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SHIP – 2000
A proposal for the study of superheavy elements

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1 Physical aims

The outstanding aim of experimental investigations of heavy nuclei is the exploration of spherical *Superheavy Elements* (SHEs). On the basis of the nuclear shell model, the next double magic shell-closure beyond ^{208}Pb is predicted at proton numbers between Z=114 and 126 and at neutron number N=184 (Fig. 1). The uncertainty of locating exactly the proton number arises from the uncertainty of locating energetically the proton subshells $2f_{5/2}$, $3p_{3/2}$ and $3p_{1/2}$, which are filled between Z=114 and 126. Their energy is determined mainly by the spin-orbit energy, which is difficult to predict for these heavy nuclei due to effects based on the strong Coulomb forces. As a consequence, the various models predict highest stability at proton number 114, 120 or 126. In the case of an even distribution of the subshell energies, the shell effect forming SHEs will be smeared out across the region from Z=114 to 126, resulting in a wider, however, less stable region of SHEs. The question, if Z=114 is a magic proton shell and how big is the shell strength, could be answered by the synthesis of element 114 and observation of α decay of the produced isotope.

All experimental efforts aiming at identifying SHEs (Z≥114) were negative so far. The most sensitive search experiment was performed in November-December 1995 at SHIP. The isotope ^{290}116 produced by *radiative capture* was searched for in the course of a 33 days irradiation of a ^{208}Pb target with ^{82}Se projectiles. Cross-section limits of 5 pb were reached at four different beam energies, which resulted in free reaction energies between 0 and 10 MeV. Radiative capture is a possible reaction mechanism for the synthesis of SHEs, however, is known so far only for lighter elements.

Positive results were obtained at SHIP in two series of experiments. Firstly, the elements 107 to 109 were synthesized and cross-sections were measured down to 10 pb. After an upgrade of SHIP the elements 110 to 112 were produced, the latter one with a cross-section of 1 pb. Through the upgrade the performance

