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Abstract. A long-term new experimental program has begun at GANIL, i.e. search for new super heavy nuclei and their structure. The first part consists in studying the structure of the $^{273}110$ isotope which involves the development of high intensity Se beam. In parallel, reactions involving Inverse Kinematics will be studied allowing to have a versatileness set-up. By adding germanium and electron detectors, spectroscopic studies could be made on trans-fermium elements. Preliminary results showed that the Wien Filter has a suppression of the incident beam with a 10^{10} factor, which is comparable with results elsewhere. We show recent results with the present set-up at GANIL in producing Fr isotopes in the Kr + Sb reaction. We present also the result of our Kr + Pb experiment, which tried to reproduce the Berkeley result of the element 118.

INTRODUCTION

During the last decades, the search for super heavy nuclei went on mainly at the Berkeley, GSI and Dubna laboratories. Searching for new elements is an attempt to answer questions of fundamental character: the investigation of nuclei at the limits of stability. GANIL and LPC (Caen), supported by CNRS and CEA, took in 1997 the opportunity to use the velocity filter LISE3 in order to investigate this field of research. For 3 years, technical developments and test experiments have demonstrated the capabilities of the GANIL set-up to pursue this quest of super-heavy elements. An attempt to produce the element 118 with the reaction ^{86}Kr + ^{208}Pb, in a repetition of the Berkeley experiment, has been performed in November-December 1999. In this experiment, as in those performed at GSI and RIKEN, no α decay channel corresponding to the Berkeley results has been observed. A new experimental program, using a beam of ^{82}Se is now suggested to pursue this research by producing "neutron rich" isotopes of the elements Z=109, 110, 111, 112, etc. Experiments on the study of the structure of the super-heavy elements and on the analysis of the possibilities offered by inverse kinematics with the set-up are also proposed and described in this article.

EXPERIMENTAL SET-UP

The super heavy elements are produced by complete fusion between an incident and a target ion. The beam is produced by the high intensity ECR Ion Sources of GANIL, it is then accelerated to low energy (4-5.5 MeV/u) in the CSS1 cyclotron and driven through the LISE spectrometer. The beam irradiates a target located in front of the Wien filter. After de-excitation at the target stage, the evaporation residues (ER) are separated from the incident beam using the LISE3 Wien Filter. After implantation in a double-stripped Si-detector, the ER's are identified by their α-decay chains.

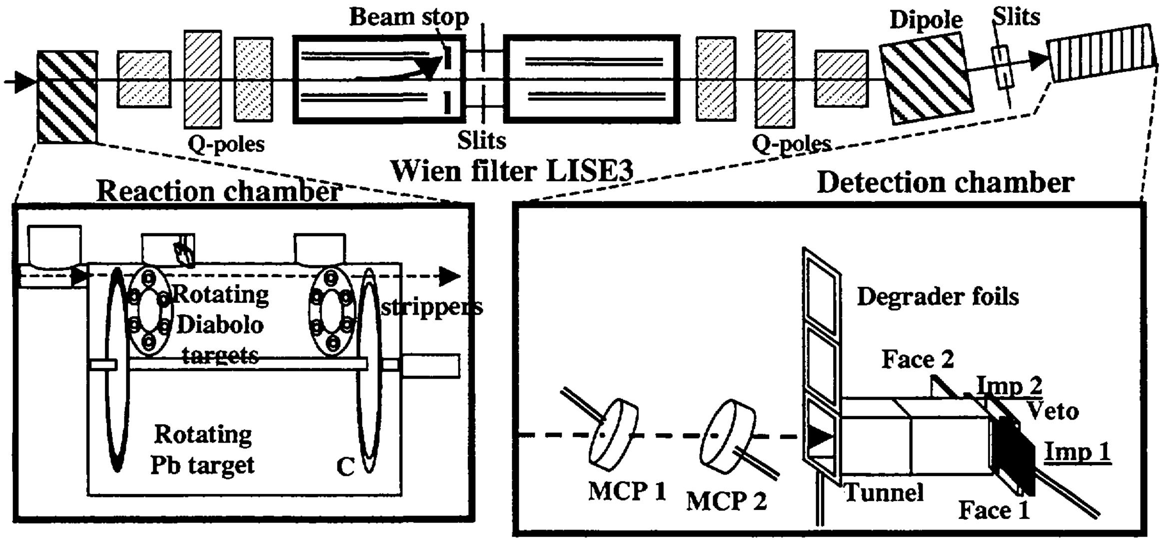


FIGURE 1. Experimental set-up.

