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GSI experiments on synthesis and nuclear structure investigations of the heaviest nuclei

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Abstract. Isotopes of elements up to $Z = 113$ have been synthesized using medium heavy projectiles and target nuclei around doubly magic ^{208}Pb. Synthesis of still heavier elements in reactions of ^{48}Ca projectiles with actinide target nuclei has been reported. To obtain more information about production mechanism of transfermium isotopes nuclear reaction studies including investigations of massive transfer were resumed at SHIP, GSI. Nuclear structure investigations at SHIP have been concentrated so far mainly on systematic investigations of low lying Nilsson levels in odd-mass nuclei. Recently this field has been extended to decay studies of isomeric states in nobelium nuclei at $E^* > 1$ MeV.

PACS. 25.60.Pj Fusion reactions – 25.70.Hi Transfer reactions – 23.20.Lv gamma transitions and level energies

1 Introduction

Since the first predictions of spherical proton and neutron shells beyond the experimentally established ones with the highest proton and neutron numbers ($Z = 82$, $N = 126$) at $Z = 114$ and $N = 184$ [1], the search for nuclei in that region is one of the most exciting challenges in nuclear physics. Since long half-lives were predicted for isotopes close to that magic numbers searches for those, which were soon called 'superheavy', was performed not only in the laboratory using nuclear reactions but also in nature. Recently, after several decades of research, results from the experiments performed at the Dubna Gas-filled Separator (DGFRS) (FLNR-JINR, Dubna) were presented and interpreted as proof to have synthesized isotopes of superheavy elements (SHE) in the range ($Z = (112-118)$) [2]. Although the interpretation of the results is still discussed controversially, it cannot be excluded that these experiments may represent a milestone in SHE research. From theoretical side for a long time original location of the shells was essentially confirmed by macroscopic–microscopic calculations [3,4]. Recently new approaches have been started using self-consistent nuclear models like Skyrme-Hartree-Fock calculations or relativistic mean-field model. These works deliver different results, predicting the spherical proton shell rather at $Z = 120$ and the neutron shell in the range $N = (172–184)$ [5].

In parallel to the synthesis of new SHE nuclear structure investigations of transfermium isotopes have been established as a second branch in SHE research during the past decade. Those experiments became feasible due to enhanced sensitivity and energy resolution of experimental set-ups and the availability of heavy ion beams with enhanced intensity (≈1 pμA). Motivations of these works were to obtain deeper insight in the structure of the well-deformed nuclei located about in the middle ($Z \approx 102$, $N \approx 152$) between the established proton shell at $Z = 82$ and the predicted one at $Z = 114$, and to test the predictive power of nuclear models for spins and parities of the ground-state and low lying excited levels, single particle energies, nuclear deformation etc. Also of interest is the relevance of nuclear properties in this region for the predictions of the next spherical shells, since some of the single particle levels expected to be relevant for the shell gap at $Z = 114$ come close to the Fermi level around $Z = 100$ (e.g. $\pi f_{5/2}$, $\pi f_{7/2}$). Techniques are as well in-beam spectroscopy as decay spectroscopy [6,7].

Investigation of heaviest elements have meanwhile a tradition of nearly thirty years at SHIP, GSI, having discovery of elements 107–112 as highlights. Recent results on synthesis of SHE, nuclear reaction studies and nuclear structure investigations will be presented here.

2 Synthesis of superheavy elements and nuclear reaction studies

The most successful way for the production of transactinide isotopes with atomic numbers up to $Z = 112$ has

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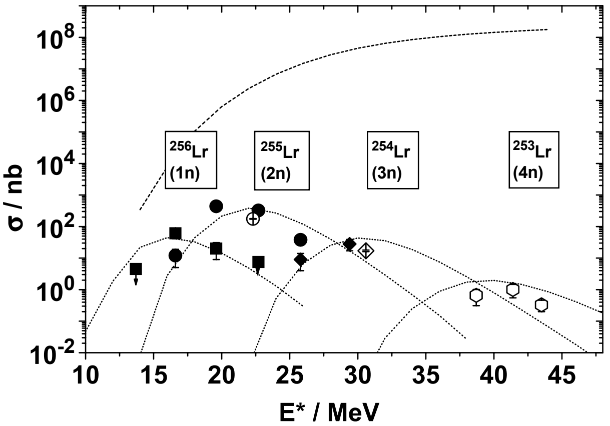

