EVIDENCE OF Z=120 COMPOUND NUCLEUS FORMATION FROM LIFETIME MEASUREMENTS IN THE ^{238}U+Ni REACTION AT 6.62 MEV/NUCLEON

A. DROUART, J.L. CHARVET, R. DAYRAS, L. NALPAS, C. VOLANT
DSM/DAPNIA/SPhN, CEA Saclay
F-91191 Gif/Yvette Cedex, France

A. CHBIHI, C. ESCANO RODRIGUEZ, J.D. FRANKLAND, M. MORJEAN, C. STODEL
GANIL
F-14076 Caen Cedex, France

M. CHEVALLIER, D. DAUVERGNE, R. KIRSCH, P. LAUTESSE, C. RAY, E.TESTA
IPN Lyon
69622 Villeurbanne Cedex, France.

C. COHEN, A. L'HOIR
GPS,Université Paris 6 , 140 rue de Lourmel
75015 Paris, France.

D. JACQUET, M. LAGET
IPN Orsay
91406 Orsay Cedex, France.

The formation of compound nuclei with Z=120, followed by fission, has been evidenced in the ^{238}U+Ni system at 6.62 MeV/nucleon by very long reaction times ($t \sim 10^{-17}$s) measured by the blocking technique in single crystals. Selections in the (Z_1,Θ_{CM}) plane gives access to regions where quasi-fission is no more the dominant mechanism.

1. Motivations

The synthesis of Super-Heavy Elements (SHE) is hindered either by quasi-fission, in the first step of the reaction, or by fission after fusion. These two mechanisms are very difficult to discriminate experimentally, as they both lead to emission of fragments with similar mass and energy distributions. Nevertheless they are characterized by largely different reaction times. Quasi-fission is a very fast process ($\sim 10^{-20}$s), as it has been shown by strong anisotropies in the fragment angular distribution [1]. On the other hand, fusion-fission process might be much slower, as it requires the formation of a compound nucleus. Time measurements are thus well adapted to discriminate between these processes. Pre- and post-scission neutron detection has been used for this purpose. Here we present an experiment using the blocking technique in single crystals to perform a direct, nuclear model free measurement of the reaction times involved in the ^{238}U+Ni reaction at 6.62 MeV/u, possibly leading to compound nuclei with Z=120.

2. The Blocking Technique in Single Crystals

In this technique, a single crystal is used as target. The ions arising from reactions and emitted inside the crystal along a lattice axis (or plane) undergo a repulsive force from the aligned atoms. This effect creates a shadowing of the angular distribution in the direction of the crystal axis. In the case of axial blocking, an azimuthal integration around the axis generates an angular distribution depleted at 0°. The shape of this dip is understood through the channeling theory (see for a review [2] and ref. therein). It depends on the reaction time, on the crystal and on the ion atomic number and energy of the detected fragment. Nevertheless, its minimum value "χ_{min}", does not depend, to first order, on the considered fragment atomic number or energy when the ion is emitted close to an atomic row (*e.g.* for elastic scattering). It arises only from the distribution of the crystal atom positions (thermal vibration amplitude) and from the defects in the crystal. However, an increase of the χ_{min} occurs if the reaction time between the initial collision and the reaction fragment emission allows the ion to be emitted from the excited nucleus beyond the range of thermal vibrations (~0.065 Å for Ni crystal at 20° C). In our experiment, the minimum time associated to this range is $7\ 10^{-19}$s for nuclei moving with the center-of-mass velocity. Thus blocking provides a direct evidence for any longer reaction time.

3. Experimental set-up

The results herein were obtained with a ^{238}U beam at 6.6 MeV/u on a natural Ni single crystal, with several advantages: *i)* the reverse kinematics allows large recoil velocities, and so reduces the minimum time reachable by the blocking, *ii)* it makes fission identification easier due to the higher kinetic energies of the fragments *iii)* the fusion cross-sections are larger for asymmetric systems. The target was mounted on a 3-axis goniometer allowing rotations for crystal orientation, with 2D translations to move the interaction point.

A two-dimensional position sensitive telescope has been used in order to measure the blocking patterns at 20°. To control the quality of the single crystal and its evolution with time, the blocking effect associated with Rutherford scattering was periodically measured by another position sensitive telescope located at $\theta_{lab} = 10°$, inside the grazing angle. These telescopes are made of a low pressure (CF_4 at 50mbar) ionization chamber followed by a 2D resistive silicon detector, providing us with a Z_1 charge identification of fragments. The spatial resolution was 0.3 mm, much smaller than the beam spot size. The angular resolution is thus 0.046°. Coincidence charged products were detected by the 4π INDRA array [3]. This detector is composed of a large number of telescopes (ionization chambers + Si + CsI) covering almost the full solid angle with a low detection threshold. It measures the Z_2 and E_2 of all coincident fragments and particles, allowing thus a selection of true binary reactions.