Targets

For targets with a low melting point (Pb, Bi, ...), two wheels, with a diameter of 670mm, bearing 36 targets are mounted on a same axis to rotate in coincidence at 2000RPM. Targets (300 $\mu g/cm^2$) are mounted on the first wheel and carbon foils on the second one. The targets are "sandwiched" between two carbon foils of 40 and 10 μg/cm2. A Si detector continuously monitors the status of each target. The Carbon foils ($\approx$50 $\mu g/cm^2$) are needed to equilibrate the charge state of the reaction products.

For materials with higher melting point, a single rotating target will be used.

Wien Filter LISE III

The incident beam is deflected out after the first half of the velocity filter. During the first tests, the distance between the beam axis and the upper electrode of the first section of the Wien filter was 5 cm and an opening of 10cm long has been built at its exit, allowing a better suppression of scattered incident particules. This suppression will be improved by increasing the distance between the beam axis and the upper electrode to 7 cm. A dipole magnet at the exit of the filter improves also the suppression of unwanted products.

Detectors

The tagging of implanted particles as well as their velocities are obtained with two micro channel plate detectors [1]. Their kinetic energy and localization are given by a X-Y silicon implantation detector. The energy of alphas and of the fission fragments escaping from the implantation detector is measured with a "tunnel" of 8 silicon detectors. A silicon veto detector is installed behind the implantation detector. In order to measure long half-life products without background, the implantation detector is moved out and replaced by a second one when a possible interesting event is registered.

Specific electronics with a double trigger data acquisition system have been developed. The dead time between two successive events is 10 μs.

Test experiments

Test experiments have begun in 1996, to get a response of the complete set-up in the fusion reaction conditions. A ^{58}Ni beam irradiated a natural tin target, with an intensity of few μAe. A rejection rate of the incident beam of 10^{10} was obtained.

SEARCH FOR ELEMENT 118

After tests in 1997 and 1998, the full experimental set up was used with the system ^{86}Kr + ^{121,123}Sb producing Fr isotopes. The excitation functions of these systems were measured at GSI [2]. With a beam intensity of 10 pnA, at 4.3 MeV/u, a rejection rate of the incident ^{86}Kr beam of 2x 10^9 was obtained. The α decay lines of Fr isotopes and their daughters were observed by the silicon detector (Figure 2).

