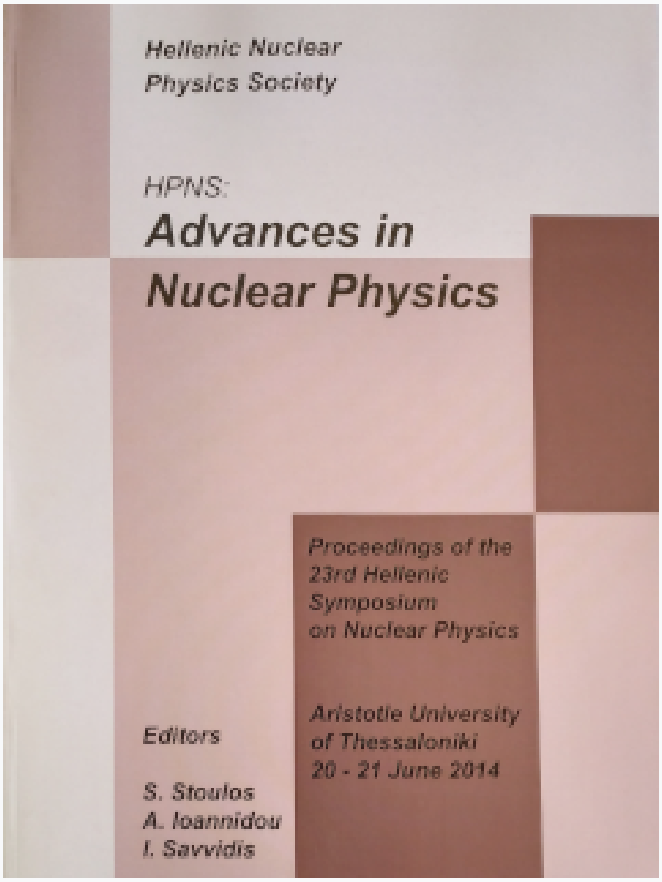
HNPS Advances in Nuclear Physics

Vol 22 (2014)

HNPS2014



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doi: [10.12681/hnps.1924](https://doi.org/10.12681/hnps.1924)

Opportunities for nuclear reaction studies at future facilities

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Abstract

Opportunities for investigations of nuclear reactions at the future nuclear physics facilities such as radioactive ion beam facilities and high-power laser facilities are considered. Post-accelerated radioactive ion beams offer possibilities for study of the role of isospin asymmetry in the reaction mechanisms at various beam energies. Fission barrier heights of neutron-deficient nuclei can be directly determined at low energies. Post-accelerated radioactive ion beams, specifically at the future facilities such as HIE-ISOLDE, SPIRAL-2 or RAON-RISP can be also considered as a candidate for production of very neutron-rich nuclei via mechanism of multi-nucleon transfer. High-power laser facilities such as ELI-NP offer possibilities for nuclear reaction studies with beams of unprecedented properties. Specific cases such as ternary reactions or even production of super-heavy elements are considered.

INTRODUCTION

Progress in construction of advanced scientific infrastructure is a main driving force for progress in many fields of science, and this applies in particular to nuclear physics. Construction of still more powerful radioactive beam facilities allows making spectacular progress in understanding of nuclear structure and post-acceleration of radioactive beams allows also performing nuclear reaction studies using unstable beams. Besides radioactive beam facilities, high-power lasers emerge as another driving force of the progress in nuclear physics. While many concepts still need to be verified in order to perform detailed nuclear physics studies, use of high-power lasers may allow various types of experiments of interest for production of exotic nuclei and for nuclear astrophysics. In this proceeding we consider several possible experiments and extensions of capabilities at both radioactive beam and high-power laser facilities.