Fig. 1. Excitation function for the reaction ^{48}Ca+^{209}Bi; full symbols: results from [8]; open symbols: results from recent experiments at SHIP; results of HIVAP calculations for fusion (dashed) and evaporation residue (ER, dotted) cross sections are given by the lines.

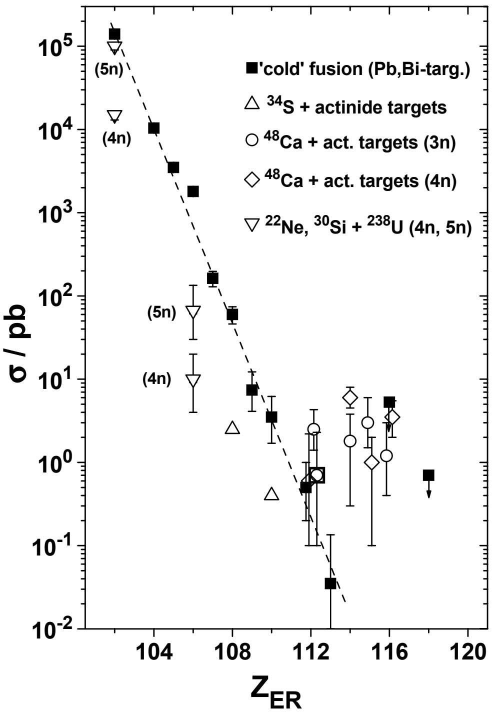

Fig. 2. Systematics of ER cross sections for heaviest elements. Data are adopted from [16] if not otherwise indicated.

been so far complete fusion of target nuclei around doubly magic ^{208}Pb with 'medium' heavy projectiles ranging from ^{50}Ti to ^{70}Zn. The advantage of these combinations are low excitation energies ($E^* < 20$ MeV) of the compound nuclei (CN) at the fusion barrier, enabling the CN to deexcite by emission of only one neutron, which means, that during deexcitation particle emission has to compete with prompt fission in only one step, resulting in a higher 'survival probability'. Indeed it was shown, that with increasing atomic number $1n$-deexcitation, although it occurs at sub-barrier energies, dominated over $2n$-deexcitation. Consequently all new elements $Z = (107$–$112)$ were produced in $1n$-deexcitation reactions. The importance of low excitation energies for the production of heaviest nuclei is shown in Figure 1. Here experimental results for the reaction ^{209}Bi(^{48}Ca, xn)$^{257-x}$Lr from [8] and from these studies are compared with HIVAP [9] calculations. Obviously isotope production cross sections are maximum around $E^* \approx 20$ MeV ($2n$-deexcitation channel) and decrease by more than two orders of magnitude up to $E^* \approx 40$ MeV ($4n$-deexcitation channel), although the fusion cross section increases by about two orders of magnitude. Nevertheless cross sections, also for $1n$-deexcitation channels, decrease steeply with increasing atomic number, typically by a factor of 3.5 per unit of Z, reaching a value of $\approx$35 fb for the production of an element 113 isotope in the reaction ^{209}Bi(^{70}Zn, n) ^{278}113 [12], as shown in Figure 2.

A similar behavior is also evident for reactions using light projectiles (^{22}Ne [10], ^{30}Si [11], ^{34}S) and actinide targets. Under this aspect the quite stable cross sections for isotopes attributed to elements 112–118 in ^{48}Ca induced reactions are somewhat surprising. As a first step to prove the results from the Dubna experiments the synthesis of ^{283}112 was attempted at the BGS, Berkeley [13,14] and SHIP [15] in irradiations of ^{238}U with ^{48}Ca. Although the sensitivity of the Dubna experiments was reached in both cases, the decays chains observed there and attributed to the decay of ^{283}112 could not be confirmed so far[1].

