Reaction studies and the synthesis of superheavy elements at GSI

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Introduction

The search for superheavy elements, predicted close to the double magic nucleus $^{298}114$ [1] was a substantial motivation for the construction of the UNILAC and the velocity filter SHIP [2] at GSI in Darmstadt. Following the concept of "cold" fusion of lead or bismuth targets with medium heavy projectiles like ^{40}Ar or ^{50}Ti, first applied successfully by Oganessian et al [3], the SHIP group succeeded to produce and identify about 25 new isotopes with atomic numbers from Z=98 up to Z=112. Mutual interaction of experimental results and theoretical calculations led to a better understanding of their stability, while measured excitation functions allowed for a reliable empirical extrapolation of optimum bombarding energies and cross sections for 1n de-excitation channels. Continuous technical development pushed the sensitivity of the set-up down to a cross section value of about 1 pb. To proceed towards higher Z an extensive development program is being followed at present. Recently the synthesis of isotopes of the elements 114 and 116 has been reported at Dubna. The unambiguous assignment of those events, however, is not yet possible. A recent review on the discovery of the heaviest elements [4] gives a complete overview over the recent achievements in the field. There can also be found a detailed description of the experimental set-up at GSI.

Recent results on the synthesis of heavy elements with Z=110-112

The elements with Z=107-112 have been synthesized and unambiguously identified at SHIP. The elements 107-109 have already been named and have been entered as Bohrium (Bh, Z=107), Hassium (Hs, Z=108) and Meitnerium (Mt, Z=109) in the periodic table of elements. The properties found for the elements 110, 111 and 112 are presented in this section. In an experiment in November 1994 four α-decay chains were observed, which were attributed to the isotope with the mass number 269 of the new element 110 [5]. The production cross section was $\sigma=3.5(^{+2.7}_{-1.8})$pb. In a directly following experiment in November/December 1994 the ER production by the reaction $^{64}Ni + ^{208}Pb$ was investigated at $E^*=(8\text{-}13)$MeV. Nine α-decay chains observed in this experiment could be attributed to $^{271}110$. A maximum cross section of $\sigma=15(^{+9}_{-6})$pb was measured at $E^*=12.1$MeV. In an experiment in October 2000 we observed in the reaction $^{64}Ni + ^{207}Pb$ eight decay chains of correlated ER-α-fission events which we attribute to the decay of the new isotope $^{270}110$. Also the daughter and grand daughter products ^{266}Hs and ^{262}Sg have not been observed before [6]. On the basis of these encouraging results for the synthesis of element 110 in the reactions $^{62,64}Ni + ^{208}Pb$ the production of an isotope of element 111 by the reaction $^{64}Ni + ^{209}Bi$ was undertaken in December 1994. A total of three decay chains attributed to $^{272}111$ was observed with a maximum cross section of $\sigma=3.5(^{+4.6}_{-2.3})$pb [7]. In the series of experiments performed in October 2000 we also confirmed the synthesis of $^{272}111$ observing additional three decay chains of this isotope. In early 1996 using the projectile target combination $^{70}Zn + ^{208}Pb$ two decay chains which had been attributed to $^{277}112$ were reported [7]. It was found later that one of the decay chains was spuriously generated [8]. In a recent experiment in May 2000 a second decay chain of $^{277}112$ was recorded. It is shown together with the first chain from 1996 in Figure 1.

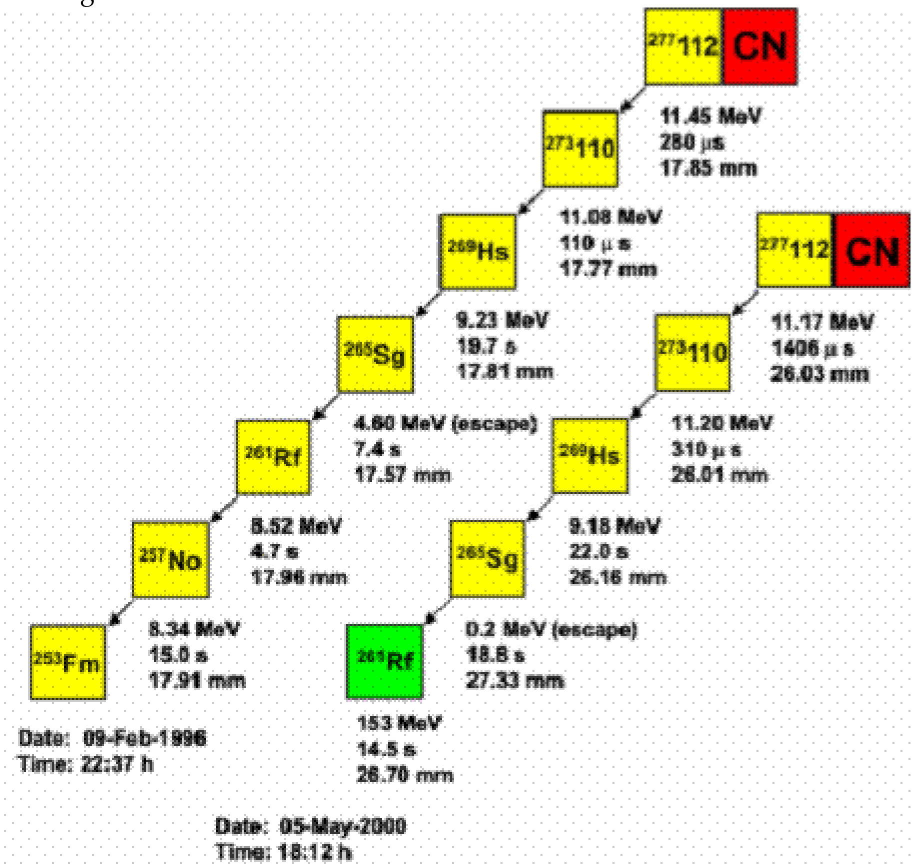

Figure 1. The two decay chains observed for $^{277}112$ in 1996 and 2000.