(d,p)-transfer induced fission of heavy radioactive beams

Nuclear fission was discovered 70 years ago and represents one of the most dramatic examples of nuclear metamorphosis, whereby the nucleus splits into two fragments releasing a large amount of energy. Fission is not only important for applications such as the generation of energy and the production of radio-isotopes, but also has direct consequences on the synthesis of the heaviest elements in the astrophysical r-process, which is terminated by fission, and on the abundance of medium-mass elements in the universe through so-called "fission recycling" [1]. Furthermore, the fission process itself enables the study of nuclear-structure effects in the heaviest nuclei. Until recently the low energy fission was studied in the region from thorium to fermium using spontaneous fission, fission induced by neutrons and light stable beams or using beta-delayed fission. Recently, the probability of the electron-capture delayed fission of 178,180Tl was measured at ISOLDE and a new asymmetric mode of fission was observed [2]. One of the open questions in fission is the height of the fission barriers of neutron-deficient nuclei. The region between lead and uranium is of special interest since around the closed neutron shell N=126 the fission barrier height is strongly influenced by shell structure, with direct implications to predictions of production of super heavy nuclei, where fission barriers exist purely due to shell structure. Statistical model calculations, used to reproduce experimental evaporation residue cross sections in this region between lead and uranium, typically lead to extracted values of fission barrier heights in disagreement with theory, since available theoretical values [3, 4] need to be scaled down by 15 - 40 %. The measured beta-delayed fission probability was also used to deduce fission barrier height of the daughter isotope 180Hg [5], and deduced fission barriers were again 10 - 40 % smaller than theoretical estimates. However, since 180Hg (and other nuclei accessible in beta-delayed fission) is even-even nucleus, uncertainty remains concerning the magnitude of the pairing gap in saddle configuration and also concerning the extracted fission barrier height.

The radioactive beams at the HIE-ISOLDE can be used to determine fission barrier heights of exotic heavy fissile nuclei. Possibilities to observe fission following the transfer reactions are investigated using the Talys code [6]. The estimates in the region between lead and uranium show that energy upgrade of the REX-ISOLDE post-accelerator to 4-5 AMeV will allow this type of low energy fission studies. Specifically, it is of interest to observe transfer-induced fission of odd elements such as Tl, Bi, At or Fr, since in this case the estimated fission barriers will not be influenced by uncertainty in estimation of the pairing gap in the saddle configuration, which is the case in beta-delayed fission. Due to this circumstance use of odd-Z beams is preferential, allowing observing fission of odd-odd nuclei, while use of even-Z beams may still allow to determine fission barriers of even-odd nuclei, still more preferential than in beta-delayed fission. It is possible to identify candidates for this type of measurement for each of considered isotopic chains. Figure 1 shows that fission cross sections for the 193Tl radioactive beam increase dramatically when the fission barrier height is scaled down by 20 % (solid line) compared to standard values of fission barriers [3] (dashed line). The isotope 193Tl appears especially suitable to determine the fission barrier due to steep increase of the excitation function and eventual availability of sufficient yield from the ISOL target. In similar way, the beams of nuclei 199Bi, 201At and 209Fr can be identified in analogous systematic estimates of fission cross sections of corresponding odd elements. The observed fission rates of these beams can be used to determine values of the fission barrier heights.

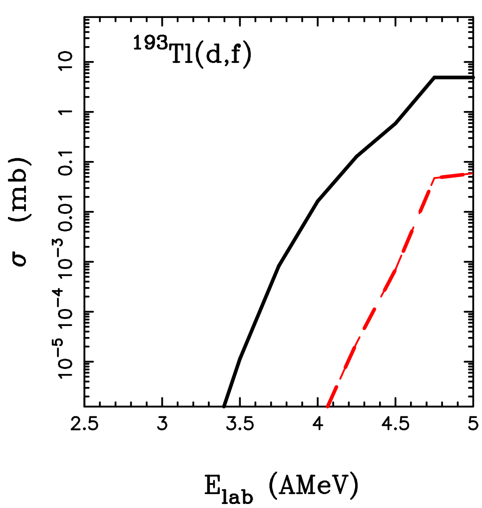

Fig. 1: Fission cross sections for the radioactive beam 193Tl, calculated with and without reduction of fission barrier [3] by 20 % (solid and dashed line, respectively). Strong sensitivity to fission barrier height offers possibility to determine it experimentally.