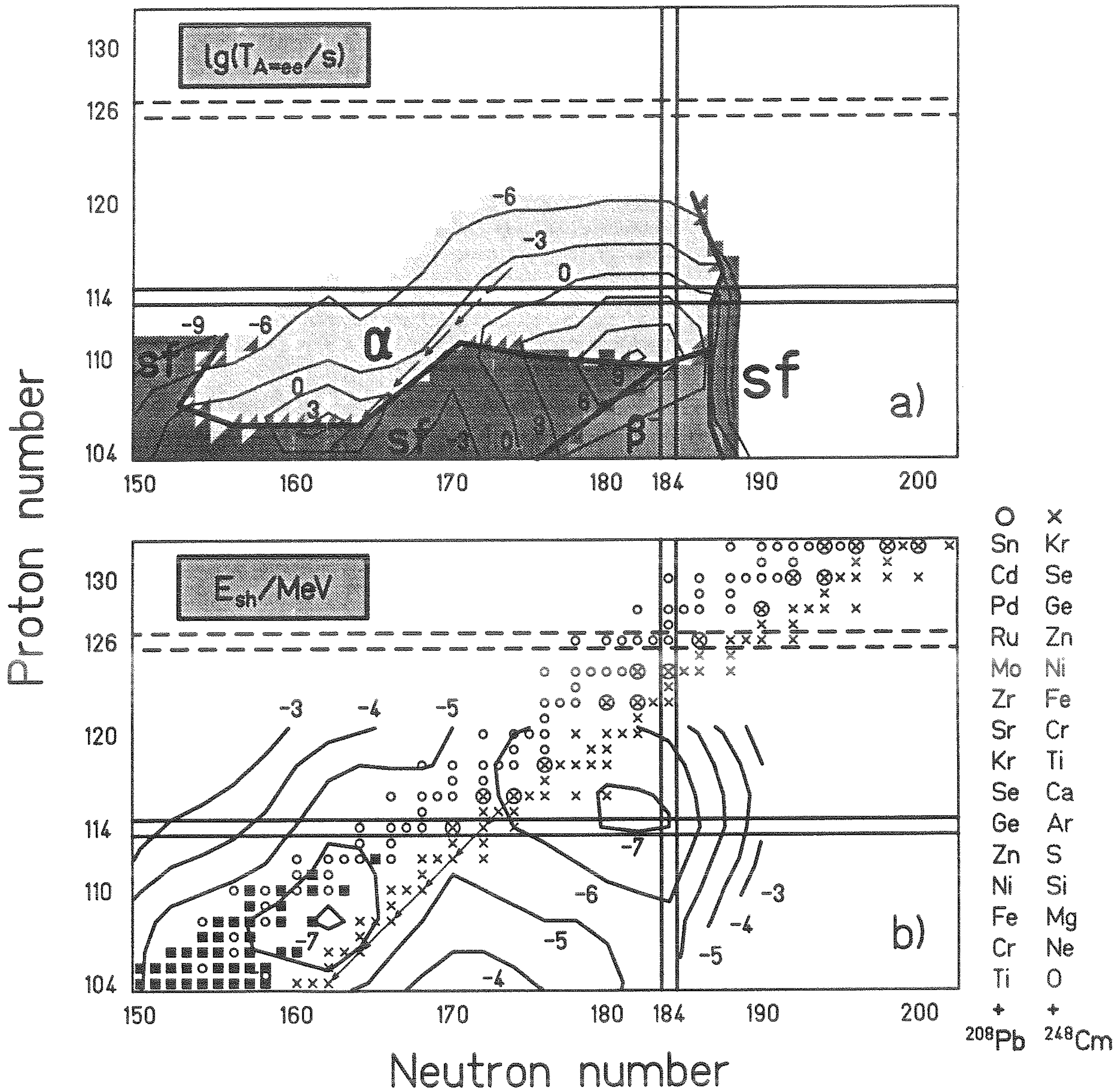

Figure 1: Dominating partial α, β and fission half-life for even-even nuclei (a). Diagram (b) shows the calculated ground-state shell-correction energy. Also marked are compound nuclei, which can be reached in reactions with targets of ^{208}Pb or ^{248}Cm and stable projectile isotopes. The presently known nuclei are marked by filled squares. The sequence of arrows indicates the hypothetical decay chain of ^{290}116 synthesized by the reaction ^{82}Se+^{208}Pb.

was considerably improved of the target, the separator, the detector and the signal processing, as well as on the accelerator side of the ion sources (PIG and ECR source with RFQ and IH accelerator). Also increased was the transmission of the beam through the accelerator and the beam line. As a result, the overall sensitivity could be increased by an order of magnitude, which allowed for extending the number of known elements up to 112. All presently known isotopes are shown in Fig. 2.

The elements from 107 to 112 were synthesized by cold fusion. However, uncertainty remains concerning the optimum reaction mechanism for the production of SHEs. We measured that the cross-sections decrease rapidly for production of elements beyond about rutherfordium (Z=104), see Fig. 3. From there on the nuclear surface tension can no longer compensate for the increasing Coulomb repulsion, a macroscopic effect, which increasingly hinders fusion of heavy systems. The reason that heavy elements can still be produced, is due to microscopic effects of both the reaction partners and, possibly, also of the compound nucleus. The latter effect may become important in the presence of strong shell effects, as predicted for SHEs by some models. However, the question remains, if these shell effects could be preserved in a compound nucleus, at least partially, and thus result in a positive modulation of the fusion cross-section for production of SHEs.

In spite of the extremely low cross-sections, the knowledge of the stability of heavy elements and of their synthesis was considerably widened in recent years. A region of increased stability for deformed nuclei with center at Z=108 and N=162 was experimentally proved. Longest half-lives were measured for ^{266}Sg (21 s) and ^{269}Hs (9.3 s). Values up to 1000 s are expected for A=267 isobars of the elements Rf, Db and Sg, see Figs. 1 and 2. Not fission, but α decay is the main decay mode up to element 112, a result which is well reproduced by calculations. The measurement of excitation functions revealed that the cross-section maxima arise at decreasing excitation energy with increasing element number, see Fig. 3. This trend is opposite to conclusions drawn from macroscopic models, which predict an extrapush in order to fuse heavy systems. Such an additional energy would have heated the compound nuclei up to several tens of MeV and thus reducing the survival probability by many orders of magnitude. Instead, the measurements revealed the importance of microscopic effects for the reaction process, and the cross-section trend shows that elements beyond 112 may still be possible to synthesize. Prerequisite for the detection, however, is an upgrade of the experimental set-up in order to make search experiments for further new elements promising and to sufficiently prepare such searches by measurement of excitation functions for the synthesis of lighter elements, i.e. up to element 112.

After the upgrade of the set-up, not only experiments aiming at synthesizing new elements will be possible to perform in reasonable measuring time, but also a whole number of various investigation covering reaction physics and spectroscopy. A list of most significant proposals is given herewith:

1. Search for the new elements 113 and 114, possibly also for 115 and 116, proof of the shell effect at Z=114 and establishing the location of SHEs. According to the calculations shown in Fig. 1, the isotopes of those elements, which are reachable using stable projectile isotopes, should be α emitters. If this is so, then the experimentally obtained α-decay data (α energy and half-life) will give a direct information on the value of the shell effect at Z=114. The predicted decay chain of $^{283}114$ is shown in Fig. 2. On the basis of the present cross-section data, we extrapolate values of 0.3 – 1.0 pb for production of element 113 and 0.1 – 1.0 pb for element 114 using ^{209}Bi and ^{208}Pb targets, respectively (see Fig. 3). However, the experimental program also has to take into account that strong shell effects may exist at Z=120 or 126. Then, this region of SHEs would be well accessible with stable projectiles in both, cold and hot fusion, with targets of lead or isotopes of the actinide elements (see Fig. 1). Although the synthesis of these very heavy systems seems to be unlikely on the basis of our present knowledge, it cannot be excluded that strong shell effects of the compound system may lead to an increase of the fusion probability.

