AN INTERPRETATION OF ENERGY DEPENDENCE OF DELAYED NEUTRON YIELDS IN THE RESONANCE REGION

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ABSTRACT

Possible fluctuation in the delayed neutron yields (DNY) in the resonance region was predicted on the basis of experimental data interpreted according to the multimodal random-neck-rupture model of fission. Using experimental data on variation in the mass distributions of fission fragments in the resonance region of U-235 and Pu-239, the DNYs were calculated by summation method considering 271 precursors. It was found that the DNY should have local dips for U-235 and spikes for Pu-239 at resonances.

1. INTRODUCTION

There are some indications that the delayed neutron yield (DNY) has a slight energy dependence in the epithermal or resonance regions. It had been considered quite unlikely that DNY would change in such a small energy range as long as we stay within conventional fission theories. Fort[1] calculated the energy-dependent DNY on the basis of the systematics proposed by Lendel *et al.*[2] for the most probable charge Zp as a function of prompt neutron multiplicity $\nu_p(E_n)$, which in turn is a function of incident neutron energy E_n. This method resulted in local peaks in the DNY at resonances of U-235 where $\nu_p(E_n)$ has local dips.

One of the present authors[3] proposed another way of calculation on the basis of multimodal random-neck-rupture fission model[4], in which mass and total kinetic energy distributions of fission fragments are represented as a superposition of standard-1 (S1), standard-2 (S2) and superlong (SL) components. It was found by Hambsch *et al.*[5, 6] that there were fluctuations in the branching rations to different fission modes at resonances for U-235 and Pu-239, which in turn implies that the fission yields of DN precursors fluctuate from resonance to resonance; this inevitably leads to fluctuations in DNY. It is worth noting that *increase* of S1-component was observed for most of the resolved resonances below 80 eV of U-235 irrespective of the spin and parity, while *decrease* of S1-component was observed only for resonances with $J^{\pi} = 1^{+}$ of Pu-239, and the magnitude of the fluctuation was much less for the latter. This difference is expected to bring about a difference in the fluctuation in the DNY for the two fissile nuclides. In order to corroborate this speculation, the authors calculated the DNY by the summation method considering 271 precursors together with the DN emission probability data evaluated by Wahl[7].

2. METHOD OF CALCULATION

2.1 FISSION YIELD FLUCTUATION IN THE RESONANCE REGION

Hambsch *et al.*[5] observed fluctuations in the fission fragment mass distributions as a function of resonance energy of U-235, which are correlated with fluctuations of the reaction *Q*-value and with the total kinetic energy(TKE) averaged over all fragments. These data were analyzed in terms of multimodal fission model, and it was found that the mode branching ratio to S1-mode w_{S1} tends to be higher at resonances than for thermal-neutron fission. This amounts to a decrease of fission yields of the outside wings (*A*=84-96, 140-152) and an increase of the inside wings (*A*=96-108, 128-140) of the mass distribution (Fig.1). Similar experiments for Pu-239 by the same author[6] revealed that, in contrast to U-235, much weaker fluctuations in mass- and mean TKE distributions were found. Interesting fact is that distinct decrease in the S1-component, compared with thermal fission, was observed only for 1^+-resonances but not for 0^--resonances (Figs.2).
Five Gaussian fit to the experimental data for U-235 was made by Hambsch *et al.*[5]. For Pu-239, it was difficult to obtain a satisfactory fit to the experimental data in the whole mass region , so a preliminary fit by Ohsawa was used in the present calculation.