Measurement at HIE-ISOLDE will be performed using the active target ACTAR TPC [7], a time-projection chamber (TPC) filled with the target (deuterium) gas. The use of ACTAR TPC offers several advantages, namely higher observed fission rates and the possibility of obtaining the fission cross sections for a range of beam energies in one measurement. As an example, using deuterium gas with pressure 250 mbar, one obtains an effective target thickness 1.6 mg/cm2 of deuterium. Assuming a target chamber length parallel to beam axis of about 20 cm (corresponding to the dimensions of ACTAR TPC demonstrator), the beam would slow down from the initial energy of 5 AMeV to about 4.1 AMeV. This interval essentially covers the range of interest in the case of transfer-induced fission of 193Tl. In ACTAR TPC the reaction vertex can be reconstructed with a resolution better than 3 mm, allowing measuring more than 60 points of the excitation function over the energy range of interest. For these points, a rate ranging from about two events/minute at highest beam energy down to one event per hour for the lowest energy can be calculated from the amount of target material in the corresponding slice, the beam intensity (10^6 pps) and a calculated cross section, with the fission barrier reduced by 20 %. Integrated over the whole chamber, with average cross section around 2 mb over the entire energy range, the fission rate can be estimated to twenty per minute. Without reduction of the fission barrier, the expected fission rate can be still estimated to some tens of fissions per hour. Thus the use of active target ACTAR TPC provides the needed sensitivity, allowing resolving the long-standing question concerning the observed fission barriers of proton-rich nuclei by way of their direct measurement. Observed fission rates will determine how detailed the investigations of the low energy fission will be. Understandably, favorable will be lower values of observed fission barrier heights, what appears quite probable for neutron-deficient nuclei in the region around the shell closures Z=82 and N=126. In such case, using the ACTAR TPC it will be possible to determine the mass distribution of the fission fragments and thus asymmetry of the dominant fission mode. The experiment was accepted as a part of the physics program of the HIE-ISOLDE and will be peformed during the year 2016. While the proposed experiment considers measurement of proton-rich nuclei, there is also principal possibility to low-energy study fission the neutron-rich nuclei. Good candidates for this type of study at the HIE-ISOLDE are the neutron-rich radioactive beams such as 228Rn, of high interest for nuclear astrophysics (study of r-process).

Production of exotic nuclei in peripheral nucleus-nucleus collisions below 10 AMeV

The fragmentation reactions offer a successful approach to produce exotic nuclei at beam energies above 100 AMeV, nevertheless they are restricted by the fact that neutron excess is achieved by stripping the maximum possible number of protons (and a minimum possible number of neutrons). To reach an even higher neutron excess, it is necessary to capture additional neutrons from the target. Such an effect is observed in reactions of nucleon exchange [8] which dominate at beam energies around the Fermi-energy (15–50 AMeV) [9, 10, 11, 12, 13].

In the Fermi-energy domain, peripheral nucleus-nucleus collisions are described theoretically using the model of deep-inelastic transfer, in combination with an appropriate model of de-excitation. Deep-inelastic transfer (DIT) occurs when the interaction of the projectile and the target leads to formation of a di-nuclear configuration which exists long enough to allow intense exchange of nucleons through a “window” formed by the superposition of the nuclear mean-fields in the neck region. Transfer of nucleons leads to gradual dissipation of the kinetic energy of relative motion into internal degrees of freedom such as intrinsic (thermal) excitation and/or angular momentum. After re-separation, the hot projectile-like and target-like primary fragments share approximately equal excitation energy and undergo de-excitation via a cascade of particle emissions or via simultaneous multifragmentation.

A very good description of experimental data from peripheral collisions in the Fermi-energy domain was obtained [9] using the Monte Carlo deep-inelastic transfer (DIT) model of Tassan-Got [14, 15] for peripheral collisions, combined with an appropriate choice of model description for central collisions. In the central collisions at Fermi energies, pre-equilibrium emission (PE) and incomplete fusion (ICF) contribute to production of the projectile-like fragments. The combined model framework is referred to as the PE+DIT/ICF+SMM model [10]. Consistent good results can be obtained using the de-excitation code SMM [16], implementing the statistical model of multifragmentation (SMM) supplemented with particle evaporation and/or fission models for the secondary emission stage.

In this context it is also of interest to investigate reactions at energies around and below 10 AMeV and to establish to what extent the production rates can be described using the model of nucleon exchange. Knowledge of the reaction mechanism at these low energies will allow us to select the optimum projectile and target combinations, the appropriate target thickness, as well as the optimum experimental setup for efficient production and collection of very neutron-rich exotic nuclei. The use of the thicker target, decelerating the beam particle to energies close to the Coulomb barrier, will, on one hand, further enhance the estimated intensities of secondary beams, as provided e.g. in refs. [11, 17], on the other hand it can simplify the set-up of the gas-cell necessary to stop the reaction products.

