What can we learn from the fission of super-heavy elements?

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Nuclear shell model calculations predict the existence of super-heavy elements (SHE) that are tentatively synthesized through heavy-ion collisions. A complete description of the reaction to synthesize super-heavy elements is necessary to bridge these predictions with the experimental results on the fission time and residue cross sections. In this contribution, we will present the constraints that can be given on the shell correction energy from experimental data and the developments that are needed for the dynamical models. We will especially focus on the fission time of heavy elements and on the role of the isomeric potential pockets.

Keywords: Super-Heavy Elements; Fission time; Isomeric state

1. Introduction

The size of the nuclei in nature is limited. But super-heavy elements are expected to exist beyond uranium due to an extra-stability given by the next shell closure for the nucleons. There has been a long quest to synthesize these elements by heavy ion collisions in various laboratories. Experimentally, the main difficulties arise from the fact that such a reaction is not favourable and the cross sections are extremely small, of the order of few picobarns, or even less.

It is very important to note that these elements should not exist if one only considers the Liquid Drop Model. Therefore, these are very fragile objects that easily decay through fission as soon as they are slightly excited. Their main properties come from the shell structure, but there are still many ambiguities on the Z of the next shell closure and on the absolute value of the shell correction energy.

At GANIL there is also a tentative to locate the super-heavy island of stability by measuring the fission time. Recent experiments based on crystal blocking techniques have shown that the $Z = 120$ and 124 elements have a long fission time, suggesting an extra-stability.

There is a need for theoretical developments on the description of the whole reaction processes between the two colliding nuclei up to the super-heavy element. The heavier elements formed up to now where identified by their alpha-decay chain and their properties are unknown. Then, a well understanding of the reaction mechanism is also necessary to link the shell correction energy predicted by structure models to the experimental results.

Actually, the fusion mechanism is not a simple extrapolation of what is known with lighter nuclei. It is well known that fusion is hindered in this region, i.e. the fusion cross section is far lower than one would expect. The origin of the fusion hindrance is nowadays well understood on a qualitative point of view,[1] but they are still many quantitative ambiguities. Therefore, we have not reached yet the state of being able to guide the experiments without ambiguity.

2. Residue cross sections

Super-heavy nuclei mainly decay though fission, but we are interested in the small neutron-evaporation channel that stabilizes the nucleus. In order to calculate this very tiny fraction, we have developed a fission-evaporation code that can calculate very low cross sections in a short time.

2.1. *The Kewpie2 code*

The Kewpie2 code[2,3] is based on the Bateman equations describing the time evolution of an evaporation cascade, including neutrons, protons, alphas, gammas... The physical ingredients are the usual ones: it can accommodate both Weisskopf and Hauser-Feschbach evaporation widths. The fission width is based on the Bohr and Wheeler formula with Kramers and Struntinsky correction factors. The collective enhancement factor is also included. For details and references, see Ref. 3.

The level density parameter is taken from Töke-Swiatecki and the damping of the shell correction energy with the excitation energy follows Ignatyuk's prescription: at the ground state, the level density parameter reads

$$a_g = a \left[1 + \frac{(1 - e^{-E^*/E_d})\Delta E_{shell}}{E^*} \right], \tag{1}$$

where the damping energy is set to its usual value, $E_d = 18.5$ MeV.

The main particularity of this code is that it is not based on a Monte-Carlo algorithm that is not well suited for very low probabilities.

2.2. *Evaporation residues*

The fission channel dominates the disintegration of the compound nucleus formed by heavy-ions collision. If we tune slightly the fission width, this will not affect much the fission probability that remains close to 1, but it will dramatically change the fate of the evaporation residue. The fission width mainly depends on three parameters that are the fission barrier height that mainly consists of the shell correction energy, the damping energy E_d, see Eq. (1) and the reduced friction parameter. If these last two parameters are fixed to their usual values, the measured residue cross section can constrain the shell correction energy with a precision of 1 MeV. This accuracy corresponds to about one order of magnitude in the residue cross section.

