

Prospects of heavy and superheavy element production via inelastic nucleus-nucleus collisions – from $^{238}\text{U} + ^{238}\text{U}$ to $^{18}\text{O} + ^{254}\text{Es}$

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Abstract. Multi-nucleon transfer reactions, frequently termed deep-inelastic, between heavy-ion projectiles and actinide targets provide prospects to synthesize unknown isotopes of heavy actinides and superheavy elements with neutron numbers beyond present limits. The ^{238}U on ^{238}U reaction, which revealed essential aspects of those nuclear reactions leading to surviving heavy nuclides, mainly produced in $3n$ and $4n$ evaporation channels, is discussed in detail. Positions and widths of isotope distributions are compared. It is shown, as a general rule, that cross sections peak at irradiation energies about 10% above the Coulomb barrier. Heavy target nuclei are essential for maximizing cross sections. Experimental results from the ^{238}U on ^{248}Cm reaction, including empirical extrapolations, are compared with theoretical model calculations predicting relatively high cross sections for neutron-rich nuclei. Experiments to test the validity of such predictions are proposed. Comparisons between rather symmetric heavy-ion reactions like ^{238}U on ^{248}Cm (or heavier targets up to ^{254}Es) with very asymmetric ones like ^{18}O on ^{254}Es reveal that the ones with ^{238}U as a projectile have the highest potential in the superheavy element region while the latter ones can be advantageous for the synthesis of heavy actinide isotopes. Concepts for highly efficient recoil separators designed for transfer products are presented.

1. Introduction

The quest for superheavy elements (SHE), chemical elements with atomic number, Z , larger than 103 [1], is driven by the desire to determine and understand one of the extreme limits of existence of matter. After an early phase of discussing the possible existence of SHE [2], the year 1966 marked a breakthrough with a seminal meeting in Lysekil, Sweden, [3] and additional theoretical work [4, 5] both shifting the focus from element 126 to 114. A maximum of stability was, and still is, expected at the neutron number $N = 184$ [6].

Early on, possible ways to reach this magical “island of stability” were discussed and were fostering developments and installations of heavy-ion accelerators. Fully exhausted are the two fusion paths; the Pb and Bi target based “cold fusion” that at element 113 has reached the sensitivity limit of today’s experiments [7] and, with element 118, the actinide target based reactions with ^{48}Ca as the projectile [8]. While the latter one gives access to the presently known most (relative) neutron-rich nuclei, like $^{289}114$ [8, 9], alternative paths are essential to reach and explore the exciting unknown territory towards $N = 184$. As the next generation radioactive ion beam facilities, which will become operational worldwide within

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the next decade, will not provide sufficient beam intensity for SHE research with potentially interesting more neutron-rich projectiles like ^{46}Ar or $^{50,52}\text{Ca}$, this leaves scientists with a path that is often termed multi-nucleon transfer. These reactions were already proposed between the mid-60s and mid-70s [10, 11]. However, it was only after ^{238}U beams with sufficiently high energy and intensity became available at the Gesellschaft für Schwerionenforschung (GSI), Darmstadt, that the entire range of multi-nucleon transfer or deep-inelastic reactions up to ^{238}U on ^{238}U and ^{248}Cm were explored [12, 13]. These reactions, their results on the synthesis of heavy actinide isotopes, the understanding of the processes leading to these products and the potential for the synthesis of new, neutron-rich isotopes will be discussed in this article. To a large extent it includes information available in [12–14] and, more recently, summarized and expanded in [15].

2. Experimental techniques

All studies on the production of heavy actinides discussed in this article were performed applying radiochemical methods. Because of the very high yield and efficiency, which includes a close to 100% collection efficiency of all products and a high-yield chemical separation of individual elements together with the nearly background-free off-line measurement of samples, this technique is best adapted to cross-section measurements of individual isotopes of heavy actinides. Discontinuous, off-line techniques, as applied in the ^{238}U on ^{238}U reaction [14, 16] and, thereafter, the ^{238}U on ^{248}Cm one [13] are most sensitive for isotopes with half-lives between about one hour and a few months that undergo α decay or spontaneous fission (SF) as their characteristic nuclear decay mode. This is the case for most isotopes in the investigated region from the target to the Fm and Md region allowing for the determination of complete isotope distributions.