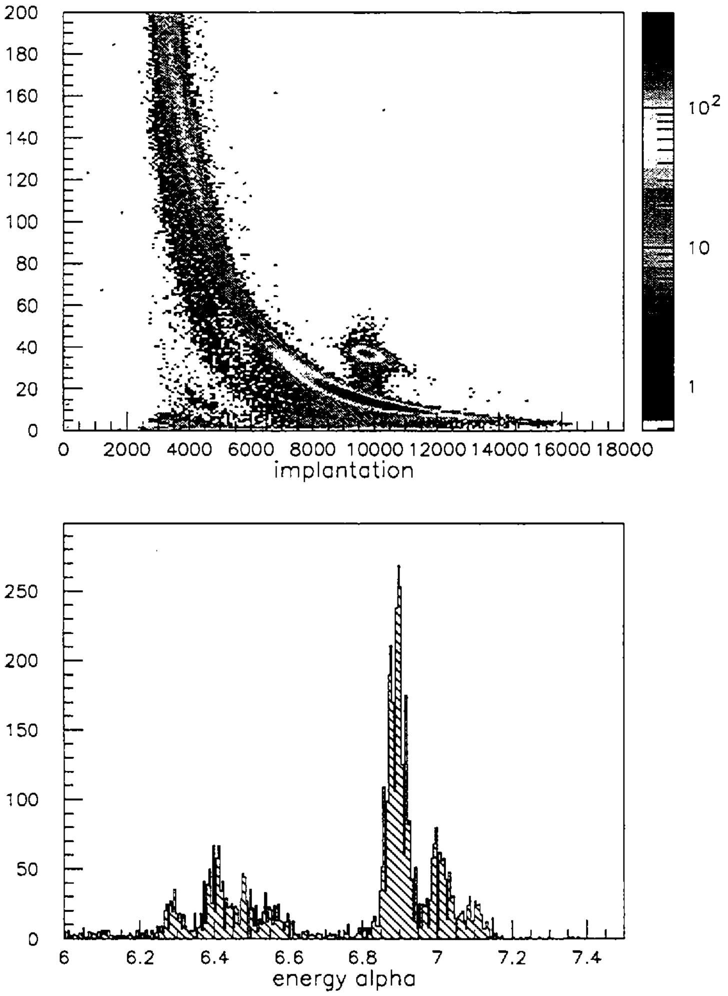
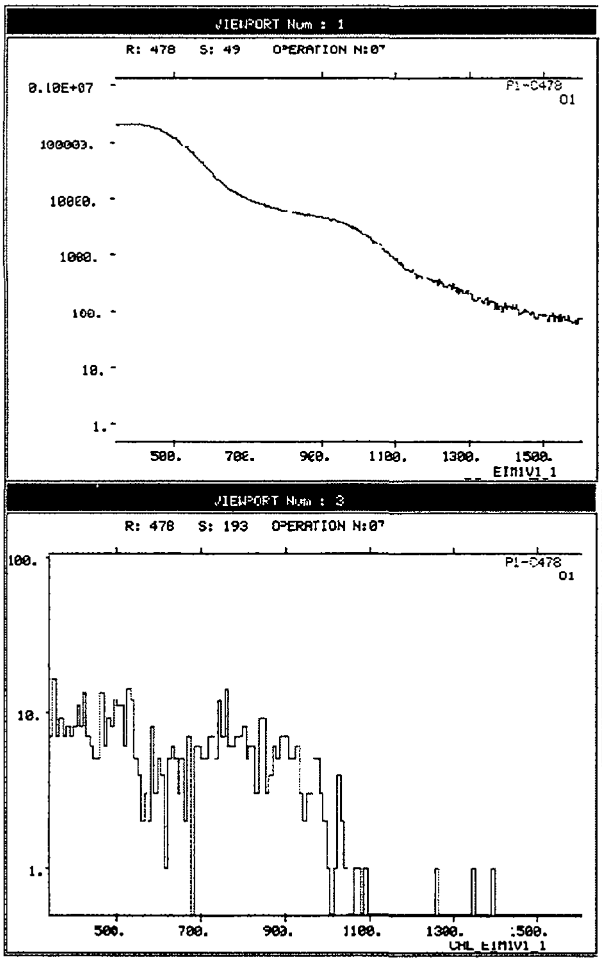


FIGURE 2. upper part: Energy versus Time-Of-flight spectrum for the system ^{86}Kr (4.3 MeV/u) + ^{121,123}Sb; lower part: α spectrum in anti-coincidence with the Time-Of-Flight.

The beam was then tuned to 5.27 MeV/u in order to make measurements on the ^{86}Kr + ^{208}Pb system for which long alpha chains attributed to element 118 were observed at Berkeley [3]. The upper part of figure 3 represents the raw energy spectrum obtained with the implantation silicon detector. Events in anti-coincidence with the Time-Of–Flight detector are plotted on the spectrum of the lower part. Figure 4 represents events detected in the two micro channel plate detectors and in the implantation Si detector. With a total dose of 1.1×10^{18} ions on a 300µg/cm^2 lead targets, no α chain within the expected energies was observed at GANIL, in agreement with the results of SHIP [4].