4. Results

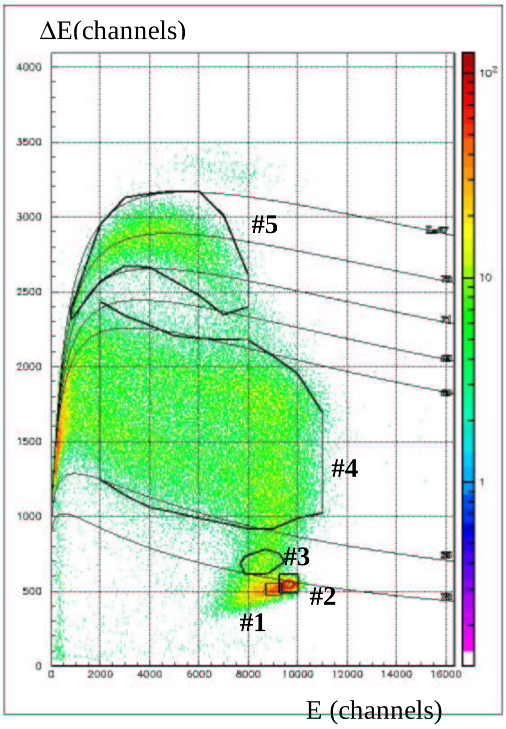

Fig. 1: ΔE-E graph obtained for the U on Ni reaction in the blocking telescope at 20° lab. The different zones are explained in the text.

Figure 1 shows the ΔE-E plot measured at 20°. We have delimited on this plot several zones corresponding to different reaction mechanisms, as identified in agreement with reference [1]. Zone #1 corresponds to deep inelastic Ni scattering and zone #2 to Ni ions from quasi-elastic scattering reactions. Zone #3, with Z from 28 to 33, corresponds to a (Z_1, Θ_{CM}) region dominated by fragments arising from quasi-fission reactions. In zone #4, the fragments arise in majority from the sequential fission of uranium-like nuclei weakly excited in peripheral collisions (as shown by the very small light charged particle multiplicity $M_{lcp} = 3.10^{-2}$ measured by INDRA). Zone #5, with $65<Z<85$, corresponds to a (Z_1, Θ_{CM}) region populated either by fragments arising from quasi-fission or from fusion-fission processes. It is only through reaction time measurements that these processes can be discriminated. Except for zone #4, the coincidences detected by INDRA show that the reactions are dominantly binary reactions and exclude the presence of incomplete fusion reactions in zone #5, signing a total charge $Z_1+Z_2=120$ for the initial system.

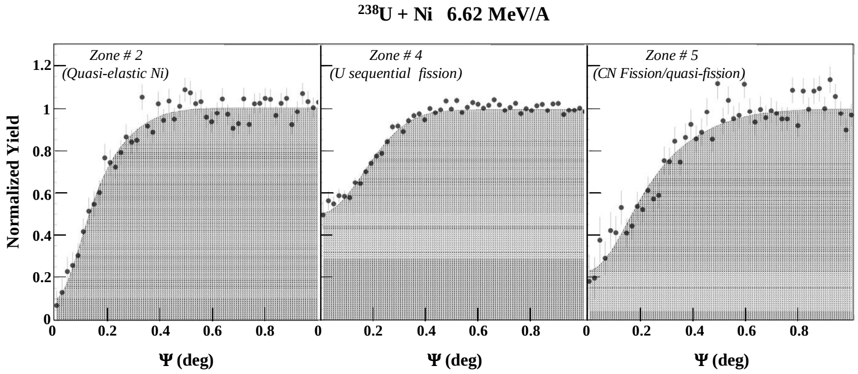

Fig. 2: Blocking dips for different zones (see text)

Figure 2 presents the blocking dips measured for *i)* zone #2, *ii)* zone #4, and *iii)* zone #5. The dips exhibit different shapes, compatible with the different Z and E of the detected nuclei, but the quite different χ_{min} values observed are direct signatures of different reaction times.

The χ_{min} values have been inferred for the 5 zones considered from fits of the dips to simple analytical expressions, requiring a derivative equal to zero at $\Psi = 0°$. The χ_{min} variations from one zone to another do not depend on the form used, making us confident in the conclusions. Figure 3 shows the χ_{min} inferred for the different zones. In this figure, zone #5 has been divided into two subzones of different energies. The similar χ_{min} values demonstrate the independence towards this latter parameter.

