Long fission times of super-heavy compound nuclei

Drouart A.[1], Charvet J.L.[1], Chbihi A.[3], Chevallier M.[4], Cohen C.[5], Dauvergne D.[4], Dayras R. 1, Frankland J.D.[3], Jacquet D.[2], Kirsch R.[4], Laget M.[2], Lautesse P.[4], L'Hoir A.[5], Marchix A.[3], Morjean M.[3], Nalpas L.[1], Parlog M.[3], Ray C.[4], Schmitt C.[4], Stodel C.[3], Tassan-Got L.[2] and Volant C.[1]

(1 DSM/IRFU/SPhN, CEA Saclay, F-91191 Gif/Yvette Cedex, France (2 IPNO, Université Paris-Sud 11, CNRS/IN2P3, Orsay, France (3 GANIL, DSM/CEA, IN2P3/CNRS ,BP 55027, F-14076 Caen Cedex 5, France (4 IPNL,Université de Lyon, Université Lyon 1 IN2P3/CNRS,, 4 rue E. Fermi, F-69622 Villeurbanne Cedex, France (5 INSP, Univ. Paris 6 et Paris 7,140 rue de Lourmel, F-75015 Paris, France

Abstract. The blocking technique in single crystals is a direct method to investigate the presence of long fission time components. With a lead beam impinging on a germanium single crystal, we tried to produce compound nuclei (CN) with atomic number Z=114 at high excitation energy. Blocking patterns for reaction products are reconstructed with position sensitive detectors at 20° relative to the beam direction. The Z and the energies of all products are measured with ΔE-E telescopes of the 4π INDRA array, so that all reaction channels are unambiguously identified. With this set-up, we can reach long fission times ($>10^{-18}$s) that can be associated with CN fissions. However, in contrast to previous experiments in which such long fission times could be measured for Z = 120 and 124, no hint of long lifetimes within our sensitivity limit for Z=114 was observed, may be due to the neutron deficiency of the formed isotopes.

Keywords: Superheavy elements; Fusion; Fission times; Crystal blocking.
PACS: 25.70.Jj; 24.75.+i, 61.85.+p

INTRODUCTION

Superheavy elements (SHE) existence cannot be explained by a simple liquid drop model. SHE survive Coulomb repulsion only with the help of an additional stability arising from shell effects. Therefore, their stability zone is strongly linked with the nuclear models predicting such shell effects. Some microscopic-macroscopic models predict a closed shell around the nucleus $^{298}114$ [1]. Skyrme Hartree-Fock approaches hints at the heavier nuclei $^{292}120$ [2] or $^{310}126$ [3] depending on the parameterization. Hartree-Fock-Bogolyubov calculations with the Gogny force point at $^{310}126$ [4]. Thus experimental investigation is necessary but is rendered very difficult due to the low cross sections of SHE synthesis. They are produced by fusion-evaporation reactions and the cross sections for the heaviest nuclei are very small. The Z=113 element was produced by the fusion of ^{70}Zn on ^{209}Bi with a cross section of 31fb [5]. The production of more neutron rich SHE with a ^{48}Ca beam on actinides targets lead to cross section of the order of one picobarn [6]. Therefore, it is very difficult to study their structure through direct synthesis. We use here an alternative method to have a look at the shell effects for such heavy nuclei. Instead of investigating the surviving evaporation residues, we look at the fission of superheavy compound nuclei (CN) resulting from the fusion of the initial nuclei. The CN production cross section is much higher than the heavy residue one. With the blocking effect in a single crystal, we are able to have a direct measurement of long components in the fission time distribution of the CN. Such components are characteristic of a high stability against fission that can only be observed if the CN is stabilized by strong shell effects. Since the CN is produced at high excitation energy, it also means that these shell effects must be quickly restored by the cooling of the CN through neutron evaporations.

THE BLOCKING EFFECT

The blocking effect in single crystals has been studied since the 1960's [7]. It is due to the collective coulomb repulsion by the atoms in a single crystal on an ion moving close to an atomic alignment. This effect can be used to probe fission times of nuclei [8]. In our experiments, we observe the reaction products emitted in the direction of a crystal axis after an interaction between the beam ions and the target nuclei. If the reaction is very fast (i.e. elastic scattering, the product is emitted close to a target atom site. Its trajectory will be close to an atomic row and will be deviated from its initial direction. This induces a depletion (a "dip") in the angular distribution in the direction of crystal axes (and in the direction of the crystal planes). On the other hand, in the case of a fusion followed by fission reaction, the compound nucleus has a recoil velocity that brings it away from the initial contact point. For increasing fission times, the fission fragments will be emitted farther away from the crystal row and they will be and less affected by the blocking effect as can be probed by increasingly filled dips. The figure 1 gives a schematic view of the process for fast and slow reactions.