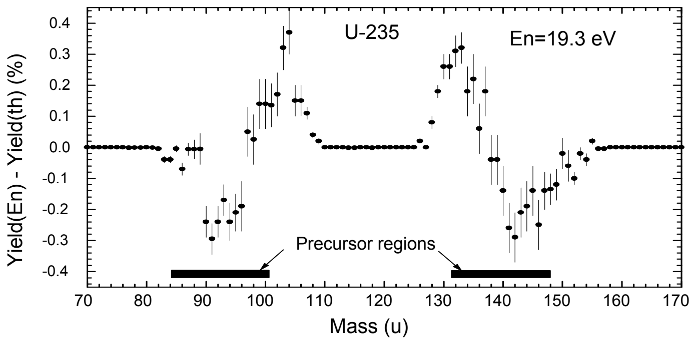

Fig.1 Fragment yield differences at 19.30eV-resonance for U-235

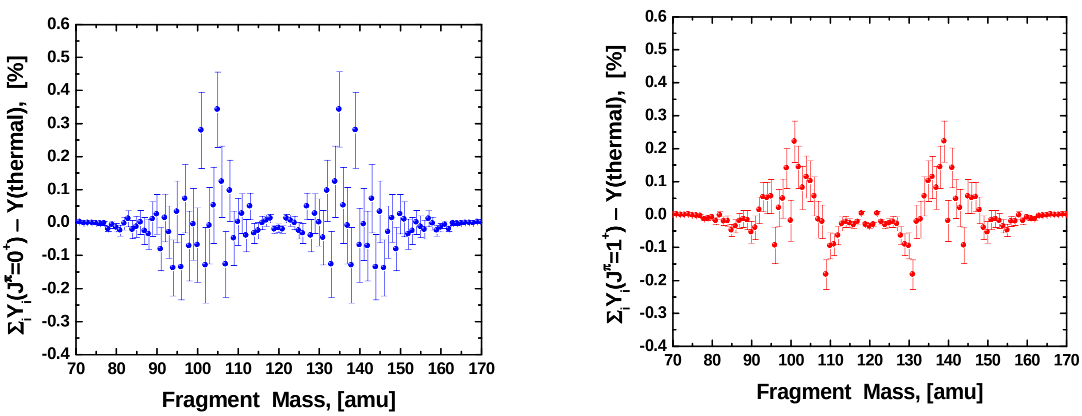

Fig.2 Fragment yield differences for 0^+-resonances (left) and 1^+-resonances (right) for Pu-239

2.2 SUMMATION CALCULATION

The total DN yield was calculated using the summation method:

$$\nu_d = \sum_i Y_i P_{ni}, \quad (1)$$

where Yi is the fission yield and P_{ni} is the neutron emission probability of precursor i. The post-neutron emission fission yield Yi was calculated by using the method of Wang and Hu[8]. The five-Gaussian representation for the pre-neutron fragment mass distribution and the prompt neutron multiplicity curve $\nu_p(A^*)$ as a function of pre-neutron emission fragment mass number A^* adjusted to approximate the experimental data[9-11] were used in the calculation. Fragment charge distribution of Gaussian shape with the standard deviation σ =0.56 and the most probable charge $Z_p = Z_{UCD} \pm \delta Z$ was used to obtain the independent fission yields, where Z_{UCD} is the charge predicted with the UCD (unchanged charge distribution) hypothesis. The deviation δZ from the UCD hypothesis is known to be undulating around 0.5, the plus sign referring to light fragments and minus sign to heavy fragments, respectively. Considering that a small change in Z_p causes large differences in fission yield calculations, we took into account these undulations[7] in the present calculations. The even-odd effect in the proton number on the fission yield, defined by

$$X = (Z_e - Z_o)/(Z_e + Z_o), \quad (2)$$

was considered, where Z_e (Z_o) stands for the fission yield of even-Z (odd-Z) fission product. The fission yield of even-Z fragments were multiplied with $(1+X)$, and those of odd-Z fragments with $(1-X)$. The proton even-odd effect with X =0.2393 was assumed for U-235 and Pu-239, respectively.

The evaluated data for the neutron emission probability P_{ni} were taken from Wahl[7], because this set comprises largest number (271) of precursors; smaller number (79) of precursors in Mann's dataset[12] were found to be inadequate to the detailed calculation like the present one.

The isomer production ratios were calculated according to the prescription of Madland and England[13].