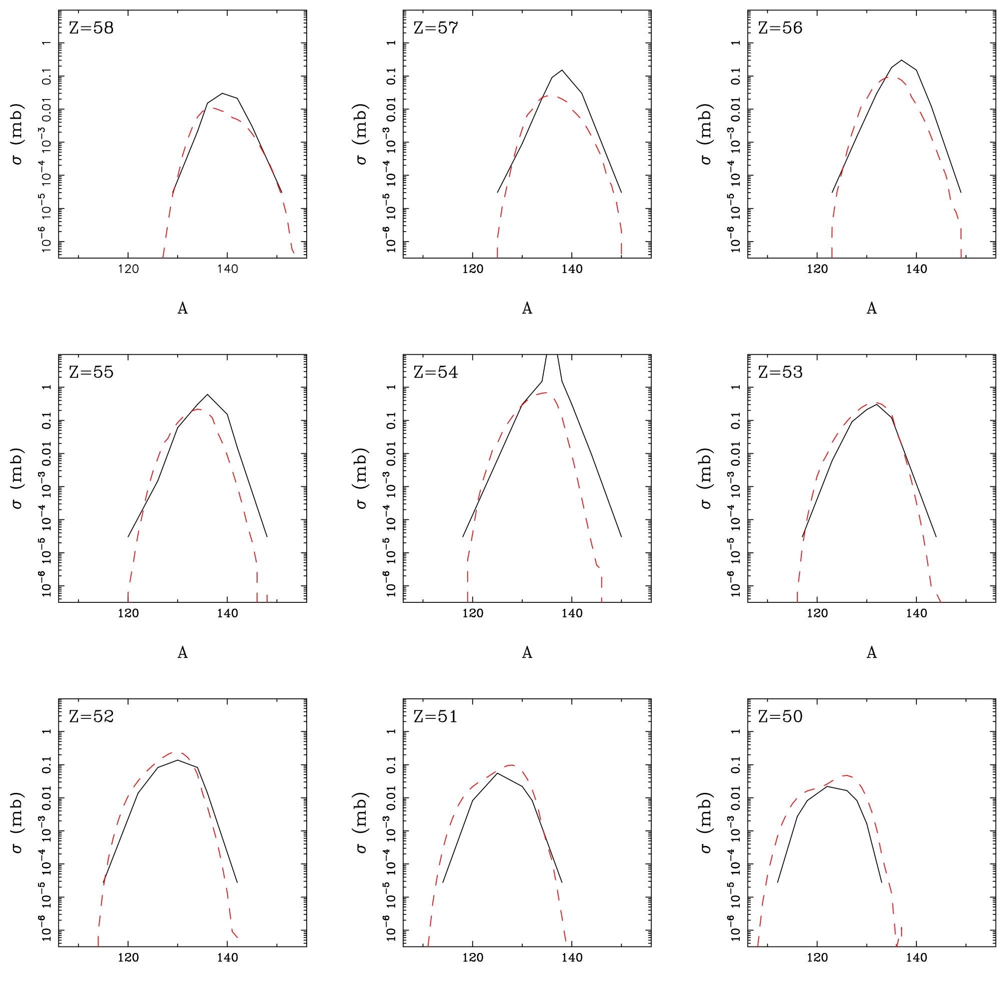

Fig. 2: Simulations performed using model of deep-inelastic transfer, with modifications described in [22] (dashed line) and compared to recent data in reaction of 136Xe+198Pt at 8 AMeV [23] (solid line).

The available experimental data from damped peripheral nucleus-nucleus collisions at beam energies below 10 AMeV, specifically in reactions of 58,64Ni beams with Pb and U targets at beam energies around 6 AMeV [18, 19, 20] and in reactions of 22Ne beam with Zr, Th targets [21], show that deep-inelastic transfer is the dominant reaction mechanism leading to the production of projectile-like nuclei [22]. As it was also demonstrated in the work [22], specific to this energy domain is a possible evolution of the extended nuclear profile in the window (neck) region, primarily in reactions with very heavy target nuclei. The effect seems to weaken with increasing beam energy, at 8 AMeV necessary extension of nuclear profile constitutes only 75 % of the same at 6 AMeV and at 15 AMeV the effect disappears at all. Presence of this effect was further verified using the recently published data from reaction of 136Xe beam with 238U target at 8 AMeV [23]. Again, using the same extension of nuclear profile as in [22] for Ne + Th reaction at 8 AMeV, the experimental yields were reproduced rather well, as can be seen in Fig. 2 (due to presence of experimental yields rather than cross sections a single normalization factor was employed). Thus the predictive power of the model simulations appears verified and it can be used for predictions of achievable rates of very neutron-rich nuclei at the facilities with post-accelerated beams such as HIE-ISOLDE.