Beam times from a few hours up to two days with cumulated numbers of 0.5 to $1.2 \cdot 10^{16}$ ^{238}U particles enabled cross-section measurements for individual isotopes in the millibarn to nanobarn range. In these experiments, thick ^{238}U -targets (300 and 500 mg/cm² depleted U metal explosion-cladded onto 1.5-mm thick Cu sheet-metal) simultaneously served as an infinitely thick target and catcher material regarding the nuclear reaction and the collection of reaction products, respectively. Irradiations were performed with different incident beam energies and calculated effective target thicknesses were used for cross-section calculations. This also allowed to determine the energy dependence of the actinide production. Chemical separations, followed by sample preparation and measurement of the characteristic radioactive decay, started immediately after end of irradiation; for further details see [15].

Up to 7.3-mg/cm² thick metallic ^{248}Cm targets [17] on Mo foils were on particular thick but thin enough to let reaction products recoil out of the target. They were collected in a Cu catcher that was dissolved and chemically processed after end of irradiation to determine cross sections for actinide isotopes up to element 101 [13].

3. Results and discussion

3.1 The ^{238}U on ^{238}U reaction

In the reaction of ≤ 7.5 MeV/u ^{238}U ions on ^{238}U , cross sections for a very large number of isotopes for chemical elements from $Z = 23$ to 100 were measured. This provided the basis not only to establish a complete cross-section surface but also to decompose it into individual reaction channels. An essential information obtained in view of the synthesis of SHE was that primary fragments of element 70 are produced with a cross section of 0.1 mb.

This means that in the symmetric and binary ${}_{92}\text{U} + {}_{92}\text{U}$ reaction also element 114 primary fragments are synthesized with the same high cross section of 0.1 mb [12, 15]. As the search for SHE, however, remained unsuccessful [18], it became especially interesting to investigate and better understand the synthesis of highly fissile actinide products formed in multi-nucleon transfer reactions. This provided the basis to clarify perspectives for the synthesis of SHE.

At ≤ 7.5 MeV/u ${}^{238}\text{U}$ on ${}^{238}\text{U}$ all isotope distributions for elements beyond the target are Gaussian in shape with a common width (FWHM) of 3.3 mass units, u. They peak at about the following mass number, A , (in brackets) and cross section: Pu (239) 1 mb, Am (241.5) 300 μb , Cm (244) 50 μb , Bk (247.5) 3 μb , Cf (249.3) 250 nb, Es (252) 10 nb and Fm (254) 1 nb. Consecutive experiments at higher and lower beam energy showed that the Gaussian shape with a width of 3.2(5) u is a common feature for all actinide isotope distributions in ${}^{238}\text{U}$ on ${}^{238}\text{U}$ reactions [15].

Experiments performed with incident ${}^{238}\text{U}$ energies of 6.49, 6.84, 7.50 and 8.65 MeV/u, corresponding to an energy, E , of 1.07, 1.13, 1.24 and 1.43 MeV/u above the Coulomb barrier, B , respectively, show an increase in cross section up to 1.13 E/B followed by a slow decrease at higher energies. As an example, peak cross sections for the Cf isotope distributions, all centred at $A = 249.3$, first increased from about 140 to 250 nb and fell off to 200 and 110 nb for the two increasingly higher energies. It is remarkable that shapes and centroids of all actinide isotope distributions remained unchanged and are energy independent.