One possibility to obtain more detailed information on the reaction mechanism is measuring excitation functions for different projectile–target combinations leading to the same (or at least very similar) CN. Of specific interest for SHE production is the influence of symmetry of the reaction partners on the fusion probability at energies close to the fusion barrier, derived e.g. from the Bass model [17]. The symmetry may be expressed by the ratio of projectile mass (A_p) and target mass (A_t), hence A_p/A_t. This subject was topic about 25 years ago and many measurements were performed in the region $Z_{CN} \leq 92$, but data in the transuranium region were rather scarce. Yet, Gäggeler et al. [18] observed a drastic decrease of the production cross sections for ^{244}Fm when increasing the symmetry. At SHIP evaporation residue (ER) production in the reactions ^{198}Pt(^{50}Ti, xn)$^{248-x}$Fm [19] (reanalyzed for this paper) and ^{208}Pb(^{40}Ar, xn)$^{248-x}$Fm [19–22] was investigated. Excitation energies of the CN are almost equal at the Bass model barrier [17] for both systems. The result is shown in Figure 3.

More essential than the somewhat lower cross sections for the more symmetric system is the ratio $\sigma(2n)/\sigma(3n)$. For ^{40}Ar + ^{208}Pb one obtains a value of $\approx$1, for

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[1] In an irradiation of ^{238}U with ^{48}Ca, performed at SHIP after submission of this paper, two decay chains each consisting of implantation of a 'heavy' nucleus, followed by an α decay and finally terminated by a spontaneous fission event were observed. α energy and life-times are in agreement with the data attributed in the 'Dubna experiments' to ^{283}112 and ^{279}110 [2].

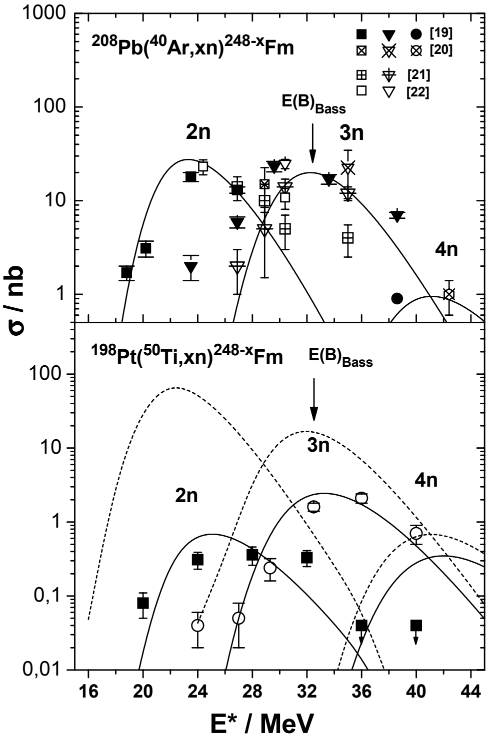

Fig. 3. Excitation functions for Ti-50 + Pt-198 and Ar-40 + Pb-208 (dots); lines refer to HIVAP calculations; see the text for details.

^{50}Ti + ^{198}Pt a value of ≈0.15. This can be interpreted as due a dynamical hindrance of complete fusion at subbarrier energies for the more symmetric reaction, although, assuming a simple one-dimensional barrier penetration an enhancement of subbarrier fusion could be expected for the deformed target nucleus ^{198}Pt ($\beta_2 = -0.139$ [4]) compared to the doubly magic, spherical ^{208}Pb. This interpretation is supported by HIVAP calculations. The dashed lines represent the results obtained using a parameter set that reproduces the experimental data for ^{40}Ar + ^{208}Pb, while the full lines are obtained using an 'extra push' energy of 9 MeV.

