Influence of neutron emission on the charge, mass and kinetic energy distribution of final fragments from $^{235}$U($n_{th}$, f) reaction

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Abstract
Using a Monte Carlo method we simulate an experiment that measures the mass, charge and kinetic energy of final fragments (after neutron emission) from the $^{235}$U($n_{th}$, f) reaction. As input data for the simulation, for primary fragments (before neutron emission), we assume (i) a distribution of mass and kinetic energy; (ii) an average number of emitted neutron as a decreasing linear function of kinetic energy and (iii) for each mass, a constant yield of charges as a function of kinetic energy, equal to that obtained by W Lang et al for the highest measured kinetic energy window (108.5 MeV) which corresponds to the lowest measured excitation energy, that corresponds to the so called cold fission. The output of the simulation is the distribution of mass, charge and kinetic energy of final fragments. From this output we obtain that, for a given mass, the charge that has the highest yield in cold fission region has a yield obeying an increasing function of kinetic energy in all other region. Conversely, the yield of the less probable charge in cold fission is a decreasing function of kinetic energy in all other region. Our results of simulation suggest that, for two primary isobaric fragmentations with similar Q-value, the preference for more asymmetric charge splits (called Coulomb effect), observed in cold fission, is valid in all region, but neutron emission shadows this property in final fragments distribution.

1. Introduction

Coulomb interaction between the complementary primary fragments from nuclear fission of actinides is responsible for most of the total kinetic energy of those fragments [1]. The knowledge of the distribution of charge, mass and kinetic energy of primary fragments (before neutron emission) is necessary to study the fission process (from saddle to scission point) [2]. That distribution would express shell effects [3] or other properties on scission configuration. However, only final fragments (after neutron emission) are detected. Due to emission of neutrons, the distribution of mass, charge and kinetic energy of final mass is different from the corresponding distribution of the primary fragments and consequently may lead to erroneous theoretical conclusions about fission process.

Nevertheless, for the thermal neutron induced fission of $^{235}$U ($^{235}$U($n_{th}$, f) reaction), there is a region of high kinetic energy where no neutron is emitted. In this region, called cold fission because it corresponds to the low excitation energy, the primary fragments are detected [4]. W Lang et al measured the mass and charge distribution for several windows of kinetic energy of final fragments, the highest of which corresponds to 108.5 MeV [5]. In this cold fission region, it was observed that for two isobaric fragmentations with the similar Q-value, the more asymmetric charge split (lower light fragment charge) occurs with higher probability. This property was named Coulomb effect [6, 7].

The Coulomb effect is due to the fact that between two isobaric scission configurations, with similar Q-values and similar shape configuration, the more asymmetric charge split has a lower Coulomb potential energy (C) then a lower total potential energy, $P = C + D$, where D is the total deformation energy of the complementary fragments. A lower P permits to reach a more compact scission configuration which implies a higher Coulomb...
energy, then a higher yield of charge for the higher values of kinetic energy [6, 7]. Moreover, a higher free energy ($F = Q - P$) of a given configuration implies a higher probability for that configuration to occur.

On the experimental data from $^{235}$U(n$_{th}$, f) reaction [5] we can also observe that the yield of the most probable charge is an increasing function of the kinetic energy of final fragment. In order to interpret this property, because fragments with lower kinetic energy emit higher number of neutrons, we will use a Monte Carlo simulation to study the influence of neutron emission on the charge yield as a function of mass and kinetic energy of final fragments.

The Monte Carlo method has been used to simulate the emission of particles in various fission and fusion processes by several authors. A Monte Carlo simulation has been used to calculate the probability of fission in binary light nuclear systems [8]. The cascade neutron emission process from excited fragments was simulated to calculate the multiplicity of prompt neutrons and the neutron energy as a function of the mass and total kinetic energy of the fission fragments [9]. A Monte Carlo Method was used to simulate the emission of neutrons, even before the complete acceleration of fragments, to calculate the multiplicity of neutrons as a function of the total kinetic energy of the fragments [10]. The Monte Carlo Hauser-Feshbach approach was applied to calculate the characteristics of $\gamma$ and neutrons to compare them with experimental data [11]. A Monte Carlo Hauser-Feshbach LILITA code was used to simulate the fusion-evaporation reaction related to neutron emission [12].