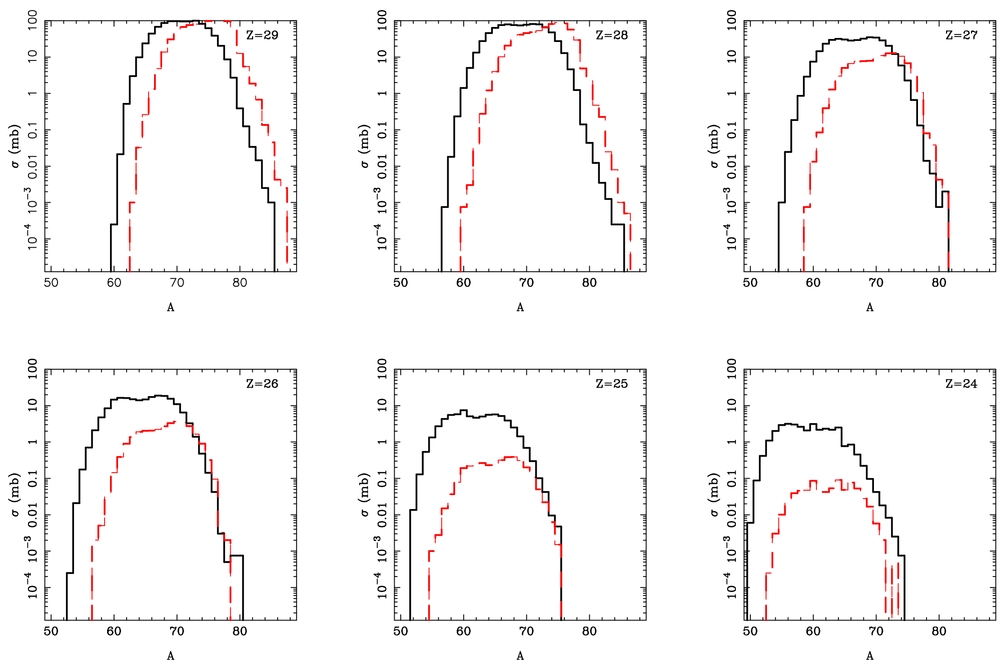

Fig. 3: Simulations performed using model of deep-inelastic transfer, with modifications described in [22] (dashed line) for reactions 74,78Zn+238U at 8 AMeV [23] (solid and dashed line, respectively).

As a first example, possibilities for production of the doubly magic nucleus 78Ni can be investigated. Figure 3 shows results for the reaction of unstable nucleus 74Zn with uranium target at 8 AMeV (solid line), using the same extended profile as above. One can see that the production cross section for 78Ni exceeds 1 mb, what assuming the presently achievable rate of low-energy RIB from primary spallation target of the order of 10^8/s, efficiency of post-acceleration process at the level of 5 % and secondary target thickness of up to 10 mg/cm^2 leads to in-target production of one 78Ni nucleus in about five seconds. This rate can be further improved by upgrade to newly built proton linac and by further optimization of the yield from the spallation target. From the experimental point of view, a sensitive method allowing collecting all the products over wide angular range will be necessary, what favors the use of a gas-cell, where total efficiency of the order of 10 % or more should be achievable. For the more neutron-rich RIB 78Zn (dashed line) the drop of the yields from the spallation target by about factor of 20 is practically compensated by increase of production cross section of 78Ni in secondary reaction and thus similar resulting yields of 78Ni can be expected.

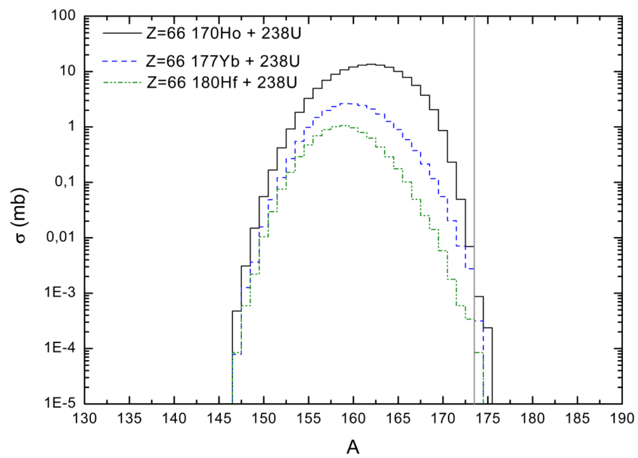

Fig. 4: Lines show production cross sections of Dy isotopes from simulations performed using model of deep-inelastic transfer, with modifications described in [22] (dashed line) for reactions 170Ho,177Yb,180Hf+238U at 8 AMeV [23] (solid, dashed and dotted line, respectively). Vertical line marks heaviest known isotope.

