# A CONCEPTUAL DESIGN STUDY OF A NEXT GENERATION SEPARATOR FOR THE IN-FLIGHT SEPARATION OF SUPERHEAVY NUCLEI

GOTTFRIED MÜNZENBERG[1,2], MOHINI GUPTA[1], HANS GEISSEL[2,3], SOPHIA HEINZ[2,3], SIGURD HOFMANN[2], WOLFGANG R. PLASS[2,3], CHRISTOPH SCHEIDENBERGER[2,3], HELMUT WEICK[2] MARTIN WINKLER[2]

[1]*Manipal University, Manipal 576104 Karnataka, India*
[2]*GSI Helmholtzzentrum für Schwerionenforschung mbH, 64291Darmstadt, Germany*
[3]*II. Phys. Inst. Justus Liebig Universität 35392 Giessen, Germany*

After more than 25 years of the successful operation of SHIP in heavy-and superheavy element research, it is due time for the development of a next-generation in-flight separator for fusion and transfer products, primarily for heavy and superheavy elements. This work is triggered by new developments including accelerators for beams of highest intensity, the availability of strong beams of radioactive isotopes at near Coulomb barrier energies, and the recent developments for efficient ion catcher-cooler systems with the capability of mass identification and measurement.

## 1. Introduction

With the discovery of the chemical elements from bohrium to copernicium the SHIP concept [1] has proven successful. The tandem of two velocity filters combined with a small magnetic deflection field provides an efficient and clean separation of fusion products with an additional suppression of scattered slow projectiles. Progress in experimental techniques, the experience gathered while conducting ongoing experiments, and the fact that the synthesis of new elements is at the very limit of detection sensitivity, present new challenges to the development of advanced detection techniques are required for detailed structure studies, to reach the spherical superheavies, and to go beyond Z=118. The answer to these questions forms the primary aim of our study presently under way. The new challenges may be itemized as follows:

- development of superconducting high current accelerators providing beam intensities of $10^{14}$particles /s or more - a factor 50 to 100 above the presently used beam intensities such as the LINAG (GANIL),
- investigation of new synthesis reactions such as deep inelastic transfer reactions,
- direct mass measurements of super heavy nuclei.

As a first step we will investigate possible separator schemes, based on our experience. When SHIP was designed it was not clear which type of reaction would be successful for SHE production. The design limit was guided by the fusion of uranium with uranium at Coulomb-Barrier energy, which determined the voltage of 600 kV for the electric condenser and required separated electric and magnetic fields. The acceptance was designed for a target-projectile combination with a projectile-to-target mass ratio of 1/3 to 2/3 which defined the aperture of the quadrupole lenses [1]. The new design will incorporate experience gained from the fact that only asymmetric target-projectile combinations, such as cold fusion with lead or bismuth targets or hot fusion with actinide targets, are successfully used to produce heavy and super heavy nuclei. The new in-flight separator should provide the option to investigate transfer reactions for SHE production and include new technical developments including direct mass measurements with an ion-catcher-cooler connected to an ion trap or high-resolving time-of-flight system, a combination already working successfully at SHIP [2, 3]. The possibility of using such a device for radioactive beams at the LEB of SuperFRS is under discussion.

## 2. Some general considerations on in-flight separation of fusion products, transfers, and resolution

In-flight separators used successfully for the discovery of new chemical elements are the velocity filter SHIP (GSI), and the gas filled separators DGFRS (JINR, Dubna) and GARIS (RIKEN). Recently, the gas filled separator TASCA (GSI) has been used for the investigation of the elements flerovium (Z=114), Z=115 and Z=117. Other types of in-flight separators like VASILISSA, upgraded as SHELS, and the recoil product mass analyzer FMA (Argonne) have been used in the investigation of trans-uranium nuclides. These schemes (Table 1) are discussed in our study. Gas filled separators which are sensitive to $A/Z^{1/3}$ with bad resolution, are sufficient to separate super heavy nuclei from the projectile beam but not the background of heavy nuclei which are also produced, for example, by transfer or incomplete fusion. In addition the very high beam intensities may be a problem because of plasma formation. The most efficient way is to make use of the kinematics. Fig. 2 shows the velocities of the projectiles, fusion products, target-like transfers, and fission products for the synthesis of element 114 plotted against the projectile mass.

Table 1. Types of in-flight separators used or planned for the investigation of the heaviest elements.

| Vacuum | Acceptance (msr) | $\Phi_B$ (deg) | $\Phi_E$ (deg) | $B\rho_{max}$ (TM) | $F\rho_{max}$ (MV) | Resolution |
|---|---|---|---|---|---|---|
| SHIP, GSI | 3 | 6,12,12,6 | 6,6 | 1.2 | 20 | v/Δv= 50 |
| SHELS | 15 | 16,16,8 | 8,8 | 1 | 26 | |
| FMA, ANL | 8 | 40 | 20 | 1 | 18 | M/ΔM=350 |
| MARA, JYFL | 9 | 40 | 20 | 1 | 14 | M/ΔM=250 |
| S3, GANIL | 9 | 22,22,22 | 25 | 1.8 | 12 | M/ΔM=350 |
| Gas filled | | | | | | |
| DGFRS, JINR | 10 | 23 | | 3.1 | | |
| GARIS, RIKEN | 22 | 45 | | 1.9 | | |
| TASCA, GSI | 13 | 30 | | 2.4 | | |