In this work, we use the Monte Carlo method simulation to just study the difference due to neutron emission between the distributions of charge, mass and kinetic energy of final and primary fragments, respectively. The distribution of final fragments produced as output of the simulation will be compared with the experimental data from the $^{235}$U(n$_{th}$, f) reaction obtained by Lang et al at the LOHENGRIIN mass separator of the Institut Laue-Langevin (ILL) [5].

![Figure 1](image_url)

**Figure 1.** Simulation of $^{235}$U(n$_{th}$, f) reaction. For primary fragments we assume: (a) the yield of mass (Y(A)), (b) the neutron multiplicity as a function of mass ($\nu(A)$) and (c) the average of kinetic energy as a mass ($E(A)$). This input data were taken from [12] where they were used to reproduce experimental distribution of mass and kinetic energy of final fragments obtained by D Belhafaf et al [14].
2. Monte Carlo simulation

As input data for the Monte Carlo simulation of the $^{235}$U(n$_{th}$,f) reaction, for primary fragments we will assume (i) the yield of mass $Y(A)$; the neutron multiplicity as a function of mass number ($\nu(A)$) and the average of kinetic energy as a function of mass number ($E(A)$) presented on figures 1(a)–(c), respectively; (ii) a standard deviation of kinetic energy ($\sigma_E$) as a linear function of mass with 4 MeV for $A = 80$ and 6 MeV for $A = 118$. For each mass number ($A$), we simulate the distribution of number of emitted neutrons ($n$) with an average $n(A)$ as a decreasing linear function of kinetic energy,

$$ n(A, E) = \nu(A) \left[ 1 - \beta \left( \frac{E - E_A}{\sigma_E} \right) \right] $$

(1)

and a standard deviation

$$ \sigma_n(A, E) = \frac{n(A, E)}{3} $$

(2)

where $\nu(A)$ is the neutron multiplicity as a function of primary fragment mass, presented in figure 1(b) and $\beta$ assumed to be 0.6.
The final fragment mass \( m \) and kinetic energy \( e \) are calculated with the relations:

\[
m = A - n, \tag{3}
\]

\[
e \equiv E \left( 1 - \frac{n}{A} \right). \tag{4}
\]

These input data about primary quantities of the fragments and calculation of final fragment mass and kinetic energy were already assumed in [13] to reproduce the distribution of mass and kinetic energy of final fragments from the \(^{235}\text{U}(n_{th}, f)\) reaction obtained by D Belhafaf et al at the LOHENGRIN mass separator [14].

In this work, for primary fragments we suppose that the yield of charges as a function of kinetic energy is constant, equal to the corresponding to cold fission \( e = 108.5 \text{ MeV} \) measured by W Lang et al for \(^{235}\text{U}(n_{th}, f)\) [5].

For final fragments, because no emission of charged particle is assumed, the final fragment charge will be equal to the primary one:

\[
z(m, e) = Z(A, E). \tag{5}
\]

Nevertheless, in this expression, due to neutron emission, the mass and kinetic energy of final fragment are different from the corresponding values of primary fragments.

As the output of the simulation, for final fragments we obtain the distribution of mass \( m \), charge \( z \), and kinetic energy \( e \).
3. Results

In order to compare the output of the simulation with the experiment data from the $^{235}$U$(n_{th}, f)$ reaction obtained by W Lang et al [5], we chose the yields of charges corresponding to mass numbers 85, 90 and 100, in kinetic energy windows of 88.5, 93.4, 98.3, 103.1 and 108 MeV of final fragments, respectively.

The experimental data for mass numbers 85, 90 and 100 are presented in figures 2(a), 3(a) and 4(a), respectively.

The corresponding results from the Monte Carlo simulation based on the curve of neutron multiplicity as a function of fragment mass $\nu(A)$ are shown in figures 2(b), 3(b) and 4(b). One can see that for final fragment number mass 85, both experimental and simulated results for yields of charges agree quite well.

However to obtain a similar result for final fragment mass equal to 90 and 100 it is necessary to use an average number of emitted neutron equal to $0.7 \nu(A)$, as it is shown in figures 3(c) and 4(c), respectively.