   A search for element 113 was performed in March-April 1998. In the course of a 46 days experiment using a ^{70}Zn beam a cross-section limit of 0.6 pb was obtained, Fig. 3. This value does not contradict the expectations, however, the experiment revealed a necessary upgrade of the experimental set-up by an order of magnitude at least.

2. Ground-state to ground-state α decay of even-even nuclei for more accurate evaluation of nuclear binding energies and extraction of shell strength.

3. Search for α transitions of even-even nuclei into rotational levels for determining the degree of deformation. These experiments are especially important in the region of nuclei near N=162, where locally high stability is expected due to a relatively wide energy gap between the relevant Nilsson single particle levels.

4. Fission branching of even-even nuclei for comparison of the extracted partial fission half-lives with the results of calculations. Fission half-lives are the most sensitive parameter to test the predictions of nuclear models with respect to the stability of SHEs.

5. Gamma and conversion-electron spectroscopy of separated fusion products. Many isotopes of heavy nuclei have considerable β or electron capture branching, are formed and separated in long lived isomeric states, or excited levels are populated by α decay. Therefore, partial level diagrams could be established even in the case of small production cross-sections using highly efficient γ or electron detectors. For these applications, as also in the case of experiments using SHIPtrap (see the subsequent item no. 6), the detectors are mounted in

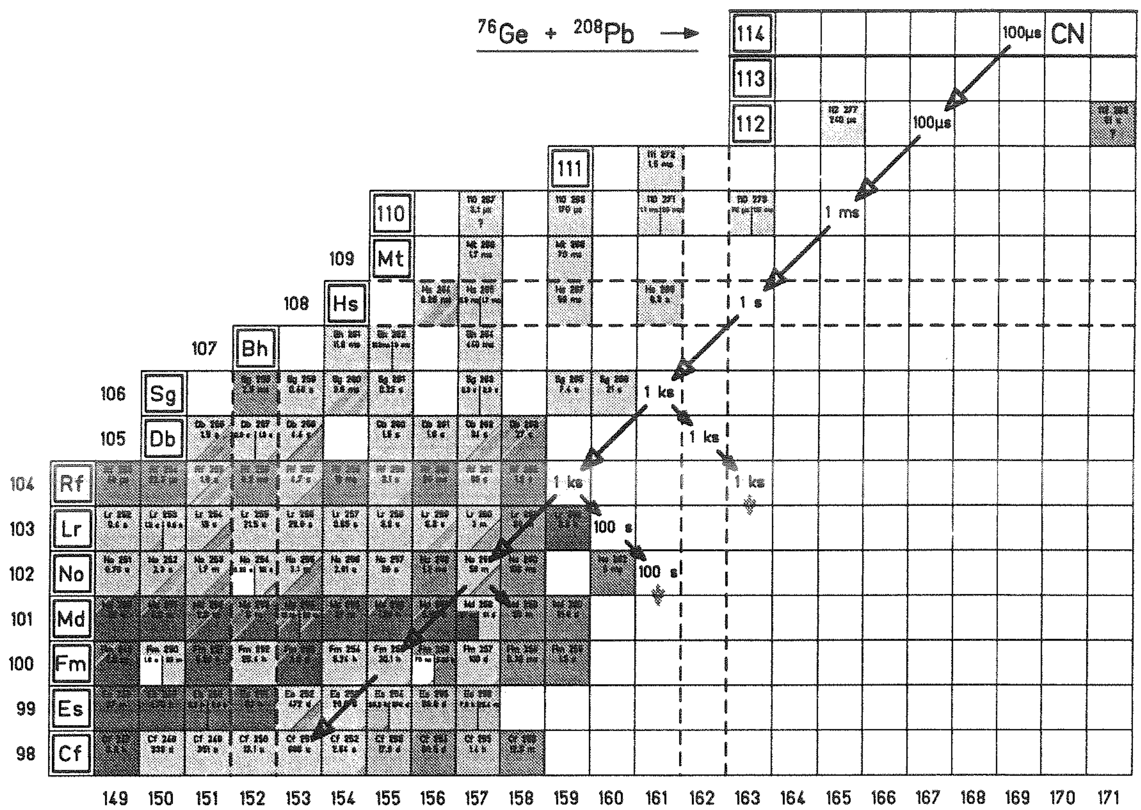

Figure 2: The presently known isotopes of the heaviest elements and the predicted decay chain of $^{283}114$. Evidence for the possible synthesis was claimed for $^{267}110$ at Berkeley and for $^{283}112$ at Dubna.