A comparison of the energy dependence for the synthesis of ${}_{98}\text{Cf}$ as the heavy partner and ${}_{86}\text{Rn}$ as the light one in the symmetric ${}^{238}\text{U}$ on ${}^{238}\text{U}$ reaction has been carried out. After a small correction for minor fission losses, the cross-section increase for ${}_{86}\text{Rn}$ represents the general trend of increasing primary yield with increasing energy for a $\Delta Z = 6$ charge (and associated mass) transfer. The rise and fall of the complementary ${}_{98}\text{Cf}$ cross section reveals the projectile energy dependence in the low-energy part of the broad excitation energy distribution [15]; see below for more details. The Cf/Rn cross-section ratio gives the survival probability of Cf. It has an exponentially decreasing slope with increasing beam energy at a rate of about one order of magnitude per 0.5 MeV/u. This slope, which depends on the number of neutrons evaporated in the deexcitation of the primary fragments, and by applying empirical systematics for the survival probability, $\Gamma_n/(\Gamma_n + \Gamma_f)$, [19] one obtains an average number between three and four neutrons evaporated for Cf isotopes that survive the fission competition in the deexcitation process of the primary formed, hot fragments. Independently, a comparison of the centroid of the experimentally observed Cf isotope distribution, $\bar{A}_{\text{Cf}} = 249.3$, with the most probable primary fragment mass, $\bar{A}'_{\text{Cf}} = 251.9$, derived from a generalized systematics of ground-state Q -values, Q_{gg} , [20] again yields an average of 3.5 neutrons evaporated [15].

To obtain deeper and more quantitative insights into the reaction mechanism leading to surviving heavy actinides and to SHE, calculations were performed to reproduce measured isotope distributions of ${}_{98}\text{Cf}$, ${}_{99}\text{Es}$ and ${}_{100}\text{Fm}$ in the reaction of ≤ 7.5 MeV/u ${}^{238}\text{U}$ on ${}^{238}\text{U}$; for details see [12, 15]. These calculations started with measured isotope distributions of the complementary light elements ${}_{86}\text{Rn}$, ${}_{85}\text{At}$ and ${}_{84}\text{Po}$, assuming that these distributions were not strongly altered by prompt fission. Furthermore, it was assumed that (i) for a given element, the most probable primary fragment mass, \bar{A}'_Z , can be deduced from a generalized Q_{gg} -systematics including corrections for pair breaking of the transferred neutrons [20] and (ii) the variance of an isotope distribution, $\sigma^2(A)$, can be described as a superposition of the mass dispersion of the primary fragments, $\sigma^2(A')$, the excitation energy dispersion, $\sigma^2(E^*)$, and the dispersion in the number of evaporated neutrons, $\sigma^2(\nu)$.

For the ${}_{84}\text{Po}$ - ${}_{100}\text{Fm}$ pair, discussed here as the prime example, evaporation code calculations show that the latter one is a minor contribution with $\sigma^2(\nu) \leq 0.5 \text{ u}^2$. The largest

part, $\approx 4.5 u^2$, comes from the wide excitation energy dispersion, which has an estimated FWHM of about 100 MeV. For the primary fragment distribution a dispersion of $\sigma^2(A') \approx 2.1 u^2$ was estimated [12, 15].

A comparison of \bar{A}'_Z with the measured mean product mass number, \bar{A}_Z , gives the average number of neutrons evaporated from the primary light fragment and from this, the mean excitation energy in the lighter element fragments. With the conventional assumption that the mean total excitation energy of the combined light and heavy fragment is shared between the two fragments according to their initial masses, the mean excitation energy in the heavy fragments was calculated.

Using these ingredients as input for calculating isotope distributions, and by comparing these with the measured distributions, the following was found [12, 15]:

- (i) The most abundant isotopes of the complementary *light elements* are predominantly formed in collisions where energies close to the mean value are present in the system, e.g. ≈ 168 MeV for the combined di-nuclear system associated with a $\Delta Z = 8$ charge split leading to an excitation energy of ≈ 77 MeV and, consecutively, an average number of 8.6 neutron evaporated for Po isotopes.
- (ii) The *surviving heavy actinides* originate exclusively from the low-energy tail (!) of the excitation energy distribution. Heavy element fragments with excitation energies above ≈ 45 MeV have such a low probability to survive the fission competition that they do not significantly contribute to the product distribution.
- (iii) To reproduce the shape and centroid, e.g. of the measured Fm isotope distribution, a cut-off of 35 MeV needed to be introduced on the low-energy side of the excitation energy distribution. This reflects the very steep fall-off and extremely low probability for the formation of fragments with a given number of transferred number of protons and neutrons. A steep fall-off was also obtained in a diffusion model calculation [21].
- (iv) As a result of (ii) and (iii), heavy actinide isotopes are produced in a narrow excitation energy bin; e.g. for Fm from approximately 35 to 45 MeV, which corresponds to a deexcitation with typically three and four-neutron evaporated.
- (v) While shape and centroids of the measured Cf, Es and Fm distributions are excellently described by the calculation, it overpredicts their absolute cross section by about one order of magnitude. As discussed in [15], this discrepancy may have its origin in shell effects, higher fission probabilities originating from high angular momenta, nonstatistical processes leading to nonequilibrium states or large fragment deformations in the exit channel.