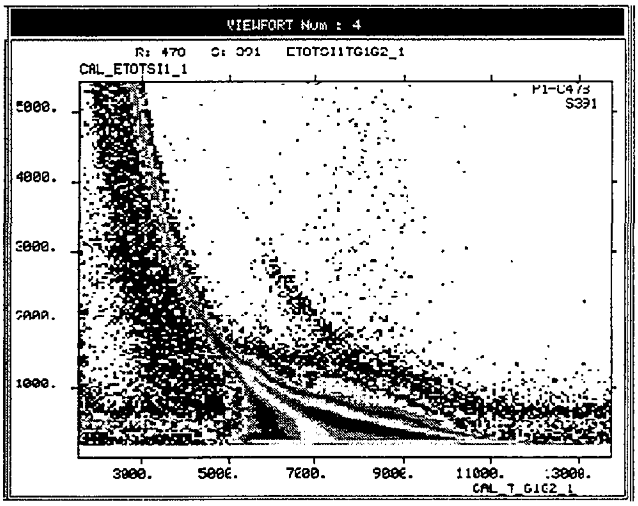


FIGURE 3 (LEFT). α spectra with and without Tof anti-coincidence for the system ^{86}Kr + ^{208}Pb at 5.27 MeV/u.

FIGURE 4 (RIGHT). Time of flight-Energy spectrum for the system ^{86}Kr + ^{208}Pb at 5.27 MeV/u

FUTURE

Study of super-heavy elements using a ^{82}Se beam.

Since 1987, the super-heavy element (107 to 112) were first synthesised by cold fusion reactions at GSI, Darmstadt, with the Wien filter SHIP: complete fusion of ^{208}Pb or ^{209}Bi targets with neutron rich natural projectiles up to ^{70}Zn at excitation energies lower than 20 MeV. Up to element 110, the identification was unambiguous via known α radioactive decay chains of the daughter nuclei. For the elements Z=111 [5] and 112 [6], the identification is not so clear because of unknown daughter nuclei:

The element 111 [5] produced in the reaction ^{64}Ni(^{209}Bi, 1n)^{272}111, decays by α emission on the unknown ^{268}109 and ^{264}107 isotopes and the chain finally ends on the known ^{260}105 and ^{256}Lr isotopes.

The element 112 [6] was produced in the reaction ^{70}Zn(^{208}Pb, 1n) ^{277}112. Two α decay chains were then observed, ending on the known ^{265}106, ^{261}104 and ^{257}No. Unfortunately, data on the daughter nuclei ^{273}110 and ^{269}108 are very scarce. Energy of 11.35 MeV was previously reported for the α decay of $^{273}110$ by the Dubna-Livermore group [7]. However, in the two decay chains of element 112, the second α corresponding to the decay of the same $^{273}110$ isotope was observed with energies of 9.73 and 11.08 MeV and with decay-times of 170 ms and 110 µs, respectively. These significant differences in energy and lifetime could only be imputed to different levels in the $^{273}110$ isotope. A new experiment made at GSI recently [8] with the same reaction ^{70}Zn(^{208}Pb, 1n)$^{277}112$ lead to the observation of only one α -chain. The α -energies are 11.17, 11.20 and 9.18 MeV for the decay of the isotopes $^{277}112$, $^{273}110$ and $^{269}108$, respectively, and therefore, there is no definite conclusion concerning the α -decay energy of the $^{273}110$ isotope.

In order to check precisely this point, it seems obvious that a direct production of the $^{273}110$ isotope is necessary. Moreover, this isotope of the element 110 was never produced directly by the cold fusion method; the most "neutron-rich" element thus produced being the isotope $^{271}110$.

We propose to synthesize directly this isotope ($^{273}110$) in order to determine its decay properties and to, indirectly, confirm the existence of element 112, by the reaction ^{82}Se(^{192}Os, 1n)$^{273}110$. This system has a low fusion barrier, which enables the reaction to occur at low excitation energy for the compound nucleus (see Table 1). Compared to typical cold fusion reactions with lead or bismuth targets (^{64}Ni(^{208}Pb, 1n)$^{271}110$) (σ_{max}=15pb), the cross-section may be, on one hand lowered due to the decreased asymmetry of the system and the absence of closed shell in the reaction partners, but on the other hand, it should increase due to the more "neutron rich" compound nucleus. From systematic and extrapolations, a cross section in the range of picobarns can be expected for the production of element $^{273}110$.