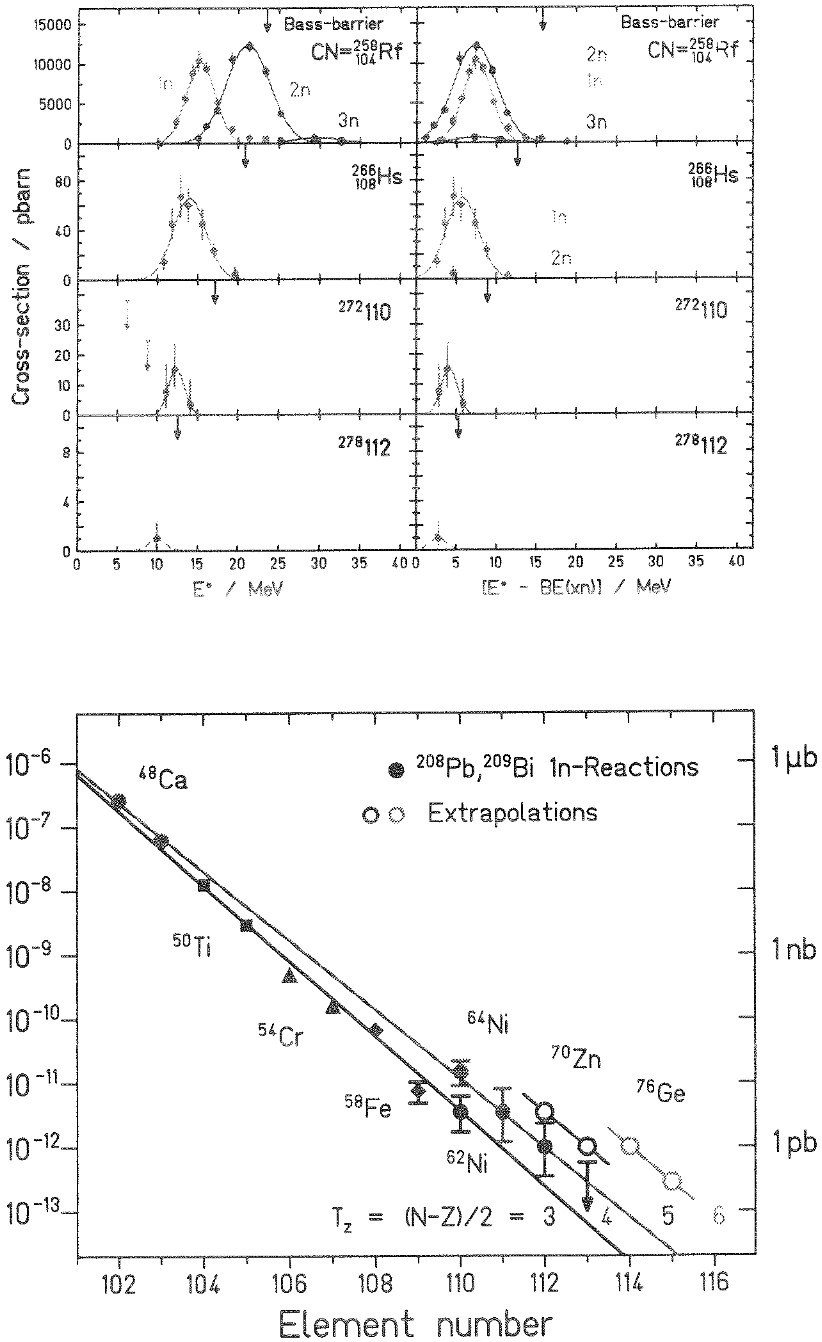

Figure 3: Upper part: Measured even-element excitation functions (solid curves) and extrapolation (dashed curve in the case of element 112). Lower part: Measured cross-sections for cold-fusion reactions (1n channel) using ^{208}Pb and ^{209}Bi targets.

a region of low background behind SHIP, and the highest currents can be used for producing the wanted species.

6. The installation of an ion-trap behind SHIP will considerably widen the possibilities for investigation of separated nuclei. Precise mass measurement, e.g., can be performed, and the electronic configuration of heavy ions can be studied by laser spectroscopy. These methods are well applicable to the study of relatively long lived species, as predicted for isotopes close to the center region of SHEs. More details of planned experiments are given in the SHIPtrap proposal.

7. The measurement of excitation functions is the most important topic in order to estimate the optimum beam energy for production of new elements and to learn more about the reaction mechanism. Particularly, the reactions ^{64}Ni+^{209}Bi $\rightarrow$ ^{272}111+1n and ^{70}Zn+^{208}Pb $\rightarrow$ ^{277}112+1n need to be studied for an optimum preparation of experiments searching for element 113 and 114.