Unfortunately, such a precision can only be obtained if we know precisely the fusion probability. But it is well known that the fusion mechanism is hindered for heavy elements because of the appearance of the so-called quasi-fission process. Experimentally, it is very difficult to distinguish between fission and quasi-fission, and then to evaluate the fusion probability without ambiguity. On a theoretical point of view, it is commonly accepted that the fusion hindrance is due to the appearance of an additional inner barrier that has to be crossed after the Coulomb barrier, but the various models differ on the size of this barrier and on the strength of the dissipation mechanism. Therefore, the main challenge is to find ways to assess the fusion models by other means.[1,4]

One of the ways to get rid of these problems is to send the projectile at energy well above the barriers in order to have a large fusion probability. Then, the compound nucleus will have no chance to survive, but one can get some information by measuring its fission time. This is the topic of the second part of this presentation.

3. Fission time measurements

The fission time of the $Z = 114$, 120 and 124 nuclei was measured at GANIL using the crystal blocking technique.[5] It has been found that for the $Z = 120$ and 124 nuclei, at least 10% of the capture events had a fission time longer than 10^{-18} s, which is very long. No such events were observed for the $Z = 114$ nucleus.

Such a long fission time cannot be calculated using a Langevin equation, as it is traditionaly done.[6] But the Kewpie2 code that solves Bateman equation in time can calculate dynamical observables.[3,7] It appears that whatever the mass table we use as an input of the code, we cannot reproduce such a statistics for the fission times longer than 10^{-18} s.

How can we understand such results? Some hints will be given, using a simplified model.

With excitation energy of the order of 70 MeV, we can safely neglect the evaporation of charged particles like protons and alphas. We will therefore only consider neutrons and gammas. The characteristics of the nuclei entering the evaporation chain are not known. As a toy, model, we will first fix the fission barrier of each isotope of the chain to an identical value, B_f.

The average fission time is plotted as a function of the fission barrier compared to the neutron binding energy B_n in Fig. 1.

With a small fission barrier, fission occurs rapidly at the beginning of the chain. When B_f increases, the fission time increases. But for large barriers, it is the opposite. In this case, fission events are becoming rare and are mainly first chance fission. After the evaporation of few neutrons, the nucleus is too cold to undergo fission.

This means that the long fission times that were observed correspond to fission events that occurred after evaporating several neutrons. Then, in order to reproduce the experimental data, one has to guess the fission barrier or shell correction energy of several isotopes, up to 9. The only thing we can say is that large shell correction energies are necessary to reproduce the data, far larger than the prediction of any mass table.

In this model, the description of the fission width is based on the Bohr and Wheeler model with a single saddle. But there are predictions[8] that the potential landscape along the fission path has several humps. How does it influence the fission time?

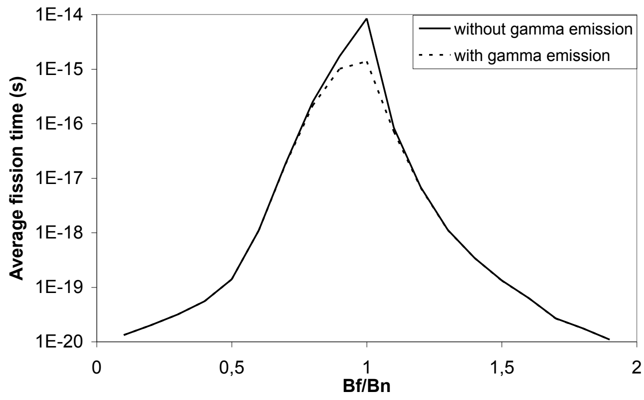

Fig. 1. Average fission time as a function of B_f/B_n assumed to be the same for all the isotopes of a $Z = 120$ like nucleus at an excitation energy of 70 MeV.

4. Influence of structures in the potential on the fission time[10]

It is well known that in the actinides region, the potential has a complex structure along the fission pathway. It might be the same in the super-heavy region. Then, we cannot simply apply the previous model based on a single saddle.