Before attempting to produce element Z=110, the entire set-up will be tested and calibrated using a reaction with a higher cross-section. For this purpose, the detection system will be checked with auxiliary targets from ^{138}Ba to ^{154}Sm (See Table 1) producing by emission of few neutrons, isotopes of Th to Cm which decay by α emission. The cross-sections are expected to be at the microbarn level. The system ^{82}Se +^{138}Ba is of particular interest because it gives a compound nucleus (^{220}Th*) already produced via other entrance channels [9]. The measured cross sections could then be used to study the influence of the entrance channel on sub-barrier fusion.

TABLE 1. Compound nuclei produced with a selenium beam, E^*_{Bass} is the excitation energy at the Bass barrier [24].

Target	Compound nucleus	E^*_{Bass} (MeV)
^{197}Au	$^{279}113$	7.2
^{198}Pt	$^{280}112$	11.6
^{193}Ir	$^{275}111$	12.7
^{192}Os	$^{274}110$	14.6
^{187}Re	^{269}Mt (Z=109)	15.6
^{186}W	^{268}Hs (Z=108)	17.2
^{180}Hf	^{262}Sg (Z=106)	17.7
^{176}Yb	^{258}Rf (Z=104)	20.1

Table 1 shows other targets` which lead to isotopes of elements 104, 106 and 108:

a) Using ^{176}Yb and ^{180}Hf targets, the selenium beam enables to form the same compound nuclei (^{258}Rf* and ^{262}Sg*) as the reactions ^{50}Ti+^{208}Pb (σ_{max} (E*=15MeV)=10nb) [10] and ^{54}Cr+^{208}Pb (σ_{max} (E*=16MeV)=400pb) [11]. The results of the measured cross-sections of the one neutron evaporation channel will be useful to compare the entrance channels using lead targets or selenium beam leading to the same compound nuclei.

b) A comparative study can be made using a ^{186}W target giving the compound nucleus ^{268}Hs* (Z=108). The isotope ^{265}Hs was produced from the reaction ^{58}Fe +^{208}Pb [11], with a maximum cross section of 50 pb at 13 MeV of excitation energy. The measured cross-section will indicate the effects, on one hand of the absence of the closed shell in the entrance channel and the decreased asymmetry, and on the other, of the increased mass (N=N+2) of the compound nucleus.

Furthermore, the same selenium beam could be used in the future to search for new isotopes of the elements 111 (^{82}Se(^{193}Ir, 1n)^{274}111), 112 (^{82}Se(^{198}Pt, 1n)^{279}112). The advantage of a ^{82}Se beam is to produce isotopes richer by 2 neutrons than those produced with ^{208}Pb or ^{209}Bi targets for elements Z=108-112.

Inverse Kinematics

Experiments are also proposed to compare direct and inverse kinematics Fusion. In the fusion-evaporation reactions, the difficulty is to detect with a high efficiency the few ER's emitted close to 0 degree in a X-Y implantation detector and to reject the beam particles. At GANIL, the tool used for this rejection is Lise3. However there are some multi-scattered projectiles and other reaction products which have velocities and magnetic rigidities close to the ER's values. The importance of this "background" cannot be calculated and must be measured experimentally and reduced by adjustments of several parameter settings.

The proposal consists in using the method of complete fusion reactions, cold or hot, in inverse kinematics: beams of ^{208}Pb or other heavy nucleus. Compared to usual kinematics, this method has one drawback but several assets.

Drawback :

Due to the smaller velocity difference between the beam and the evaporation residues, larger magnetic and electric fields are needed in the Wien filter Lise3 to deflect the beam: the Wien filter is powerful enough for this.

Assets :

- The ER's are strongly focussed at forward angles and have a much larger velocity, which ensures a good transmission even after α-emission in the target or α-decay in flight
- In usual kinematics, the target thickness is limited by multiple scattering. A thickness of 300-400 μg/cm^2 corresponds to an excitation energy range ΔE* = 2-3 MeV. In inverse kinematics, the velocity of the ER's is larger, the target mass is smaller, therefore the thickness of several mg/cm^2 could be used allowing one to cover a larger excitation range.