8. Important for a better understanding of the cold-fusion reaction mechanism on a microscopic level is also the investigation of reactions using neighboring projectile or target nuclei and thus making small, however well defined changes. E.g., the reason for the cross-section increase for production of element 110 isotopes using ^{64}Ni instead of ^{62}Ni is not yet understood. An explanation would help in clarifying the usefulness of more neutron rich, radioactive projectiles for the synthesis of SHEs.

9. The energy window for production of heavy elements by cold fusion and 1n-evaporation channels gets more and more narrower with increasing element number. A possibility to overcome this limitation could be the *radiative capture* process or the use of less bound neutron deficient projectiles. The former reaction type is possible at free reaction energies less than the neutron-binding energy and the latter would increase the excitation energy at the fusion barrier to values needed for emission of a neutron.

10. A possible alternative to synthesizing SHEs by cold fusion is the hot fusion using actinide targets. Advantageous at increasing element number could be the decreasing excitation energy at the fusion barrier. The use of the strongly bound ^{48}Ca as projectile is especially favorable. Studies using ^{48}Ca as a beam are presently undertaken at FLNR–JINR in Dubna. At SHIP, the hot fusion was not investigated extensively so far, because of low transmission values. However, the investigation of more neutron rich isotopes using stable projectiles is only possible with actinide targets. The measurement of excitation functions, which are are known only very insufficiently, would provide a solid basis for extension of the experiments into the region of SHEs.

11. The reaction studies should be completed by investigating also symmetric reactions. In this case the projectile and target nuclei are close to the magic proton and neutron shell Z=50 and N=82 resulting in cold compound nuclei. In spite of great amount of extrapush energy predicted for symmetric reactions, the use of closed shell nuclei as projectile and target could result in interesting, so far not observed entrance-channel effects. The proposed reactions range from $^{124}Sn + ^{124}Sn \rightarrow ^{248}Fm^*$ to $^{136}Xe + ^{136}Xe \rightarrow ^{272}Hs^*$. The latter reaction would be the ideal case for the use of a gas-jet target.

12. Study of the deexcitation of the compound nucleus by in-beam γ spectroscopy using the recoil-tagging technique. This method was recently applied in Argonne and in Jyväskylä for studying the 3-μb 2n-evaporation channel of the reaction $^{48}Ca + ^{208}Pb \rightarrow ^{256}No^*$. With the use of the new highly efficient γ-detector arrays and a highly efficient recoil separator, these experiments could be extended to in-beam studies of lawrencium and possibly rutherfordium isotopes.

13. Experiments using the inverse reaction (beams of lead or uranium isotopes and targets of light elements) have different kinematic properties. The kinetic energy of the reaction products is high, and their momentum is directed into a more narrow cone. These properties may allow for an identification in flight at almost 100 % transmission through the separator.

14. Finally, the chemistry of the transactinide elements is of particular interest. Using SHIPtrap, the possible studies will be extended considerably compared with conventional radiochemical methods. The chemical behavior of relatively short lived isotopes ($T_{1/2}$<100 ms) can be investigated. Also, the study of the reaction kinematics using trapped ions will become possible.

2 Program for the upgrade of SHIP

The necessity for an upgrade of SHIP (Fig. 4) is based on the recently made and for the future expected ion-source developments at the UNILAC, both at the HLI injector as well as the new high current injector. Beam intensities ranging up to 5×10^{13} and 3×10^{14} /s, respectively, will become available. These currents are 1 – 2 orders of magnitude higher as used in SHIP experiments by now. Therefore, the upgrade will cover primarily three items:

1. **Development of target cooling and gas-jet targets for experiments at high beam intensities.**

2. **Improvement of the ion-optical properties of the separator with respect to high transmission and reduced background.**