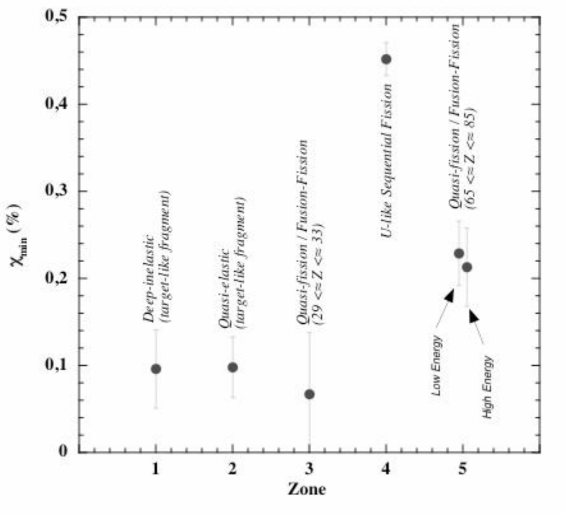

Fig 3: χ_{min} for the different zones (see text)

As expected, the lowest χ_{min} (~ 0.1) are associated with the quasi-elastic scattering of zone #2 corresponding to reaction times far shorter than our sensitivity, t_{min}. = 7 10^{-19}s. This rather high value is due to the presence of crystal defect. Zone #1 (deep inelastic) shows similar χ_{min}, in agreement with the very short times indicated by the angular distribution which are strongly peaked toward the grazing angle [1]. The large χ_{min} (~0.45) of zone #4 corresponds to the long expected [4] lifetimes for uranium fission at low excitation energy. In zones 3 and 5, the kinetic energies measured are found slightly lower than expected from systematics for compound nucleus fission fragments. As already stressed, zone 3 corresponds to a region in the plane (Z_1,Θ_{cm}) where quasi-fission is known from previous studies [1] to be the quite dominant reaction mechanism. In agreement, a χ_{min} value indicating reaction times shorter than t_{min} is found. In contrast, a χ_{min} significantly larger is obtained for zone 5 that can only result from reaction times longer than 7 10^{-19}s. Reaction times of the order of 10^{-18}s can be considered, for very heavy systems, as a signature of compound nucleus formation followed by fission.

Basic considerations on the dip shapes give already access to orders of magnitude of the reaction times involved. The χ_{min} value is minimum (χ_{min} ~

0.1) for times shorter than 7 10^{-19}s and reaches 1 (no more dip) when the reaction times become of the order of 10^{-16}s, the time needed by the fissioning nucleus to reach the next crystal row. With the very rough assumption that the χ_{min} measured in zone #5 results from a mixture between fast mechanisms (quasi-fission for example) leading to χ_{min} ~ 0.1 and a slow one (fusion-fission) at time longer than 10^{-16}s, leading to χ_{min} = 1, 10% of the events in zone #5 have to arise from fusion-fission in order to get the χ_{min} ~ 0.2 measured for zone #5. Any other assumption of faster (but with a distribution extending at times beyond 7 10^{-19}s) "slow mechanisms" would lead to a larger percentage of such events. The other rough assumption that can be made is to consider a single reaction time in zone #5. This assumption leads to an estimate of 100% of fusion-fission events with times of the order of 10^{-17}s. The actual sharing between fast and slow mechanisms has to be determined by full simulations, under progress, but these rough assumptions show that at least 10% of the events in zone #5 arise from fusion-fission events and that the average inferred reaction time is of the order of 10^{-17}s.

5. Conclusion

The very long reaction times (t ~ 10^{-17}s) measured by the blocking technique in single crystals constitute a direct evidence for the formation, with sizeable cross-sections, of compound nuclei with Z=120 in the reactions ^{238}U+Ni at 6.62 MeV/nucleon. Selections in the (Z_1, Θ_{CM}) plane gives access to regions where quasi-fission is no more the dominant mechanism. Considering the high excitation energy involved (~67 MeV) that makes the initial fission barrier very low, the very long fission times measured constitute a strong hint for shell effect restoration after cooling by evaporation [5].

References

1. J. Töke et *al.*, Nucl. Phys. A440 (1985) 327. R. Bock et *al.*, Nucl. Phys. A388 (1982) 334.
2. D.S. Gemmel, Rev. Mod. Phys. 46 (1974) 129.
3. J. Pouthas et *al.*, NIM A357 (1995) 41.
4. F. Goldenbaum et *al.*, Phys. Rev. Lett. 82 (1999) 5012. M. Morjean et al., Nucl. Phys. A630 (1998) 200c.
5. Y. Abe et al., J. Phys. G 23 (1997) 1275