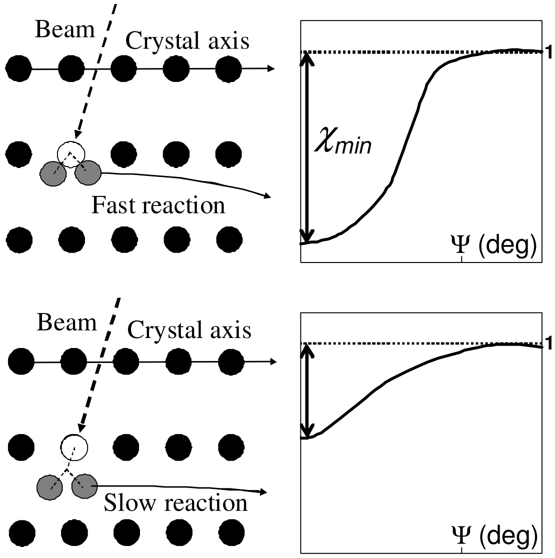

FIGURE 1. Principle of the blocking effect on reaction products for fast reactions (top) and slow reactions (bottom). A schematic angular distribution is shown on the right. Ψ is the angle between the fragment trajectory and the crystal axis direction.

The minimum yield in the direction of the crystal axis is noted χ_{min}. The shortest reaction time that can be reached through this method is the time required for the CN to leave the thermal vibration domain of the crystal atom (~0.065 Å for a Ni crystal at 20°C). It depends on its recoiling angle and velocity. In our case, this leads to a lower limit of ~10^{-18}s. For reactions faster than this limit, the minimal χ_{min} is reached. This minimal value is essentially linked to the crystal quality and other experimental conditions (beam size, angular resolution...). For this reason, the quality of the crystal was regularly checked with known fast reactions which are taken as benchmarks. The beam impact point was periodically changed to avoid too large crystal damages. In given conditions for a perfect crystal, any increase of the χ_{min} value in comparison to its minimal value does mean that there is a proportion of events with times much larger than 10^{-18}s. The dip gets filled according to the distribution of events with reaction times greater the 10^{-18}s. By contrast to the χ_{min} value that does not depend, on first order, on the kind of ions, the dip shape brings more quantitative information but its analysis requires specific simulations taking into account all the experimental information. This method has already been successfully used for the measurement of the fission times of uranium [9].

EXPERIMENTAL SET-UP

The experiment was performed at GANIL with beams accelerated by the CSS1 cyclotron. The 6.16 MeV/u ^{208}Pb beam was impinging on a 2 µm thick Germanium target. A possible complete fusion would lead to the Z=114 CN with excitation energy around 70 MeV. The target was a single crystal with natural isotopic composition. It was mounted on a goniometer in order to point one axis towards the "blocking" detectors located at ~1m. These detectors were composed of an ionization chamber followed by a position-sensitive resistive silicon detector. The first stage measured an energy loss and the second stage the residual energy and the position of the ions. Thus the Z of the fragment as well as its incident angle could be calculated. The resolution on the Z was ±2 charge units. The angular resolution was 0.02° (FWHM). The blocking detectors were mounted at 11° for reference elastic scattering measurements and at 20°, beyond the grazing angle, for the detection of the heavy fragments. The INDRA charged particle detector [9] was used to detect the nuclei emitted in coincidence with the fragment in the blocking telescope. It could detect heavy ions as well as light charged particles with a solid angle close to 4π. It provided energy loss and residual energy measurements for Z identification, as well as a crude angular distribution. With the identification of the coincidence fragment in INDRA, we were able to distinguish between the different reaction mechanisms for each event.

ANALYSIS

In previous papers, we described the first results obtained for the U+Ni [11, 12] and U+Ge [13] reactions. We describe here the very similar analysis for the ^{208}Pb+Ge reaction. The figure 2 shows the E versus Z distribution plot for the fragments detected in the blocking detector at 20°.