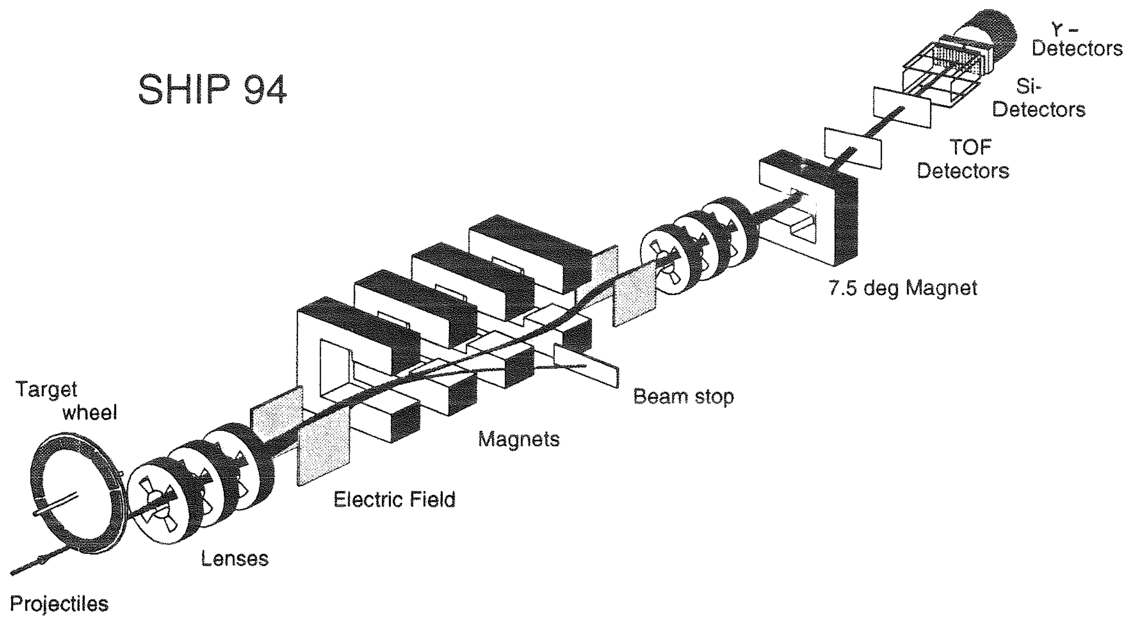

Figure 4: The 1994 version of SHIP. The proposed upgrade of SHIP-2000 is not yet drawn into the figure.

3. Increase of the detector granularity and installation of an appropriate signal processing and data acquisition system.

In the following Table estimates are given for the costs and the time schedule. Details of the planned upgrade are described in Appendix A to C.

An extensive reference list concerning the physics motivation can by found in
Rep. Prog. Phys. 61, 639 (1998).
For the SHIPtrap proposal see http://www.gsi.de/~shiptrap.
VEGA is a proposal for Versatile and Efficient GAmma-detctors, by J. Gerl et al., GSI, October 1998, p. 1-18, unpublished.

Table 1: Costs and time schedule.

	Topic	Costs/1000 DM	Year
1.a.	**Gas-cooled target wheel** vacuum chamber, pumps, target control, IR camera	600	1999
1.b.	**Gas-jet target** extension of the gas-cooled target pumping system, roots pumps, compressor, cleaner and gas cooler	400	2000
2.a.	**Separator upgrade for background suppression** using existing NASE quadrupoles behind SHIP	50	2000
2.b.	**Separator upgrade for higher transmission** large acceptance quadrupoles, power supplies, vacuum chambers	350	2001
3.b.	**Detector and data acquisition upgrade**	300	2001
	Total	1,700	

3 Collaborations

The work of the upgrade of SHIP and later of the experimental program will be performed within the following collaboration:

GSI SHIP
GSI KPII nuclear chemistry
GSI ion-source, accelerator and target laboratory, experiment electronic and data acquisition

Univ. Bochum
Univ. Bratislava
JINR Dubna
JYFL Jyväskylä
LBL Berkeley
GSI SHIPtrap collaboration
GSI VEGA collaboration

Appendix

A Target developments

The following aspects make the development of an improved or new target necessary:

1. Presently, we use low melting targets: lead with a melting point of 327 °C and bismuth, 271 °C. Bismuth is used for the investigation of odd elements and its lower melting point already caused a reduction of the UNILAC beam intensity during our last experiment searching for element 113.

2. The energy-loss in the target increases quadratically with the element number of the projectile. The values are, e.g., 6.2 MeV/(mg/cm^2) for 5 MeV/u argon in lead for production of fermium and 12.7 MeV/(mg/cm^2) for 5 MeV/u zinc in lead for production of element 112.

3. The recent ion source developments (PIG and ECR) resulted in currents up to about 1 pμA for ^{70}Zn, e.g., and further increase of the current can be expected also from these conventional ion sources. Much higher currents will become available at the new 'High Current Injector'. For certain projectiles we may expect an increase by a factor of 10 to 50. Also important for the performance of the target and the separator is a change of the macropuls structure from now 50 Hz and 5.5 ms wide pulses to 16.7 Hz and 1 ms wide pulses at HCI.

In order to use the high currents in experiments searching for SHEs, we plan to develop two kinds of high current targets at SHIP, a gas-cooled target and a gas-jet target.

A.1 Gas-cooled target, beam focusing and monitoring

In a first step, we plan to cool the presently used thin foil targets mounted on a rotating wheel. The cooling medium will be a stream of He, blown with low pressure (1 – 10 mbar) from both sides into the direction of the beam spot. The cooling effect of a gas acting on a target is well known from gas-filled separators and He-jet systems, where the currents could be increased by a factor 5 – 10 compared to targets in vacuum with only radiative cooling.