Besides the region of 78Ni, it is also interesting to know what can be achieved for heavier neutron-rich nuclei above heavier than fission fragments produced in fission of uranium. Figure 4 shows situation for production of isotopes of Dy in reactions of radioactive beams of 170Ho and 177Yb (with yields of low-energy beams of 10^8/s) with uranium at 8 AMeV (solid and dashed lines, respectively). The vertical line shows the heaviest known isotope. It appears, that many neutron-rich isotopes can be produced with reasonable rates and even the presently unknown isotopes appear reachable. For comparison also stable beam 180Hf is considered, where in principle higher primary beam rates can be considered, however it might require rotating target and also use of stable beam would result in much higher background from scattered beam in the gas-cell, from which the products of interest need to be separated. For even heavier nuclei, the secondary beam of 226Fr appears as good candidate for production of wide range of neutron-rich isotopes down to Z=80.

Based on the above examples, it appears that the use of post-accelerated neutron-rich beams at HIE-ISOLDE for production of even more neutron-rich nuclei needs to be considered as an option for further upgrade.

High-power laser as a tool for nuclear reaction studies

Basic reason for the implementation of high-power laser in nuclear physics is the eventual possibility to generate extremely high gradients of electric field, which can be used for acceleration of nuclei. As of now, electrons and nuclear particles with energy reaching several hundreds of MeV can be generated using the table-top laser with ultra short pulses focused to energy densities 10^{20} W/cm^2. Such kinetic energies are sufficient to initiate nuclear reactions and processes like photo-fission initiated by the laser were first observed at Rutherford Appleton Laboratory and Lawrence Livermore National

Laboratory [24, 25], and more recently even using the table-top laser system [26]. This field of nuclear physics thus can be considered as established.

At the present, the most powerful laser is the BELLA Petawatt laser at Lawrence Berkeley National Laboratory, with the peak power of 1 PW (10^{22} W/cm^2) and repetition rate of 1 Hz. At present time a major European research center ELI-NP is being constructed in Bucharest, as a nuclear physics branch of the ESFRI project ELI, focusing on the use of high-power lasers in material and nuclear physics. A laser system with peak power of 2 times 10 PW, worth 60 MEUR, will be installed in the nuclear physics branch. Among the proposed experiments there is an experiment proposed by the Habs et al. [27], aiming to observe fusion of two unstable light fission fragments. Both fission fragments will be produced by intense laser pulses, one impinging on thorium foil, thus producing projectile-like fission fragments, and the other one impinging on CD2 foil, thus producing protons and deuterons, which will initiate fission of thorium in the target and thus production of target-like fission fragment. Scheme of this experiment is shown in Figure 5a. The proposal plans to use the so-called hole-boring variant of the Radiation Pressure Acceleration mechanism, allowing accelerating the projectile-like light fission fragment to 7 AMeV, while the protons and deuteron are accelerated to the same energy per nucleon by another laser in order to initiate fission in Th target. Around 10^{11} of Th projectile-like and 3 times more of light ions will be generated per laser burst. At an estimated purely geometric fusion cross section and for normal stopping in the target material, the proposal arrives to a rate of 1.5 fusion products per laser bunch, which is experimentally observable.

