larger electron energy. If we choose the low electron energy of around 200 – 250 MeV, energy spread of about 0.5 \(\%\) or better is possible. This results in energy resolution of about 20 keV, allowing experiment on resonance fission with reasonable quality.

I have estimated the time needed to obtain the significant results. Data in ref. \cite{11} is again cited for the estimation. This work reports the photon yield of about 50 photons/s/mA/W/mrad. By assuming the electron beam current of 100 mA and laser power of 100 W, we obtain \(2.6 \times 10^4\) photons/s for 0.056 mrad collimation. When we use actinide target of 1 mg/cm\(^2\) and assuming photon absorption cross section of 10 mb, it takes about 18 days to accumulate 1,000 fission events for the specific resonance peak. When the photon intensity of \(10^6\)–\(10^7\) is obtained, this experiment will be practical.

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