3. RESULTS

3.1 MASS-DEPENDENT VARIATION OF DNY IN THE RESONANCE REGION

A result of calculation of the difference of the DNY with reference to thermal value as a function of fragment mass for 19.3-eV resonance of U-235 is shown in Fig. 3. A similar result for 1^+-resonances for Pu-239 is shown in Fig.4. The structures observed reflect the over-up (product) of the mass yield difference (Figs.1, 2) and the exist-region of DN precursors with high P_n for U-235 and Pu-239, as can be expected from eq.(1). For U-235, positive and negative contributions almost cancel out in the heavy fragment(HF) region, while negative contribution prevails in the light fragment(LF) region, thus resulting in negative total value. However, for Pu-239, the situation is opposite; positive and negative contributions in the LF region almost cancel out, while positive contribution prevails in the HF region, although the magnitude is smaller compared with the U-235 case. This results in all-over increase in the DNY at 1^+-resonances for this case.

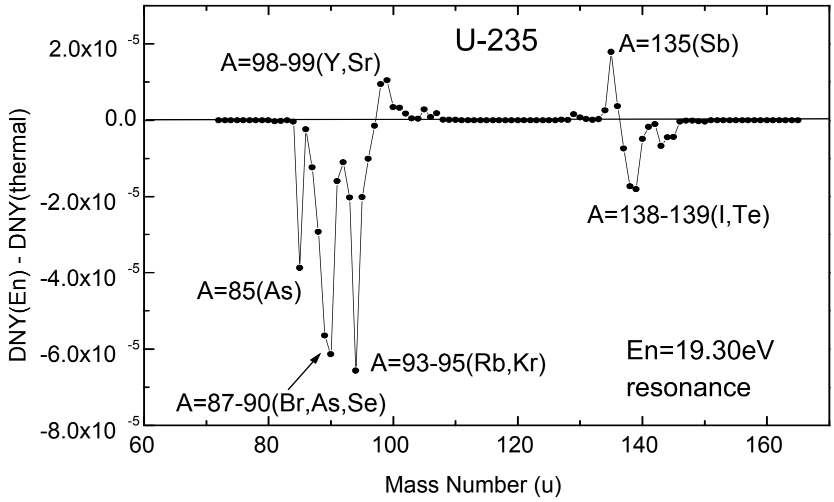

Fig.3. DNY at 19.30eV-resonance relative to thermal fission value of U-235

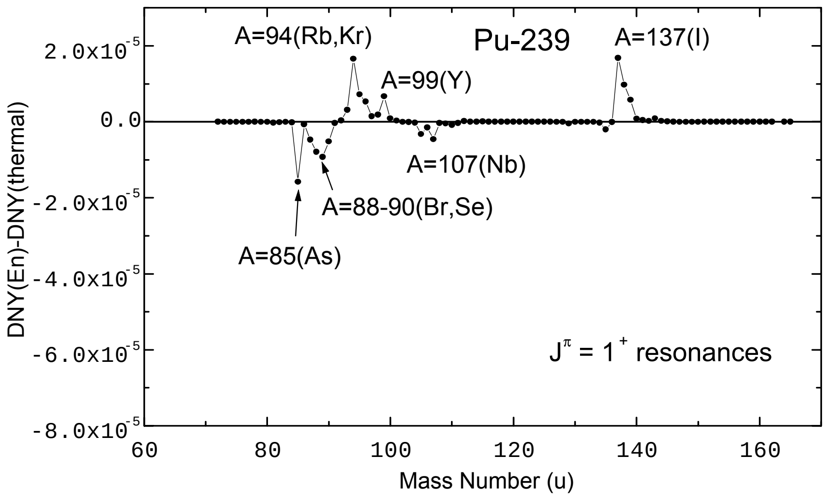

Fig.4 DNY at 1^+-resonances relative to thermal fission value for Pu-239

3.2 ENERGY-DEPENDENT VARIATION OF DNY IN THE RESONANCE REGION

The DNYs as a function of the incident neutron energy for U-235 and for Pu-239 were plotted in Figs.5 and 6. We observe local *dips* at resonances below 100 eV, except for several resonances between 82 and 87 eV, for U-235, while we observe local *peaks* at 1^+-resonances. The maximum fluctuation is about -3.5% for U-235, and +0.65% for Pu-239. The fluctuation amplitude of each resonance is different for U-235 since mode branching ratio for each resonance is known to be different, while the amplitude is constant for Pu-239, because only average data of fragment mass distribution over 1^+-resonances are available.