The gas-cooled target will be used in experiments, where the maximum current is limited by the accelerator to values from 1 – 5 pμA. This may the case in experiments using projectile isotopes of rare natural abundance, e.g. neutron rich isotopes from ^{48}Ca to ^{70}Zn. In these cases the ECR source will be used also in future because of its low consumption of material.

The cooling method will be also interesting in the cases, where the target material is not available in gaseous form or where radioactive, fixed targets will be used, e.g. curium or californium.

Another advantage concerns the ion-optical properties of the separator. These are mainly determined by the mean charge state of the projectiles and reaction products escaping from the target. In a low pressure helium medium of short length the charge states of the ions escaping from the solid target will not be changed, and thus the separator properties will not change compared to the presently used technique.

For the technical realization a differential pumping system has to be built, using for the main stream a turbo-molecular pump just below the target and two turbo pumps on either side of the target in order to reach a vacuum of 10^{-5} to 10^{-6} mbar at the exit of the UNILAC beam-line and to the entrance of SHIP. No windows will be installed to separate the different vacuum sections. A new target chamber has to be constructed allowing for the differential pumping. The four ion-getter pumps mounted at SHIP have to be replaced by turbo-molecular pumps.

A crucial item is also the intensity distribution of the beam across the target. The presently installed ion-optical elements allow only for a gaussian shaped beam intensity with still the highest intensity in the center region and tails at the outer areas. The former most likely melts the target in the middle and the latter causes background when hitting the target frame. The intensity distribution can be optimized using one or two octupole magnets in addition to the quadrupoles in the beam line in front of the target. With the use of these magnets an almost rectangular intensity distribution should be achievable.

The intensity distribution and the resulting temperature distribution across the target will be monitored by an infrared video camera. The monitor system will be developed so that it can be used also as a control of the beam current and beam position during the irradiation.

The gas-cooled target system should be available by the end of 1999. The preparations are underway. The work is being performed together with the people from the target laboratory, the ion-source group and the UNILAC.

A.2 Gas-jet target

At the highest beam currents ($\geq$5 pμA) gas-jet targets will be mandatory. Densities of the order of 10^{18} atoms/cm^2 are required. Gas-jet targets of this type are already in use, e.g. in experiments for investigating reactions of astrophysical interest at the University of Bochum. There, helium is used as a target gas. In our case, gaseous compounds of lead and bismuth will be examined. Also experiments will become possible using targets of elements, which exist only on gaseous form, like krypton or xenon. The alternative of using high temperature vapor targets was examined, however rejected, because of the complications due to the high temperatures needed ($\gtrapprox$ 1500 °K) and the less flexibility.

We are aware of some possible complications, which may arise from the use of a gas-jet target and are trying to estimate quantitatively their influence on the operation of SHIP. Using a gas-jet target, the separation properties of SHIP will be different, because of the smaller charge state of the ions escaping from a gaseous medium compared with a solid target. A resulting higher background, more than due to the higher beam current, may cause an additional separation stage behind SHIP. The interaction of an intense projectile beam with a jet of chemical compounds will result in cracking of a part of the molecules into its components. This effect may result in failures of the pumping system.

The technical design of the gas-jet target is so that the target wheel will be replaced by a Lavalle nozzle. In order to reach the desired density, gas pressures of 10 to 30 bar are needed. The resulting flow is about 40 g/s or 100 kg/h of a gaseous lead compound. This high amount of material demands appropriate pumping power and a recycling system. Therefore, the main parts of the pumping system will be a roots pump with subsequent compression, cleaning and cooling stage.

The gas-jet target will be able to accept the highest currents, however, the system is complicated, especially in the case of gaseous metallic compounds as target material. Therefore, we start with the gas-cooled target and design the target chamber and the differential pumping system so that most parts can be used also for the gas-jet target. Experience concerning the interaction of an intense heavy ion beam with a gas-jet and the resulting separation properties will be studied already using the pumping system prepared for the gas cooling, however, at a factor of 1000 lower gas densities.

In the case that the results of the preexperiments do not reveal severe objections, the final version of a gas-jet target could be available by the end of the year 2000. The developments are made together with people from the ion-source group, the target laboratory and the nuclear chemist group.

B Upgrade of the separator SHIP

The purpose for the upgrade of SHIP is a further reduction of background and an increase of transmission.

B.1 Background

Using high currents, we expect that the background rate will increase more than proportional with the intensity. The reason is an unavoidable beam halo due to space charge effects. This means that at a factor of 10 higher currents the background rate on the detector will increase to more than 500 /s on the average. In reality, the beam is pulsed and the background rate during the 1 ms wide macropulses from HCI will be 30,000 /s. This high rate does not allow for data taking during the macropulse, only the pauses can be used, which restricts the experiment to search for daughter decays with half-lives longer than about 1 ms.