- The ionic charge state distributions of super-heavy nuclei are better estimated at higher energies [12, 13, 14, 15].
- The energy of an ER is large allowing to better control the depth inside the Si detector.

The purpose of this experiment is to find out how useful and convenient is the inverse kinematics method and then to apply it to the production of super-heavy nuclei.

Structure of super heavy elements

A new experimental research program at GANIL on the study of trans-fermium isotopes is proposed. The main goal is to achieve spectroscopic information of these nuclei in order to have a better understanding of their shell structure. It is proposed to initiate this program with the α-, e^--, and γ-spectroscopy of ^{251}Md and ^{251}Fm populated by the α-decay of ^{255}Lr.

The [521] 1/2- and [514] 7/2- orbitals are expected to be close to the Fermi surface in the Md isotopes. Experimentally a spin of 7/2- was assigned to the ground state of ^{255,257,259}Md [16, 17] and the 1/2- is expected as the first excited state but the prediction is reversed as compared to the other Md isotopes : 1/2- as ground state and 7/2- as first excited state at 300 keV [18] which should decay via an M3 transition. However, experiment performed on ^{251}Md indicate the presence of an excited state at 160 keV with a branching ratio of ~50% [19].

^{251}Fm was studied in 1971 by α-decay of ^{255}No [20, 21]. Two rotational bands were found and two gamma transitions were deduced. The ground state spin and parity was tentatively assigned to 9/2- by favored alpha transition to the 9/2- state in ^{247}Cf.

The ground state of the N=151 isotones is based on the [734] 9/2- Nilsson orbital. The 9/2- ground state character was firmly established in ^{249}Cf. The [622] 5/2+, [624] 7/2+ and [620] 1/2+ bandheads have also been firmly established in ^{249}Cf and tentatively in ^{251}Fm. The Z=100 is a gap in the proton single particle energy level and N=151 is one neutron below the stabilizing shell effect at N=152 so that ^{251}Fm is well suited to study neutron single-particle states.

The goal of the experiment is to measure precisely via e^-- and γ-spectroscopy the single particle structure of ^{251}Md and ^{251}Fm. The compound system ^{255}Lr produced in the 2n channel of the ^{48}Ca + ^{209}Bi fusion evaporation reaction [22] is expected to decay by 85% to the 4 min half-life ^{251}Md. This nucleus should decay with less than 10% by α-decay to ^{247}Es and with more than 90% by EC to ^{251}Fm. Since the ground state parity and spin of the first level of ^{251}Fm are known, we should be able to determine the ground state of ^{251}Md and possibly the one of ^{255}Lr.

The experimental set-up should be the same as the one described above, additional detectors will be added. A tunnel of Si detectors will detect conversion-electrons and α particles escaping the Si strip detector. In this way also α-conversion-electrons angular correlations which are sensitive to the spin of the level involved can be measured. A set of Ge clover detectors from the EXOGAM collaboration positioned in a close geometry (at 15cm around the silicon strip detector and at 5cm at 0°) will detect γ- and X-rays (in particular those associated with the electron capture of ^{251}Md).

SUMMARY

A long-term new experimental program has begun at GANIL, i.e. search for new super heavy nuclei and their structure. The first part consists in studying the structure of the ^{273}110 isotope which involves the development of high intensity Se beam. In parallel, reactions involving Inverse Kinematics will be studied allowing to have a versatileness set-up. By adding germanium and electron detectors, spectroscopic studies could be made on trans-fermium elements. Preliminary results showed that the Wien Filter has a suppression of the incident beam with a 10^{10} factor, which is comparable with results elsewhere. The perspective of having very high intensity beam on the target [23] and the versatility of the Wien filter of LISE (unique in the world) allows us to contribute in this field in a worldwide frame.

Particularly to the development involving the Se beam, this program opens to GANIL the opportunity to confirm the new element 112 in a first step, and to go on with the synthesis of new elements by a channel which is different from the one used up to now at GSI, Berkeley or Dubna, i.e. with Lead, Bismuth or Actinide targets.

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