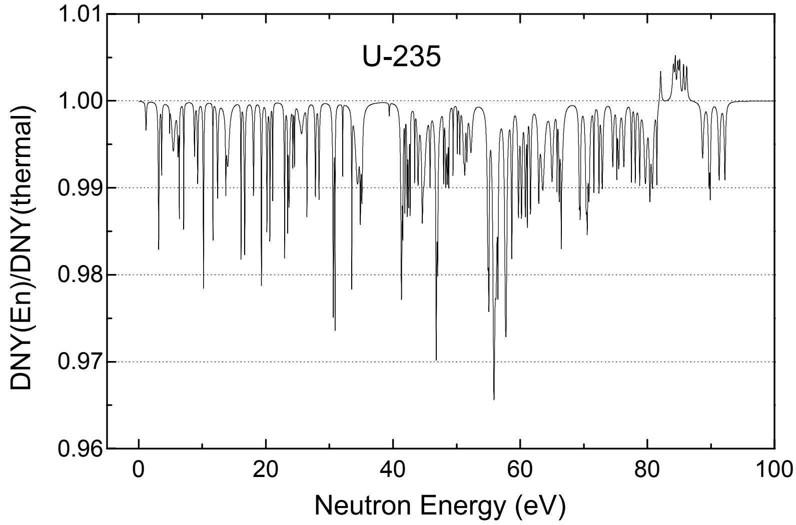

Fig.5 DNY ratio relative to thermal fission value for resonances of U-235.

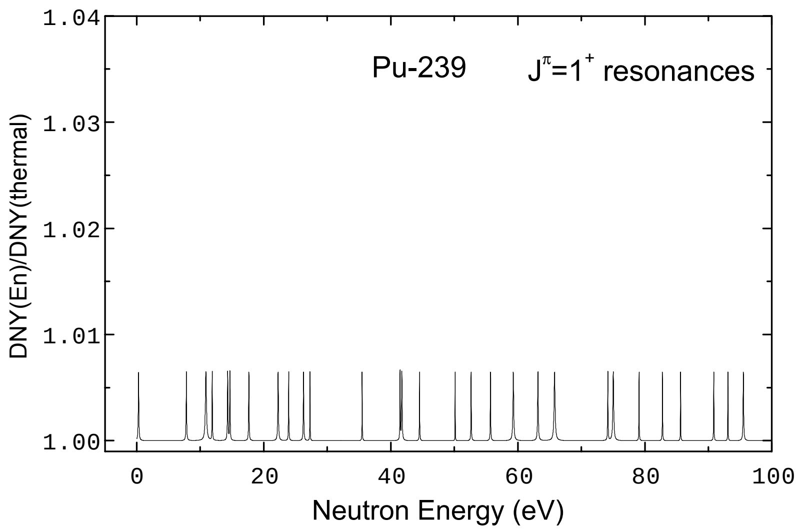

Fig.6 DNY ratio relative to thermal fission value for 1^+-resonances of Pu-239

4. CONCLUSIONS

Summation calculation on the basis of measured data on fluctuation of the fragment mass yields for U-235 and Pu-239 showed the following results: *(a)* The fluctuation in the mode branching ratios from resonance to resonance brings about fluctuation in the DNY, resulting in dips of -3.5% at maximum in DNY for U-235. This is due to the fact that (1) the S1 component increases while S2 component decreases at most of the resonances for U-235, and (2) precursors in the light-fragment

region lie just in the region where the S2 component prevails, in contrast to the heavy fragment region where positive contribution from S1 region and negative contribution from S2 region cancel out.
(b) Similar calculations for Pu-239 using the most recent result[6] revealed that the DNY showed positive peaks of about 0.65% at resonances with $J^{\pi}=1^{+}$. This is because positive and negative contributions in the LF region almost cancel out, while positive contribution prevails in the HF region, although the magnitude is smaller compared with the U-235 case.

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