3.2 The ^{238}U on ^{248}Cm reaction

Inelastic collisions between ^{238}U and ^{248}Cm were believed to provide a closer and more widespread approach to synthesize SHE in multi-nucleon transfer reactions. Aqueous and gas-phase radiochemical experiments, with a sensitivity down to ≈ 50 pb for isotopes with half-lives in the range from about an hour to several years, only resulted in cross-section upper-limits [22]. However, simultaneously performed studies on the production of heavy actinides up to Md revealed a strong enhancement in their synthesis [13]. In the reaction of ≤ 7.4 MeV/u ^{238}U ions on ^{248}Cm cross sections for Fm isotopes increase by about three orders of magnitude as compared with ^{238}U targets [13, 15]. This distinctly underlines the importance of the highest possible target- Z for the synthesis of heavy actinides and SHE.

Maximum cross sections for Cf, Es, Fm and Md were about 2 mb, 20 μb , 1 μb and 100 nb, respectively. For ^{259}No , an upper cross-section limit of 30 nb was determined.

Despite orders of magnitude different cross sections, it is remarkable that the Cf, Es and Fm isotope distributions originating from ^{248}Cm do not only have the same shape and width as the ones from ^{238}U but their centroids are also located at the same mass number; e.g. $\bar{A}_Z = 254$ for Fm. As the measured cross sections for the lighter fragments $_{84}\text{Po}$ and $_{85}\text{At}$ were nearly the same in reactions of ^{238}U with ^{238}U and ^{248}Cm , it was assumed that also the primary actinide fragment yield before fission are about the same for a given $(\Delta Z, \Delta N)$ transfer channel in both reactions. If this is the case, then cross-section differences for the same $(\Delta Z, \Delta N)$ products should simply reflect the different survival probability of the different product nuclei. With an assumption of unchanged excitation energies and angular momenta, a calculation was performed, which took into account the different survival probabilities. For a given number of neutrons evaporated, cross sections were calculated for Es, Fm and Md. Very good agreement between calculated and experimentally determined isotope distributions were obtained for an average of three to four neutrons evaporated. As in the reactions with ^{238}U , this again implies a very similar reaction mechanism and average fragment excitation energies between about 35 and 45 MeV for surviving products. In addition, differences between experimentally determined most probable masses, \bar{A}_Z , and calculated ones for primary fragments, \bar{A}'_Z , also indicate the synthesis predominantly in $3n$ and $4n$ evaporation channels; for details see [13, 15]. While heavy element products from ^{238}U based reactions are produced in $3n$ or $4n$ evaporations channels [12, 13, 15], results from experiments with ^{136}Xe indicate a production in $2n$ to $3n$ channels and for ^{48}Ca and lighter projectiles it is closer to the $2n$ and $1n$ channel [23, 24]. The higher survival probability of products formed in the latter reactions is in reactions with ^{238}U overcompensated by a much larger charge and mass transfer, giving rise to much large production of primary fragments. This makes the ^{238}U reaction the most favourable one for synthesis of neutron-rich isotopes further away from the target, i.e. for superheavy elements.