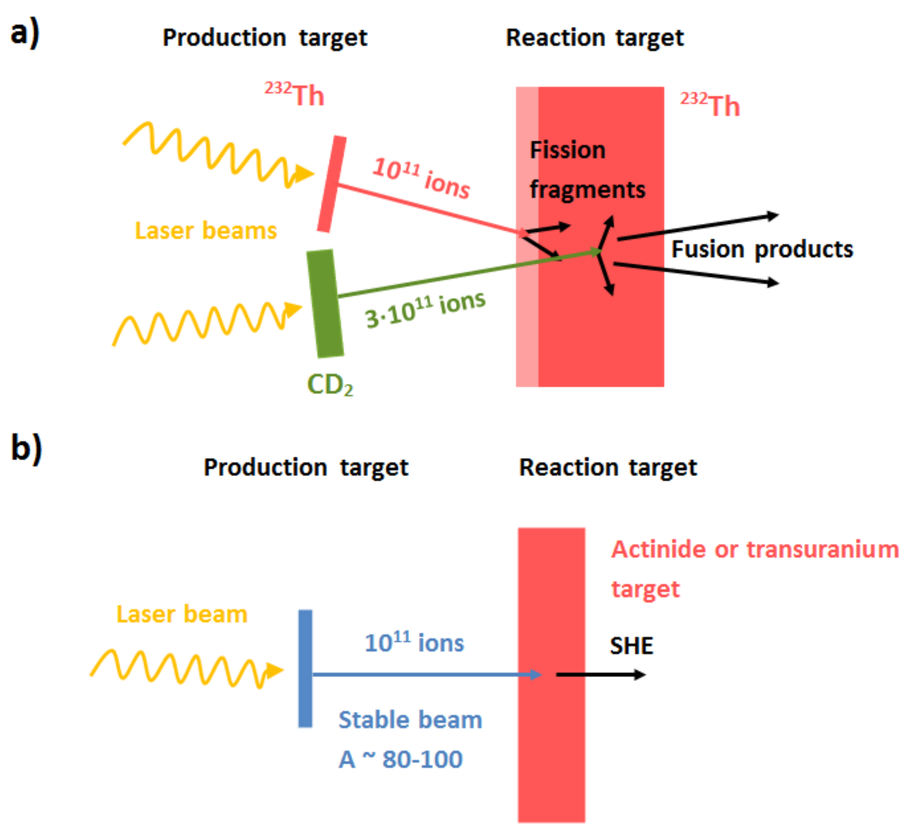

Fig. 5: Scheme of the experiment (a) proposed by Habs et al. [27] and (b) considered here for SHE production.

The proposal further considers an effect of reduced stopping power for dense ion bunches in solid target and in this estimates production of more than 10^{10} of projectile-like and target-like fission fragments per laser burst. At an estimated purely geometric fusion cross section the expected rate of fusion products rises to 4×10^4 per laser burst. Due to uncertainty concerning the possible reduction of stopping the expected value is lowered to 10^3 per laser burst. The fusion products will be separated from the background using recoil separator and brought into its focal plane in order to identify them and study their properties. As a result of such experiment, properties of neutron-rich exotic nuclei in the vicinity of neutron shell N=126 can be explored, gaining valuable information for nuclear theory and nuclear astrophysics.

Due to emerging limitations for production of further super-heavy elements using the contemporary accelerator technology such as cyclotrons and linacs, it is interesting to understand whether high-power laser can provide an alternative. Already in the above mentioned experiment, in principle also reactions of e.g. fission fragments with Th target nuclei can be imagined, however its observation will be disfavored by many orders of magnitude due to drop in the fusion cross sections. Also the possibility to produce heavy nuclei with Z=100 by fusion of two heavy fission fragments in a similar way as described above will be influenced by dramatic drop in cross sections.

More conventional option would be to fuse the lighter stable beam with heavier Th-like (actinide or transuranium) target nucleus. In the scenario with the stable beam-like nuclei and normal stopping (see Fig. 5b) the thorium production foil will be replaced with lighter material and irradiated by the high-power laser. Similar number of accelerated nuclei should be obtained as in the case of thorium (thus gaining a factor of about $\times10^3$ when compared to beam-like light fission fragments) and the difference in yield of evaporation residues will be determined by the production cross section of SHE and by the fact that target-like nucleus does not need to fission (so another factor 4×10^4 will be gained!). This means that e.g. for ER cross section of 1 pb the expected rate appears to be 4×10^{-5} per laser burst, with the expected repetition rate of 0.1 Hz (which is foreseen at ELI-NP) it will be one nucleus in about 100 hours! Such rate would not be too far from the existing best facilities. However, it is known that excitation functions of production of super-heavy nuclei are quite narrow what may limit the expected rate. Typical thickness of heavy targets used for production of SHE is 0.5 mg/cm^2, corresponding to about 2000 layers of material. Main reason for such thin targets is the low velocity of evaporation residues and thus a relatively small range in the material. Use of thicker targets typically does not increase the observed rate of SHE and saturation is observed, thus demonstrating that only a limited thickness of about 0.5 mg/cm^2 contributes. As a result an additional factor of 10^{-2} might be expected, thus reducing the expected rate in the case of normal stopping to 4×10^{-7} per laser burst or one nucleus in 10000 hours (more than one year) at production cross sections of 1pb. As mentioned above, for the production of SHE by the beam of light fission fragments (at normal stopping) the rate will be 10^3 times lower.