A solution to reduce the background considerably will be the extension of the already installed magnetic dipole behind SHIP by a quadrupole doublet. As proper elements we plan to use the already existing quadrupoles of the postseparator NASE. The complete NASE is not suitable, because its dispersive element is a 30° deflection magnet, which widens the beam too much, resulting in a transmission of only 30 %. The deflection angle of the presently used magnet is variable between 0° and 25°. In operation with the NASE quadrupoles the deflection angle will be optimized for highest background suppression and transmission.

This part can be finished in 1999, because all elements are on site, only a flexible support for the magnets has to be constructed and manufactured.

B.2 Transmission

The calculated transmission for asymmetric, hot fusion reactions using actinide targets is a few percent only. The reason is the wider solid angle filled by the relatively slow reaction products due to recoil effects from the emitted neutrons ($n \geq 3$) and scattering in the target. Therefore, the potential of hot fusion for the production of heavy elements was not investigated yet systematically. In order to make this reaction type better accessible for SHIP, we plan to increase the solid angle after a careful study of ion optical calculations and reproduction of the results by transmission measurements.

The design work will profit from the experience gained at the VAMOS spectrometer at SPIRAL, GANIL. For VAMOS a large-acceptance quadrupole doublet was developed with an aperture of 200 mrad, whereas SHIP has presently 70 mrad opening angle.

The improvement of the transmission for hot-fusion reaction products takes also into account the requirements of SHIPtrap experiments for investigation of long lived isotopes of heavy elements. One region of long lived isotopes is situated at neutron number N=162 and accessible only by hot fusion. A larger aperture will also increase the transmission for the reaction products from cold fusion, our present method for the synthesis of new elements. A calculated value is 40 to 50 %, which could be increased to a value close to 100 %.

C Detectors, signal processing and data acquisition

The presently used position-sensitive silicon detector array was developed during the years 1988 – 1990 for the identification of new isotopes by establishing α-decay chains. The granularity of the detectors and the connected electronics allows for the measurement of decay sequences with lifetimes in a range from 3 μs to about 2 min. The upper time limit depends sensitively on the background rate. It could be prolongated by increasing the detector granularity, which is possible using new detectors with smaller pixel size or by defocusing the reaction products across a larger detector area. In both cases the signal processing has to be adapted to the higher number of channels. Automatic procedures for the setting of the electronics (amplification, baseline, threshold) and for the detector calibration are mandatory.

The extension of the SHIP detectors by γ arrays and SHIPtrap demands medium-term an appropriate interface between the devices in order to take full advantage of the combined facilities.

Because the target and SHIP upgrade has priority, the upgrade of the detector and electronic system will not start before the year 2001.

D Availability of the beam and concluding remarks

Experiments for the investigation of phenomena, which determine the limits of stability, will always need relatively long irradiation time. This will be the case also at higher beam currents and soon after realization of the proposed upgrades. In recent years the activity of work at SHIP was concentrated on the investigation of heavy elements. This strategy will be kept in the future. However, the investigation of heavy-ion fusion reactions by SHIP is promising also in the region of lighter nuclei. Examples are the proton radioactivity, isomeric states and other phenomena discussed in the VEGA and SHIPtrap proposal. Even concentrating on reactions with beams of stable projectiles only, the demand for beam time will increase in the future.

Presently, the extension of the GSI accelerator facilities is discussed, aiming at higher currents at relativistic beam energies and radioactive beams. Some of the proposals do not allow for a time sharing of the beam for high energy experiments and such at the Coulomb barrier. Trying to reach maximum beam intensities and high availability of the beam, showed up some problems in organizing an optimum beam schedule already using the present mode of parallel operation of ECR and PIG source. Several proposed experiments had to be postponed or were rejected.

The investigation of SHEs and the experimental program using the supplementary equipment like VEGA and SHIPtrap will need almost permanently a high current beam with energies at the Coulomb barrier ($E_p \leq 6$ MeV/u). Therefore, the planning of the future GSI accelerators should possibly take into account the construction of a specific accelerator for low energy experiments delivering high current DC beams. Such a solution may become necessary in the case that a high energy accelerator does not allow for a parallel operation with more than 80 % duty cycle and a permanent availability for low energy experiments, as it was possible by now.

The combination of an ECR ion-source and an accelerator capable of delivering DC beams would instantaneously result in an increase of the beam intensity at minimal consumption of source material. An intensity increase by a factor of 3.3 would arise from the prolongation of the duty factor from now 30 % to 100 %. Another factor of $\approx$2 can be expected, if the accelerator could be constructed for ions of lower charge state, for which the ECR source delivers higher currents. Further options for increasing the current at high charge states are sources operating at higher microwave frequency: the development of a 30-GHz ECR sources is in progress at Grenoble.