4. Conclusion

Using the Monte Carlo method we have simulated the emission of neutrons by the primary fission fragments from the $^{235}$U$(n_{th}, f)$ reaction, and the measurement of mass and kinetic energy of the final fragments as it was carried out by W Lang et al at the LOHENGRIN mass separator [5].
Assuming, for a given primary fragment mass, a constant yield of charge (equal to the measured by W Lang et al in cold fission) as a function of kinetic energy as the input of the simulation, the output shows that, for a given final mass, the charge that has the highest yield in cold fission region has a yield obeying an increasing function of kinetic energy in all other region. Conversely, the yield of the less probable charge in cold fission is a decreasing function of kinetic energy in all other region. This property is observed on experimental data obtained by W Lang et al [5]. The output of our simulation suggests that this property is due to neutron emission.

As a consequence, the output of our simulation suggests that, for a given primary fragment mass, the charge yields are mostly independent of kinetic energy and close to the charge yield corresponding to cold fission region, where Coulomb effect (preference for more asymmetric charge split, between two isobaric fragmentations with similar Q-value) was observed. In other words, Coulomb effect would be valid in all other kinetic energy region.

Unfortunately we do not know similar calculation of the yield of charge as a function of kinetic energy of final fragments to compare it with our simulation results.

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References

[1] Lise Meitner and Frisch O R 1939 Disintegration of uranium by neutrons: a new type of nuclear reaction Nature 143 239–40
[2] Schmitt HW, Neiler JH and Walter F J 1966 Fragment energy correlation measurements for 252Cf spontaneous fission and 235U thermal-neutron fission Phys. Rev. 141 1146
[3] Wilkins B D, Steinberg E P and Chasman R R 1976 Scission-point model of nuclear fission based on deformed-shell effects Phys. Rev. C 14 1832
[4] Signarbieux C, Montoya M, Ribrag M, Mazur C, Guet C, Perrin P and Maurel M 1981 Evidence for nucleon pair breaking even in the coldest scission configurations of 235U and 238U J. Physique Lett. 42 437–40
[5] Lang W, Clerc H-G, Wohlfarth H, Schrader H and Schmidt K-H 1980 Nuclear charge and mass yields for 235U(nth, f) as a function of the kinetic energy of the fission products Nucl. Phys. 345A 34–71
[6] Montoya M 1984 Mass and kinetic energy distribution in cold fission of 235U, 239U and 239Pu induced by thermal neutrons Z. Phys. A—Atoms and Nucl. 319 219–25
[7] Montoya M, Hasse R W and Koczon P 1986 Coulomb effects in low energy fission Z. Phys. A—Atoms and Nucl. 325 357–62
[8] Sanders S J, Szanto de Toledo A and Beck C 1999 Binary decay of light nuclear systems Phys. Rep. 311 487–531
[9] Kornilov N V, Hambisch F J and Vorobyev A S 2007 Neutron emission in fission Nucl. Phys. A 789 55–72
[10] Matsumoto A, Taninaka H, Hashimoto K and Ohsawa T 2012 Monte Carlo simulation of prompt neutron emission during acceleration in fission J. Nucl. Sci. Technol. 49 782–92
[11] Becker B, Talou P, Kawano T, Danon Y and Stetcu I 2013 Monte Carlo Hauser–Feshbach predictions of prompt fission γ rays: application to 235U, 239U, 239Pu and 252Cf(sf) Phys. Rev. C 87 014617
[12] Hüyük T et al 2016 Conceptual design of the early implementation of the Neutron Detector Array (NEDA) with AGATA Eur. Phys. J. A 52 55
[13] Montoya M, Rojas J and Saetone E 2007 Effects of neutron emission on fragment mass and kinetic energy distribution from thermal neutron-induced fission of 235U AIP Conf. Proc. 947 326
[14] Belhafaf D, Bocquet JP, Brisset R, Ristori C, Grançon J, Nifenecker H, Mougey J and Ramamurthy V S 1983 Kinetic energy distributions around symmetric thermal fission of U235 and U238 Z. Phys. A—Atoms and Nucl. 309 253