While excitation functions for the synthesis of heavy actinides are not available for the ^{238}U on ^{248}Cm reaction, it can safely be assumed that it will also have its maximum at about 10% above the Coulomb barrier. This expectation does not solely rely on the ^{238}U on ^{238}U data and the above mentioned successful reproduction of isotope distributions from the ^{238}U on ^{248}Cm reaction but is most strongly supported from results obtained with ^{136}Xe , ^{86}Kr , ^{48}Ca and ^{18}O projectiles on ^{248}Cm and ^{249}Cf targets [23–27] all clearly showing a cross-section maximum at $E/B \approx 1.1$.

Measured heavy actinide cross sections in the ^{238}U on ^{248}Cm reaction provide pivotal data challenging results and predictions of recent two-center shell-model calculations; see [28] and references therein. On the one hand, they exhibit excellent agreement with experimentally determined cross sections [13]. On the other hand, these theory results [28] show a most highly desired but unexpected extension of all isotope distributions towards the neutron rich side, which was never seen before. These isotope distributions have an enormous width of about 10 u (FWHM) and they are – in contrast to all experimental findings so far – not Gaussian in shape anymore. If these theoretical results reflect what can be achieved experimentally, this would dramatically open up intriguing perspectives to synthesize and investigate more than 20 new, neutron-rich isotopes from $_{100}\text{Fm}$ to $_{108}\text{Hs}$ with cross sections ranging from hundreds of microbarn to the picobarn level. Among these are fascinating isotopes like the ones between $^{262}, ^{264}\text{Fm}$ and $^{266}, ^{268}\text{Rf}$ with cross section of more than 1 nb, or ^{272}Rf and ^{274}Sg accessible with more than 1 pb. However, as the authors of [28] point out, these cross section essentially depend on the strength of shell effects. Fortunately, the validity of these calculations on the neutron-rich side can be tested in the Fm, Md and No

region, where cross section between 1 μb and 1 nb are predicted. As previous experiment did not anticipate such high cross section, they did not look for the decays of these isotopes with unknown α energies or spontaneous fission half-lives. New and dedicated experiments are required to answer this pressing question.

4. Summary and perspectives

Multi-nucleon transfer reactions with ^{238}U as a projectile and targets with the highest Z and N/Z -ratio as possible, are the prime, and sole, candidates for the synthesis of new neutron-rich transactinides or superheavy elements. Presently, no other nuclear reaction, including radioactive ion beams, provides a competing alternative. Based on current theoretical predictions [28], ^{248}Cm as a target can provide access to most interesting new isotopes in the heavy actinide and light transactinide region, like the $N = 162$ nuclei ^{262}Fm , ^{264}No and ^{266}Rf . Moreover, it is essential for putting these theoretical predictions on the synthesis of new isotopes for heavy and superheavy elements on the test bench. Only after having verified the predicted high cross sections for neutron-rich isotopes, which show that shell effects are strongly enhancing the synthesis of these isotopes, trustable predictions for the synthesis of SHE isotopes approaching $Z = 114$ and $N = 184$ can be made. However, the use of such an elusive target material like ^{251}Cf , or much better ^{254}Es , would increase the scope of studies into the SHE region by orders of magnitude over the use of ^{248}Cm . So far, the enormous potential of ^{254}Es as a target material in multi-nucleon transfer reactions has only been demonstrated in reactions with light projectiles like ^{18}O , ^{22}Ne [29] and ^{48}Ca [30]. Subsequently, results of ^{18}O and ^{22}Ne reactions with ^{254}Es led to the discovery of ^{260}Md and enabled extended studies of “bimodal fission” [31, 32].

The tools to embark on the endeavour to discover and investigate new neutron-rich isotopes of the heavies actinides and SHE are readily at hand or in an advanced conceptual state. The former ones are discontinuous off-line and continuous on-line radiochemical techniques, which are optimized and highly sensitive to study isotopes with half-lives in the range from hours to years and from seconds to hours, respectively. Over the last decades, these techniques were developed and applied to chemically investigate heavy actinides and transactinides; for aspects of automated separations in the aqueous phase see, e.g. [16, 33] and [34] for a comprehensive review focusing on techniques applied in SHE studies.