For this isotope a maximum cross section of $\sigma=0.5(^{+1.1}_{-0.4})$pb has been observed [8]. The chain observed in the second measurement ends with the fission of ^{261}Rf in difference to the first chain which ran all the way down to. Both decay modes of ^{261}Rf have been observed also in an experiment on the chemistry of Hs where this isotope was produced in the decay chain of ^{269}Hs [9] confirming our findings.

Reaction mechanism studies

The steep decrease with increasing Z of production cross section observed for reactions with Pb and Bi-targets and for previous reactions on actinide targets has been contrasted by recent observations made in Dubna. There decay chains have been seen in bombardments of ^{244}Pu and ^{248}Cm with ^{48}Ca projectiles, which were interpreted as the decay of $^{288}114$ [10] and $^{292}116$ [11] with a more less constant production cross section of about 1pb. According to recent self-consistent calculations [12] these nuclei are close to the region where a stabilisation due to shell effects can be expected. However, it was up to now not possible to detect an increasing production cross section for heavy ER's with magic proton or neutron numbers [13,14,15]. For medium to heavy masses it has been shown that nuclear structure and nuclear deformation are important ingredients for the formation of the compound system [16,17]. We have started a program to examine the reaction mechanism in the vicinity of the closed proton shell at Z=82 and N=126 using the partial wave (spin) distribution σ_ℓ [18]. It has been shown that one can extract from the spin distribution information on the barrier structure for heavy ion collisions [19]. Moreover, it yields information on the single partial wave cross sections and can reveal effects at high angular momentum, which might hint at a stabilisation due to shell effects as shown schematically in Figure 2.

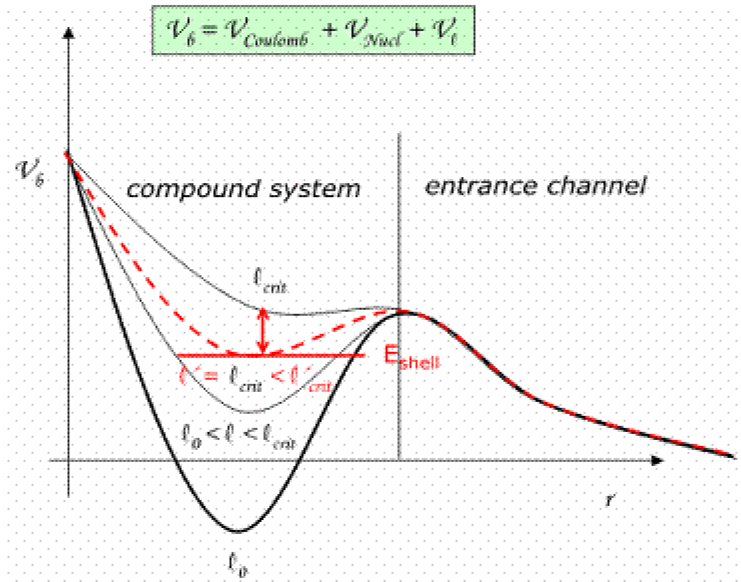

Figure 2. Cartoon illustrating the effect of a shell correction energy E_{shell} on the critical angular momentum for fusion l_{crit}.

Technical development at SHIP

The three areas presently under technical investigation at SHIP are beam development, target development and background reduction. To access a region of lower cross section the number of interactions and, therefore, the number of projectiles has to be increased. The UNILAC at GSI delivers the beam with a duty cycle of about 28%. Apart from raising the beam current, the use of an accelerator with 100% duty cycle (DC) would already provide a factor of 3.5 in higher beam intensity. The ongoing progress in the development of high frequency (28GHz) ECR ion sources promises an increase in beam intensity of another factor of 2-10. The increased beam current, together with a higher Z of the projectiles in some cases, asks for measures to protect the Pb and Bi targets, both having a low melting point. A first step is to spread the beam as homogeneous as possible over a maximum area. With the target wheel presently in use we have already reached the limit for the presently available beam intensities. The introduction of ion optical elements like octupole magnets in the UNILAC beam-line will help to approach the desired optimum of a rectangular beam profile, illuminating the target as uniformly as possible. Besides those “passive” measures also an “active” target cooling is now under development. A set-up providing a gas jet blown onto the spot where the beam hits the target is currently being developed. Chemical compounds of Pb or Bi with higher melting temperatures are also under investigation. We have obtained first promising results with PbS foils sandwiched between two thin layers of carbon. The higher projectile rate required for a successful investigation of reactions with lower cross section will have as a consequence an increase of background per time unit. To improve the background suppression we test the use of foils to stop scattered beam particles which pass SHIP with low kinetic energy. The high energy particles can be suppressed more effectively by in increased deflection in the last magnetic dipole of SHIP.

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