Another interesting aspect concerns massive transfer as a possibility to produce SHE. At SHIP studies of transfer reactions are limited due to the restriction to the forward direction (≈ ±2.5 degree). Nevertheless one can investigate different target–projectile combinations, vary bombarding energies and also measure the velocity distributions of the reaction products, which supplies information on the reaction kinematics. As a starting point we chose the system ^{25}Mg + ^{206}Pb at beam energies of 5.9 AMeV and 6.3 AMeV. Isotope identification was restricted to those decaying by α emission with half-lives above about 3 μs (separation time). The preliminary results for the production of ^{214,215}Ra are shown in Figure 4. Evidently the velocity distributions for both isotopes peak at v/v_{CN} = (1.4–1.5). The explanation as production by transfer of about half of the projectile mass to the target nucleus, while the residual projectile fragment is rejected, is in-line with elementary kinematics and Q-value considerations. The latter result in excitation energies of about 36 MeV for ^{218}Ra or about 32 MeV for ^{219}Ra, produced by transfer of ^{12}C or ^{13}C 'clusters' to the target nucleus, leading to residues $^{214-216}$Ra.

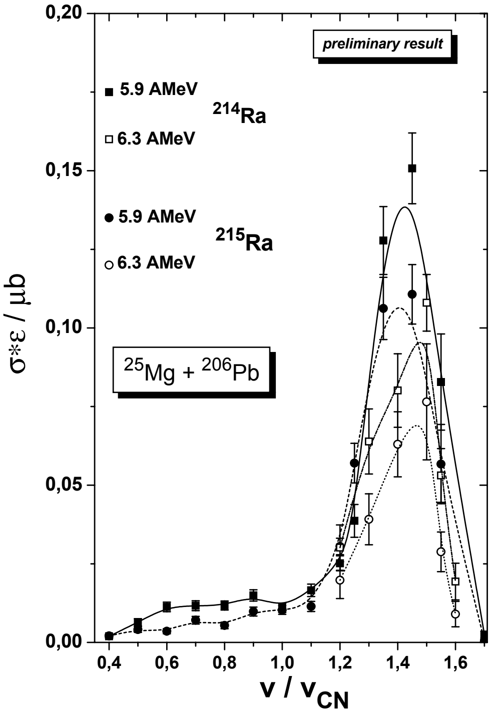

Fig. 4. Velocity distributions for ^{214,215}Ra nuclei produced in bombardments of ^{206}Pb with ^{25}Mg projectiles at 5.9 AMeV and 6.3 AMeV. The lines are to guide the eye.

3 Nuclear structure investigations

Taking advantage of the high beam currents available from the UNILAC accelerator, nuclear spectroscopy has been performed so far by decay studies in the focal plane of SHIP by means of γ-ray measurements in conjunction with particle registration (evaporation residues, α particles, conversion electrons) either in prompt or delayed coincidence, depending on the subject of interest. Delayed coincidences between evaporation residues and γ-rays (or prompt coincident pairs of conversion electrons and γ-rays) are a tool for investigation of the decay of isomeric states populated during deexcitation of the compound nucleus. By this method K-isomers in ^{252}No [16] and ^{253}No [23] were identified in recent experiments at SHIP. Investigation of EC decay may also be possible in some specific cases in future, provided γ-rays are emitted sufficiently during deexcitation of the daughter. Coincidences (prompt or delayed) between α particles and γ-rays on the other side deliver information on nuclear levels, which also might be isomeric, populated by the α decay. Since in odd-mass nuclei energies, spins and parities of low lying levels are essentially determined by the unpaired nucleon, systematic trends are observed along

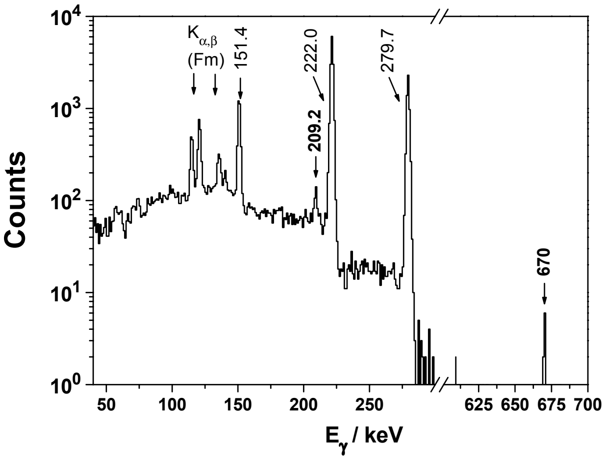

Fig. 5. Spectrum of γ-rays observed in prompt coincidence with ^{253}No α decays.