In the $_{100}\text{Fm}$ to $_{103}\text{Lr}$ region, half-lives from seconds to hours, even up to days, are expected for all new isotopes up to $N \leq 165$ and in some specific cases, like $^{274,275}\text{Db}$, $^{269,273}\text{Db}$ and $^{279,280}\text{Hs}$, also for transactinides [35]. Generally, beginning with $_{104}\text{Rf}$, half-lives of less than one second are estimated for all SHE. This clearly calls for in-flight separation of SHE in dedicated recoil separators specially designed for multi-nucleon transfer reactions. While today’s recoil separators are often excellently suited to separate fusion-evaporation products emitted in a very narrow angular cone around 0° , their limited aperture and only partial coverage of the angular spread limits their use for transfer products.

Despite such severe limitations, multi-nucleon transfer studies were performed, e.g. at the SHIP in collisions of $^{58,64}\text{Ni}$ on ^{207}Pb at E/B values from about 0.9 to 1.2 [36]. With an angular range acceptance of $(0 \pm 2)^\circ$, products with atomic number 84 to 89 were measured. They are relatively stable against fission and are not representative for highly fissile SHE. As this experiment inherently could not measure products emitted at scattering angles larger than two degree, it was not sensitive to products from typical quasi-elastic or grazing collisions for all experiments performed above the Coulomb barrier. Any data analysis that requires efficiencies, e.g. cross-section evaluations, are therefore strongly model depended. This is also true for any conclusion drawn on the synthesis of the heaviest elements in transfer

reactions from such an evaluation. However, experiments performed at or slightly below the Coulomb barrier, where the grazing angle for heavy transfer products is 0° , can be very useful and can provide important information.

None of the presently operated recoil separators, not even advanced versions like VAMOS, a recently for multi-nucleon transfer reactions applied separator with a relatively high angular aperture of $\pm 5\%$ and the possibility to position it at a suitable angle [37], provide sufficiently high efficiency for sensitive and meaningful searches for new isotopes of the heaviest actinides and SHE below the microbarn level.

What is required for an optimized investigation are separators and peripheral components which are best adapted to the following necessities, characteristics and kinematic features of the emission of heavy actinides and SHE:

- (i) Indispensable is the use of often highly radioactive, typically about 0.5-mg/cm^2 thick actinide targets; generally as rotating wheels to accept heavy-ion beam intensities beyond $100\text{ nA}_{\text{part}}$, ideally in the range of particle microampere.
- (ii) As discussed, all excitation functions for the production of heavy elements in multi-nucleon transfer reactions peak at about 10% above the Coulomb barrier. Based on experimental evidence collected over a long period of time, e.g. [38], and preliminary data from a recent dedicated experiment [39], it can be safely assumed that transfer products are formed in reaction with kinematics very much resembling quasi-elastic transfer reactions. Therefore, recoil separators should accept in forward direction all products, which are emitted within a conical angular range of (minimum) of $\pm 5^\circ$ (ideally $\pm 10^\circ$ or more) and the centre of the cone located at the grazing angle, Θ_{gr} . For target-like heavy fragments, the corresponding angle in the laboratory frame is at about 32° relative to the beam direction. It should be noted, that a theoretical calculation including modelling of the kinematics of neutron-rich platinum isotopes formed in collisions of ^{136}Xe with ^{208}Pb targets shows the emission of these products predominately under 0° [40]. From this calculation it was concluded that “head-on” collisions mainly contribute to the synthesis of heavy target-like transfer products. As Pt isotopes are much less fissile and can survive high excitation energies, this system cannot be seen as a suitable model for SHE. However, extending their model calculations to the ^{238}U on ^{248}Cm system, again the authors concluded that heavy actinides and SHE do not reveal any “grazing feature” and their widespread angular distribution ($\pm 25^\circ$ in the laboratory frame) peaks at 0° ; not only for reactions at the Coulomb barrier but also about 6% higher [40]. The discrepancy between results of this theory, with no grazing feature seen, and the assumption about typical grazing features for the kinematics of heavy and superheavy element products, as derived from the experimental observations outlined above, provides an interesting challenge.
- (iii) Following the arguments based on experimental observations, as outlined in this work, products will be emitted with typical “grazing” velocities, which span a very wide kinetic energy range from about 20 MeV to ≥ 1000 MeV when going from ^{22}Ne to ^{238}U induced reactions, respectively. Consequently, when designing a separator, a decision has to be made to build (i) a universal one with a very large velocity acceptance or (ii) one which is dedicated either to studies of the heaviest actinides synthesized with light to medium heavy ($A \leq 50$) projectiles or to SHE where ^{238}U beams are advantageous.
- (iv) Highly desirable is a separator design, which shows flexibility in the usual trade-off between separation efficiency and collection efficiency. While the former is required