There are various theoretical tools in the literature to evaluate the average fission time.[9] Solving numerically the Langevin equation or using the so-called Non Linear Relaxation Time formula, we can show the largest effect on the average fission time with a double-humped potential is when the barriers have the same size (see the dashed curve of Fig. 3). Then, the average fission time is three times longer than with a single barrier having the same height. We will assume such a potential in the following.

The Langevin formalism including neutron evaporation that is usually used to calculate the fission dynamics[6] can hardly be applied in this context because of the extremely long fission times we need to calculate. We have developed another model based on master equations.

To estimate the rate of jumping into the other potential well or to escape, we use Kramers formula. Evaporation of neutrons that cools down the nuclei is estimated within the Weisskopf formalism. Assuming that the potential structure is the same for all isotopes, we can calculate the average fission time and the probability to have a fission time longer than 10^{-18}s and compare these results to the single humped potential case. See Fig. 2. Note that for small fission barriers, this model was validated with a Langevin type approach.

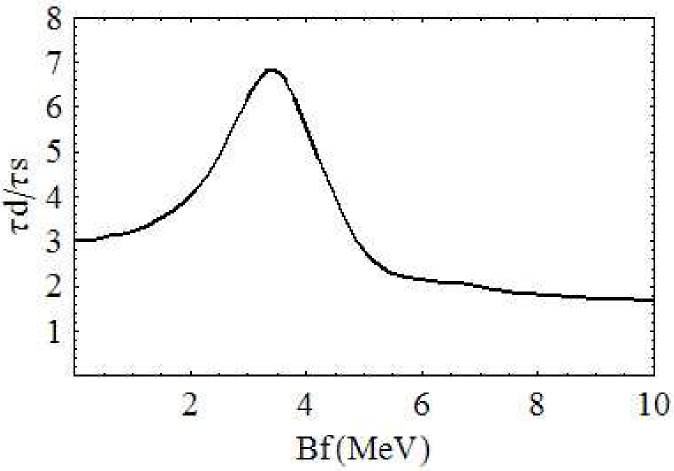

Fig. 2. Average fission time calculated with a double-humped potential divided by the same time calculated with a single-humped potential as a function of the fission barrier B_f. B_n is fixed to 6 MeV.

It can be noted that structures in the potential can naturally enlarge the average fission time of at most a factor 7.

Of course the assumption of a uniform potential for all the isotopes is not realistic. It should not be the same for each isotope, and especially structure should disappear at high excitation energy.[8] In order to evaluate this effect, we have considered a potential depending on the excitation energy as shown on Fig. 3 and solved numerically the Langevin equation with neutron evaporation. We have found that there is almost no difference on the average fission time and the number of events having a fission time longer than 10^{-18} s between a single-humped potential and a double-humped potential.

This means that the large tail of the long fission time distribution that was observed in the experiment cannot be explained by the structure of the potential.

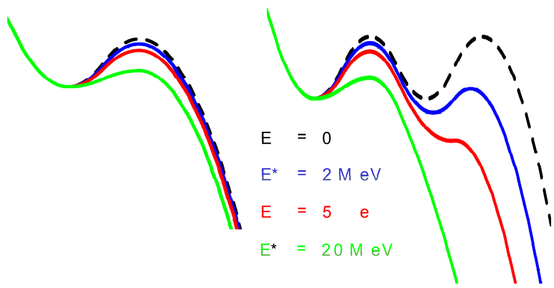

Fig. 3. Evolution of the test potential as a function of excitation energy.

5. Conclusion

Super-heavy elements formed by fusion reaction of heavy ions mainly decay by fission. Measuring the tiny residue cross sections can give a precise information on the fission width and the fission barrier provided we know the fusion probability. Unfortunately it is not the case and one of the main challenges is to find ways to assess the fusion models.[1,4]

An alternative way is to use fission time measurements to locate the super-heavy island of stability.[5] The very long fission times measured by crystal blocking techniques for the $Z = 120$ and 124 nuclei remain unexplained.[7,10]

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