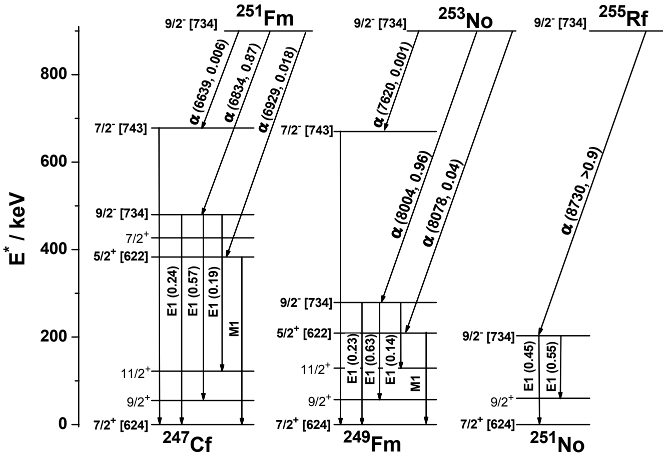

Fig. 6. Decay systematics $N = 151$ isotones.

the isotope line in odd-Z nuclei [24] and along the isotone lines in even-Z nuclei [25]. As an illustrative example latest results on decay of ^{253}No are shown in Figures 5 and 6. In Figure 5 the γ spectrum observed in coincidence with α decays is shown. Besides K-X-rays and the known γ lines at 151.4, 222.0 and 279.7 keV [7,25] two new lines at 209.2 keV and 670 keV are observed. The 209.2 keV line evidently is identical to the transition recently identified by CE measurements and interpreted as an M1 transition from a $5/2^+$[622] level into the ground state [26]. Here for the first time the γ transition, allowing for a more precise determination of the energy of the level was observed. The M1 multipolarity was proven by estimating the K-conversion coefficient from the intensity ratio of γ decays and K-X-rays (corrected for contributions of the E1 transitions of 151.4, 222.0 and 279.7 keV). A value of $\alpha_K(\text{exp}) = 4.4 \pm 1.2$ is obtained, while theoretical values $\alpha_K(\text{theo}) = 0.08$, 0.13, and 4.7 are expected for E1, E2, and M1 multipolarity [27]. Decay schemes for the $N = 151$ isotones ^{251}Fm [28], ^{253}No and ^{255}Rf [29] are compared in Figure 6. In addition to the known decrease of the $9/2^-$[734] level with increasing proton number, the new results indicate a similar trend for the $5/2^+$[622] level.

The assignment of the second γ line of 670 keV is tentative and based on comparison with the decay of ^{251}Fm, where a 678 keV γ line in coincidence with α decays was observed and attributed to the transition from the $7/2^-$[743] Nilsson level into the ground state [28]. On this basis we also attribute the 670 keV transition observed here to the decay of the same level as shown in Figure 6.

4 Conclusions

Isotopes of elements up to $Z = 113$ have been synthesized by complete fusion reactions of Pb- and Bi-target nuclei and 'medium heavy' projectiles as ^{64}Ni or ^{70}Zn, but the cross sections were found to drop exponentially. Interesting results on the synthesis of elements with atomic numbers up to $Z = 118$ using ^{48}Ca beams and actinide targets were obtained at the DGFRS, attempts to reproduce specific results in other laboratories are going on. In addition also other reaction processes than complete fusion are considered. Therefore a program to investigate transfer reactions was started at SHIP.

Nuclear structure investigations are concentrated on decay spectroscopy to investigate systematic trends in single particle level energies in odd-mass nuclei. Another interesting feature are investigation of isomeric states at excitation energies above about 1 MeV [30].

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