to reach an acceptable data rate in a focal-plane detector the latter one is needed when a second-stage in-flight separation is foreseen and for devices to further investigate chemical and physical properties. Automated chemistry set-ups, ion-traps, remote low-background nuclear spectroscopy devices or lasers for atomic excitation and ionization are just examples. All of them use rate insensitive buffer gas cells as an interface.

Within the IRiS project, a first step design study, it was shown that various separator options can provide the required high efficiency, selectivity and flexibility [41]. As the primary choice, a solenoid with 2-m length, a bore radius of 0.3 m and a maximum magnetic field of $B_{max} \approx 2.3$ T was studied. Adjustable positions of the target outside the solenoid and of the beam dump in its centre are valuable features. For ^{48}Ca -based reactions and ^{260}Fm as a typical transfer product, collection efficiencies between about 40% and 56% can be achieved depending on the desired separation efficiency from unwanted species, which ranged from >99.9% to 98%, respectively. For the ^{238}U on ^{248}Cm reaction collection efficiencies range from 12% to 30%, again with associated separation efficiencies of >99.9% to 98%, respectively. More options, including gas-filled magnets, are conceivable which may also include new designs of very large aperture quadrupoles in combination with a dipole. Obviously, not only the understanding of nuclear reactions leading to surviving heavy elements in multi-nucleon transfer reactions has made a breakthrough but also the technical options to perform such experiments and significantly move into the fascinating and yet uncharted territory of neutron-rich actinides and superheavy elements.

The time is ripe to revive multi-nucleon transfer reactions to discover and investigate neutron-rich isotopes of heavy actinides and of SHE with readily available, highly sensitive radiochemical techniques and dedicated, highly-efficient and “tailor-made” recoil separators down to today’s experimentally achievable picobarn level.

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References

- [1] M. Schädel, *Phil. Trans. R. Soc. A* **373**, 20140191 (2015).
- [2] G. Herrmann, *Historical Reminiscences: The Pioneering Years of Superheavy Element Research*. In *The Chemistry of Superheavy Elements*, 2nd edn. (eds. M. Schädel, D. Shaughnessy), p. 485 (Springer, Berlin, 2014).
- [3] *Proceedings International Symposium. Why and How Should We Investigate Nuclides far off the Stability Line*. Lysekil, 1966. *Arkiv Fysik* **36** (1967).
- [4] W.D. Myers and W.J. Swiatecki, *Nucl. Phys.* **81**, 1 (1966).
- [5] A. Sobiczewski, F.A. Gareev, B.N. Kalinkin, *Phys. Lett.* **22**, 500 (1966).
- [6] R.-D. Herzberg, *Nuclear Structure of Superheavy Elements*. In *The Chemistry of Superheavy Elements*, 2nd edn. (eds. M. Schädel, D. Shaughnessy), p. 83 (Springer, Berlin, 2014).
- [7] K. Morita *et al.*, *J. Phys. Soc. Jpn.* **81**, 103201 (2012).