In the case of reduced stopping the total Th target thickness is expected to grow by a factor of 100, and assuming that the"active" part of the target will grow also by factor of 100 (to 50 mg/cm^2) for stable beam particle one arrives to the above mentioned rate 4×10^{-5} one nucleus per 100 hours at production cross section of 1 pb, which is quite encouraging. For reduced stopping, the beam rate of the light fission fragment rate will be equal to the initial Th beam (and thus only by a factor of 3 lower than for stable beam) and one can expect one nucleus per 300 hours. Furthermore, one can expect an increase of fusion cross section for neutron-rich fission fragments which can make this option preferential to the use of stable beam. Of course these considerations depend on existence of the reduced stopping, so one can adopt more modest estimate by taking geometric mean of the options with and without reduced stopping. In that case the rates would be one nucleus per 1000 hours for stable beam particle and 55000 hours (more than 6 years) for light fission fragment.

Thus one can conclude that the production of SHE using high-power laser is not excluded, however it strongly depends on the expected reduction of stopping in the dense ion bunches, which was not proved yet and for practical application also increase of laser power by several orders of magnitude would be necessary, in order to compensate also separation and detection efficiency. Still, the dynamical evolution of still more powerful lasers leaves much room for optimism.

Besides other possible applications, it appears that high-power laser technique with ultra-dense beams might open pathway to ternary reactions of unstable nuclei e.g. ternary fusion of three light fission fragments. In the case of the above experiment, any of the 10^3 fusion products might fuse again and using similar considerations it appears that about 10^{-4} of such ternary fusions can occurs per one laser bunch, about once per day at the ELI-NP setup. While it is still hardly observable, due to additional reduction of rate due to fission, laser facilities appear to provide environment to facilitate studies of ternary reaction in principle, due to high density of accelerated nuclei. This concept can be in principle tested e.g. using the accelerated Al nuclei hitting the Al target. If the high-density bunch of Al hits the target, fusion will occur and the fusion products will be able to fuse again. Assuming that the number of accelerated ions per laser bunch will be again of the order of 10^{11} and taking into account that each atom of the target will be again Al, the probability of the ternary fusion will rise to the order of 10^3 per laser burst. This number was obtained assuming normal stopping, thickness of Al-target of 50 μm (as in the case of Th), and considering first two thirds of the Al-target as producing the fusion products which fuse again with Al-nucleus in the remaining third of the target. That should be obviously possible to observe. Of course the initial energy of the Al beam should be set so that the fusion products will be still fast enough to undergo fusion so some fine tuning of the above assumptions will be needed. Such experiment appears quite feasible and the ternary fusion may open pathway e.g. for simulation of astrophysical processes on Earth.

CONCLUSIONS

Future nuclear physics facilities such as radioactive ion beam facilities and high-power laser facilities offer many opportunities for investigations of nuclear reactions. Post-accelerated radioactive ion beams offer possibilities for study of the role of isospin asymmetry in the reaction mechanisms at various beam energies. Fission barrier heights of neutron-deficient nuclei can be directly determined at low energies. Post-accelerated radioactive ion beams, specifically at the future facilities such as HIE-ISOLDE, SPIRAL-2 or RAON-RISP can be also considered as a viable candidate for production of very neutron-rich nuclei via mechanism of multi-nucleon transfer. High-power laser facilities such as ELI-NP, using the beams of unprecedented properties, offer possibilities for nuclear reaction studies such as ternary reactions and high power lasers with even higher intensities, which will be available in foreseeable future, can be even considered for production of super-heavy elements.

ACKNOWLEDGMENT:

This work is supported by the Slovak Scientific Grant Agency under contracts 2/0121/14, by the

Slovak Research and Development Agency under contract APVV-0177-11 (M.V.), by the NSFC of China under contract Nos. 11035009, 10979074, and by ELKE account No 70/4/11395 of the National and Kapodistrian University of Athens (G.S.).

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