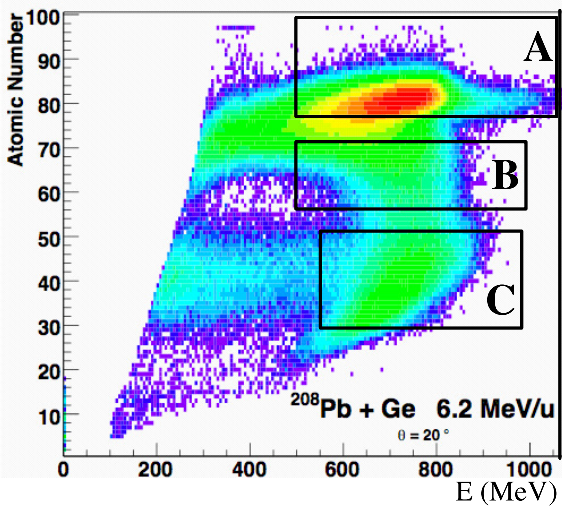

FIGURE 2. Atomic number versus kinetic energy of the fragments in the blocking detector at 20°. The meaning of the A, B, C zones is detailed in the text.

We select in this figure three different zones, corresponding to different reaction mechanisms. In zone A (Z>77, E>500 MeV), we observe mainly projectile-like fragments around Z=82, produced with very high cross section. They come from deep inelastic scattering of the projectile on the target. Zone B is restricted to 56<Z<71 and 500<E<1000 MeV. Such fragments are associated with only one heavy fragment in the INDRA detector (a negligible intermediate mass fragment multiplicity is measured as well as a very low light charged particle multiplicity). Therefore we can say that they are the heavier fragments from the dissociation of a full Z=114 system. The zone C is selected by 29<Z<51 and 550<E<1000 MeV. It is populated by fragments from two kinds of reactions: either from the sequential fission of Pb-like nuclei or from the binary dissociation of a Z=114 system. We select this second kind of fragments by requiring the detection of the heavy counterpart in the INDRA detector. We call this population of selected events C1.

From these three selections of events, we can build the angular distribution of the fragments in the direction of the crystal axis. In order to fully fit the shape of the dip, we need to use Monte-Carlo simulations that modelize the interaction of the fragments with the atoms in the crystal. This has to take into account the energy and Z distributions of the fragments. From simulations done for a perfect crystal, in perfect experimental conditions, and for reaction times much below the sensitivity limit, an ideal "null-time" dip can be determined. We have then to convolute this ideal dip with an "instrumental response function" which takes into account in a phenomenological way all the experimental defects: mosaicity and deformation of the crystal, size and shape of the beam impact To calculate this instrumental response, we used the type A events which are known to come from very fast deep inelastic events ($<10^{-20}$s). We simulated the ideal null-time dip for these ions. Then, in order to fit the actual dip, we degrade it by the addition of a 8% constant (due to crystal defects and dechanneling) and by the convolution with a Gaussian (σ=0.9mrad), due to the emittance of the beam, possible crystal curvature, mosaicity and other imperfections. This degradation is the "instrumental response function".

Since the data for zone A, B and C have been obtained in exactly the same experimental conditions, it is now possible to simulate the dips for zone B and C1 using the instrumental response function inferred from zone A, taking into account the specific energies and charges of the fragments involved. The resulting final dips, obtained assuming reaction times shorter than the sensitivity limit, are represented by the full curves on the experimental data on the figure 3.

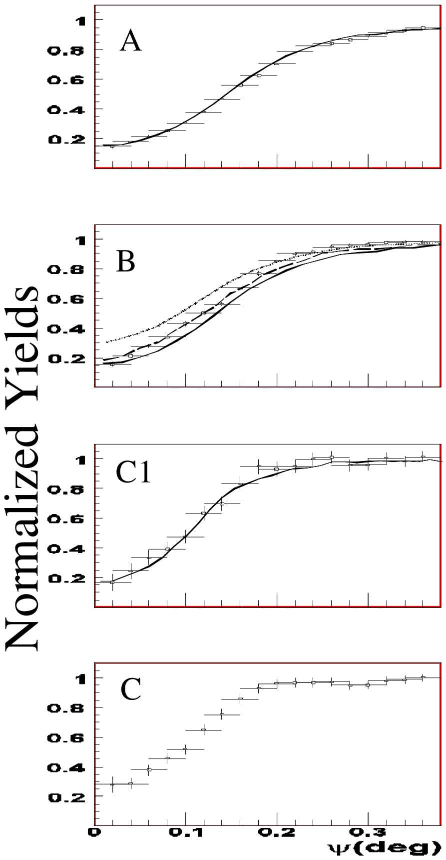

FIGURE 3. Blocking dips for different fragment selections and simulations (see text). The vertical bars represent statistical errors whereas the horizontal bars are the angular bin widths.