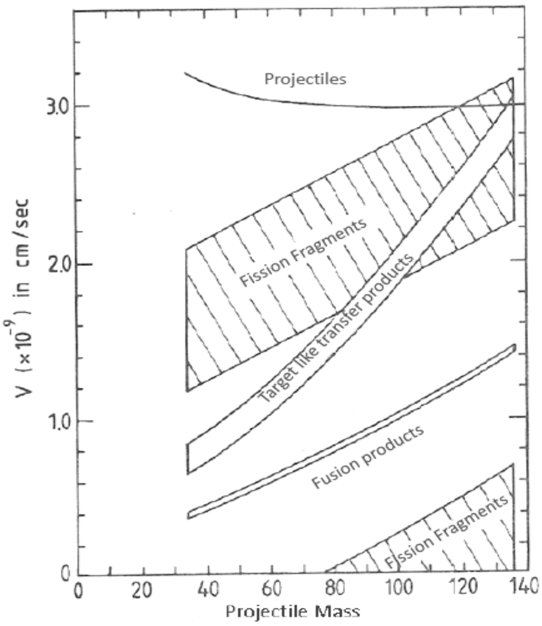

Figure 2. Velocities of projectiles, fusion products and target like transfer products for the synthesis of element 114 depicting the dependence of velocity *versus* the projectile mass.

SHE synthesis with actinide targets uses $^{48}$Ca projectiles. We see that the projectiles are well separated in velocity from the heavy fusion products, suggesting that a velocity separator of moderate resolution separates the superheavy nuclei from the beam, as has been proven with SHIP which has a velocity resolution of about 30 to 50. Fig. 3 shows the velocity distributions of the heavy fusion evaporation products $^{210}$Ac (upper figure) and $^{207}$Fr (lower figure) produced in ($x$n) and ($\alpha x$n) reactions, respectively.

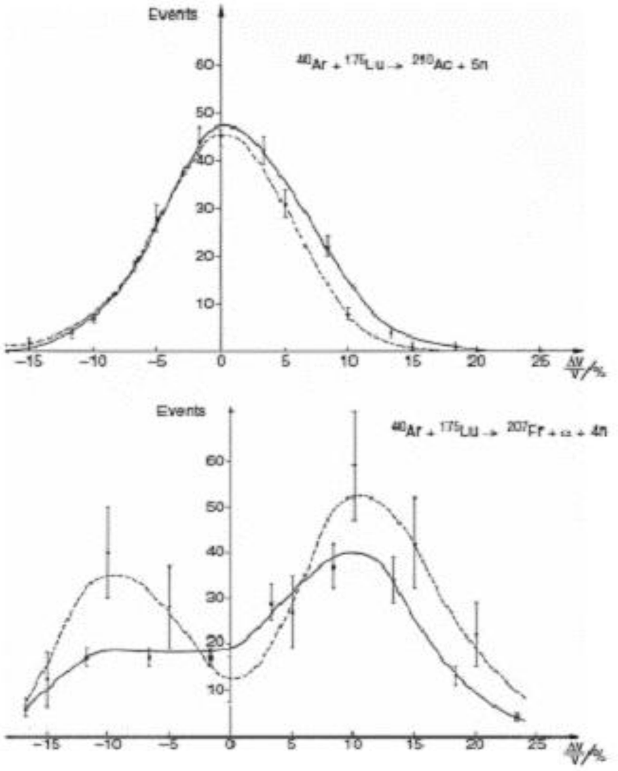

Figure 3. Tthe velocity distribution of the evaporation residues $^{210}$Ac (upper panel) and $^{207}$Fr (lower panel) produced by (xn) and ($\alpha$,xn) reactions respectively.

The momentum transfer of an evaporated $\alpha$-particle changes the velocity of the residual nucleus by about 10% which is already big enough to drive the residual nucleus out of SHIP. In this case, only evaporation residues are accepted where the $\alpha$-particle has been emitted in beam direction or opposite to the beam direction leading to the peaks at 0.9 and 1.1 times the compound nucleus velocity [4]. The velocity spectra of target-like transfer products, for comparison, have maxima in the range of 1.5 to 2 times the compound nucleus velocity.

## 3. SuperSHIP, a first approach

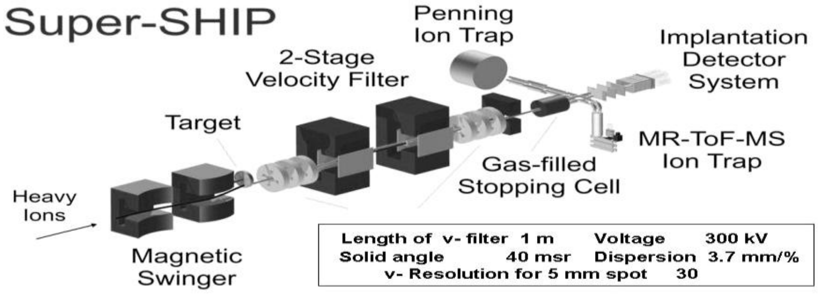

Figure 4. SuperSHIP with two crossed-field Wien velocity filters and detection systems for mass measurements and decay studies

Fig. 4 shows SuperSHIP, which is similar to SHIP but with some important improvements. A beam swinger in front of the target allows the variation of the incident beam angle to study transfer reactions which lead to broad angular distributions. Large aperture and compact superconducting quadrupole triplets will increase the solid angle. Also new are the crossed-field velocity filters. SuperSHIP will have two detector systems, one system for spectroscopic studies with implanted nuclides, and an ion catcher system with a RFQ mass separation and an MRTOF mass spectrometer [2] or an ion trap. Mass separation will be of utmost importance for the investigation of transfer products and neutron rich acitinides produced with RIB at the LEB of Super FRS. Some parameters are listed in Fig. 3. The net v-resolution of the velocity filter is 100. It is reduced to about 30-50 by the chromatic aberrations of the quadrupole lenses which cannot be corrected (Scherzer’s Rule).

## References

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