- [8] Yu.Ts. Oganessian and V.K. Utyonkov, Nucl. Phys. **A944**, 62 (2015).
- [9] Ch.E. Düllmann *et al.*, Phys. Rev. Lett. **104**, 252701 (2010).
- [10] T. Sikkeland, Ark. Fys. **36**, 539 (1967).
- [11] Yu.Ts. Oganessian, Lecture Notes in Physics **33**, 221 (1975).
- [12] M. Schädel *et al.*, Phys. Rev. Lett. **41**, 469 (1978).
- [13] M. Schädel *et al.*, Phys. Rev. Lett. **48**, 852 (1982).
- [14] M. Schädel, *Radiochemische Messungen der Bildungsquerschnitte von Aktinidenisotopen in der Reaktion von ^{238}U -Ionen mit ^{238}U* , doctoral thesis, Johannes Gutenberg-University Mainz, 1979, and GSI-Report 79–8, Darmstadt (1979).
- [15] J.V. Kratz, M. Schädel, H.W. Gäggeler, Phys. Rev. C **88**, 054615 (2013).
- [16] M. Schädel *et al.*, Radiochim. Acta **25**, 111 (1978).
- [17] R.W. Loughheed *et al.*, Nucl. Instrum. Methods **200**, 71 (1982).
- [18] H. Gäggeler *et al.*, Phys. Rev. Lett. **45**, 1824 (1980).
- [19] T. Sikkeland, A. Ghiorso, M.J. Nurmia, Phys. Rev. **172**, 1232 (1968).
- [20] V.V. Volkov in *Proceedings of the International Conference on Reactions Between Complex Nuclei*, Nashville, 1974. (North-Holland, Amsterdam, 1974) Vol. II, p. 363.
- [21] C. Riedel, W. Nörenberg Z. Phys. **A290**, 385 (1979).
- [22] J.V. Kratz *et al.*, Phys. Rev. C **33**, 504 (1986).
- [23] K.J. Moody *et al.*, Phys. Rev. C **33**, 1315 (1986).
- [24] R.B. Welch *et al.*, Phys. Rev. C **35**, 204 (1987).
- [25] K.E. Gregorich *et al.*, Phys. Rev. C **35**, 2117 (1987).
- [26] D.C. Hoffman *et al.*, Phys. Rev. C **31**, 1736 (1985).
- [27] D. Lee *et al.*, Phys. Rev. C **27**, 2656 (1983).
- [28] V.I. Zagrebaev and W. Greiner, Nucl. Phys. **A944**, 257 (2015).
- [29] M. Schädel *et al.*, Phys. Rev. C **33**, 1547 (1986).
- [30] J.F. Wild *et al.*, *Transfer Cross Sections from the Reaction of ^{48}Ca and ^{254g}Es* , Lawrence Livermore National Laboratory, Nuclear Chemistry Division Annual Report FY83, UCAR 10062-81/1, pp. 144–147.
- [31] E.K. Hulet *et al.*, Phys. Rev. Lett. **56**, 313 (1986).
- [32] E.K. Hulet *et al.*, Phys. Rev. C **40**, 770 (1989).
- [33] M. Schädel *et al.*, Nucl. Instr. Meth. **A264**, 308 (1988), and Radiochim. Acta **48**, 171 (1989).
- [34] A. Türler and K.E. Gregorich, Experimental Techniques. In *The Chemistry of Superheavy Elements*, 2nd edn. (eds. M. Schädel, D. Shaughnessy), p. 261 (Springer, Berlin, 2014).
- [35] H. Koura *et al.*, *Chart of the Nuclides 2014* (Japan Atomic Energy Agency, Tokai, 2015) and <http://www.ndc.jaea.go.jp/CN14/index.html>.
- [36] V.F. Comas *et al.*, Eur. Phys. J. A **49**, 112 (2013).
- [37] C. Golabek *et al.*, Eur. Phys. J. A **43**, 251 (2010).
- [38] Yu.Ts. Oganessian *et al.*, Atomnaya Energiya **28**, 393 (1970).
- [39] M. Götz, S. Götz, J.V. Kratz *et al.*, *Radiochemical study of the kinematics of multi-nucleon transfer reactions in $^{48}\text{Ca}+^{248}\text{Cm}$ collisions 10% above the Coulomb barrier*, to be published (2016).
- [40] V.I. Zagrebaev and W. Greiner, Phys. Rev. C **83**, 044618 (2011).
- [41] J. Dvorak *et al.*, Nucl. Instr. Meth. **A652**, 687 (2011), and priv. comm.