On panel A we can see the dip associated to the projectile-like fragments. It is our reference dip for very fast reactions. Panel B shows the blocking dip for the heavy fragments coming either from quasi-fission or from fusion-fission. The full curve (null reaction times) is compatible with the data. Nevertheless, we can see that the intermediate dashed curve, corresponding to the assumption of an exponential reaction time distribution with a decay constant $\tau=10^{-18}$ s, fits better the data. The dotted curve shows a dip corresponding to $\tau=2.10^{-18}$ s, which overestimates the data. Panel C1 shows the fit associated with the light fragments of the Z=114 dissociation. The "zero time" simulation perfectly fits the data. Considering our experimental uncertainties, the simulations cannot exclude a small proportion of long lifetimes $\sim 10^{-18}$ s. However, if long fission times are present, they contribute only very weakly to the fission time distribution and they are very close to the sensitivity limit of the experiment. On the lowest panel C, we have shown the data for all events of the C zone including the sequential fission of the Pb-like nuclei, for which long fission times are expected at such excitation energies. We have no detailed simulations, but an increase of the $\chi_{\min}$ in comparison to the other cases is observed, that shows our sensitivity to the presence of long lifetime components in the Pb-like nuclei fission.

DISCUSSION

In our previous papers [10, 11, 12] we analyzed the Z=120 and Z=124 systems. For selected events corresponding to the dissociation of the Z=120 or Z=124 systems (either coming from quasi-fission or fusion-fission reactions), we observed a significant filling of the dips in comparison with the one observed in the same conditions for known very fast reactions (deep or quasi inelastic scattering). This means that an important part of these reactions have times greater than the lower sensitivity limit which was also for these two systems close to 10^{-18} s. We interpret these long reaction times as the slow component in the fission of the Z=120 or Z=124 compound nuclei, whose strong shell effects have been restored after neutron evaporation. We concluded that these high fission barriers could be an indication for an island of stability in this region (or extending up to this region).

In the case of ^{208}Pb+Ge, there is a strong difference with the above results. The dip angular distributions show no such clear evidences of the presence of long fission lifetimes. All our dip angular distributions are compatible with reaction times lower than 10^{-18}s. Although we cannot completely exclude time components at the edge of our experimental sensitivity ($\sim 10^{-18}$s), we still can state that the fission barriers of the 114 system are much lower than the barriers for Z=120 or 124. The Z=114 initial system (before evaporation) has significantly less neutrons (N=156 to 158) than for the Z=120 (N=176 to 180) of Z=124 (184 to 188). This could clearly be a reason for a loss of stability of the possibly formed isotopes with Z = 114, since most models predict a shell closure at N=184 [1, 2].

REFERENCES

1. P. Möller and J. R. Nix, *J. Phys G* **20**, 1681 (1994).
2. M. Bender & al., *Phys. Rev. C* **60**, 034304 (1999).
3. A. T. Krupta & al., *Phys. Rev. C* **61** 034303 (2000).
4. J.-F. Berger, D. Hirata and M. Girod *Acta Phys. Pol. B* **34** 1909 (2003)
5. K. Morita & al., *J. Phys. Soc. Jpn.* Vol **76** no 4, 045001 (2007).
6. Yu. Ts. Oganessian & al., *AIP conference Proc*. Vol **947** 269-276 (2007).
7. D. S. Gemmell, *Rev. Mod. Phys.* **46**, 129 (1974).
8. J.S. Forster & al., Nucl. Phys. A **464,** 497 (1987).
9. F. Goldenbaum & al., *Phys. Rev. Lett.* **82** 5012 (1999)
10. J. Pouthas & al., *Nucl. Instr. & Meth. A* **357**, 41 (1995)
11. A. Drouart & al., Proc. of the Int. Symposium on Exotic Nuclei, Peterhof, July 5-12 2004 (world Scientific); Singapore 2005 p192.
12. D. Jacquet & al., *Proc. of the Int. Conf. on Reaction Mechanisms and Nuclear Structure at the Coulomb Barrier, March 19-23 Venezia, Italy, AIP* **853,** 239 (2006).
13. M. Morjean & al, *Eur. Phys. J. D* **45**, 27-31 (2007).