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Durability of targets and foils in experiments on synthesis of superheavy nuclei

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Summary. — Durability of targets and window foils irradiated by intense heavy ion (HI) beams in the experiments on synthesis of superheavy nuclei (SHN), which are carried out in Dubna with a Gas-Filled Recoil Separator (DGFRS), has been considered. High fluxes of HIs and heat generated within relatively small areas and thicknesses of the target and foils are inherent in such long-term experiments. The ability of these elements to withstand radiation damages, sputtering and evaporation of atoms becomes questionable. All the processes are influenced by the target (foil) temperature and none of them is independent of the others, but they can be considered separately. Thus, sputtering yields were approximated on the grounds of available models and experimental data and compared to the results of measurements carried out to verify the estimates. The temperature of the target (foil), in turn, was estimated in the conditions of pulse heating followed by subsequent cooling with a radiation emitted from their surfaces. These conditions correspond to the rotating target and window irradiated by a continuous HI beam in the DGFRS experiments. Estimates show that radiative cooling might be the most effective way of heat removal at the temperature of few hundred Celsius degrees.

1. – Motivation

Sputtering of actinide oxide targets and Ti window foils irradiated by HI beams is one of the processes determining the durability of targets and foils used in high intensity and high dose experiments on synthesis of superheavy nuclei. The detailed study of SHN with $112 \leqslant Z \leqslant 118$ produced in the ^{48}Ca fusion-evaporation reactions implies the use of higher beam intensities than those that were used in discovery experiments [1]. The synthesis of SHN with $Z > 118$ implies the use of heavier beam particles, such as ^{50}Ti, ^{54}Cr etc. For the observation of several events of these SHN one should collect the beam dose $\geqslant 10^{20}$ particles, which may cause the loss of target material toward the end of the experiment with a stationary target, if the sputtering yield is $\sim$0.01 atom/ion (according to TRIM simulations [2]). For the rotating target the yield of sputtered atoms is reduced due to an increase in the irradiation area. The question arises whether this estimate is reliable to be taken into account in future experiments.

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2. – Simulations and approximations for sputtering yields

A lack of experimental data for sputtering yields at high beam energies forced us to test TRIM simulations and to use approximations based on available data. Thus, TRIM simulations show quite satisfactory agreement with the data for backward sputtering Au and Zr, but visibly worse agreement for Ti [3]. For the last TRIM underestimates the sputtering yields by a factor of 3 to 5. The reason for the discrepancy is an additional so-called "thermal spike ('TS') component" inherent in sputtering of such metals as Ti [3]. The 'TS' component can be extracted from measured sputtering yields by the subtraction of those obtained with TRIM simulations. The 'TS' sputtering yields corresponding to the same velocity are usually well fitted with the power function of specific electronic energy losses $(dE/dx)_e$. Using the $(dE/dx)_e$ value [2] corresponding to the desired velocity (energy per nucleon), the 'TS' sputtering yields could be estimated using this approximation of available data. Thus, the sputtering yield of Ti atoms for the 5 MeV/amu ^{48}Ca beam is estimated as ∼0.05 atom/ion. It is the value that can obtained with the extrapolation of Ti data shown in fig. 1.

For the UO_2 target low yields obtained for U atoms sputtered by ^{35}Cl ions of MeV energies [4] turned out to be very close to those obtained with TRIM simulations. Similar TRIM yields for ^{48}Ca, in turn, are close to the ^{35}Cl data extrapolated to higher energies. Much higher sputtering yields, incompatible with the results of TRIM simulations, were later obtained in experiments with heavier ions at higher energies [5]. Very

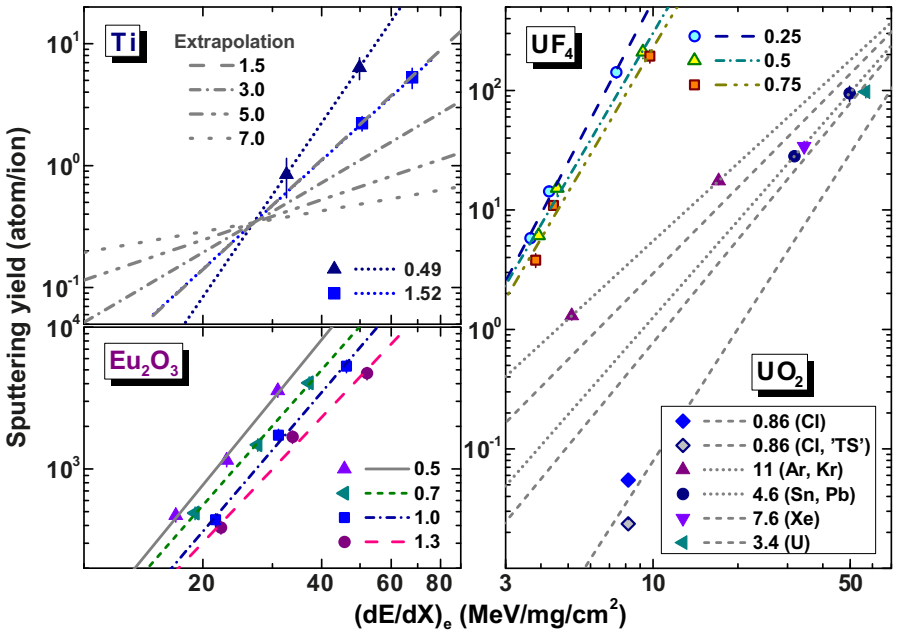

Fig. 1. – The sputtering yields associated with the thermal spike component extracted from the total yields of Ti atoms [3] and total yields of heavy atoms sputtered from the UF_4 UO_2 and Eu_2O_3 targets [4, 6] as a function of specific electronic energy losses $(dE/dX)_e$ [2] for different beam velocities (MeV/amu values indicated in the figure) are shown by different symbols. The results of approximation with the $a[(dE/dX)_e]^b$ function are shown by different lines.

high sputtering yields of U and Eu were also obtained for the UF_4 and Eu_2O_3 targets, respectively [4, 6]. As in the case of Ti data, grouping data according to the same velocity allows one to fit them with the power function of $(dE/dx)_e$ and to approximate the data to the desired velocities. Thus, the yield of U atoms sputtered from UO_2 by the 5 MeV/amu ^{48}Ca beam is estimated as ∼1 atom/ion, as it can be obtained from the interpolation of the data for UO_2 shown in fig. 1.

3. – Experimental observations

Using the approximated values of sputtering yields, the estimates of possible thinning of the Ti foils were performed for 10 different sets of window foils used in past experiments with ^{48}Ca and ^{58}Fe beams. The maximal value of ∼4% is obtained for the highest ^{48}Ca beam dose 2.75×10^{19} particles. So as it follows from the estimates, the effect of Ti foils sputtering is small. We checked it with the α-particle energy absorption experiments using a spectrometric ^{238}Pu-source and a semiconductor α-spectrometer for two pieces of randomly chosen undamaged Ti foils used in the experiments carried out between 2005 and 2012 (see References in [1]). The thicknesses of these foils, which were estimated with the range-energy curve for α-particles stopped in Ti [2], turned out to be larger than those of fresh non-irradiated foils. This thickening, seeming quite unexpected one at the first sight, can be explained by an increase in the α-particle energy losses in the irradiated foils. The increased energy losses could be attributed to the adsorption of hydrogen by the heated Ti surface during the irradiation of the foils by an intense ^{48}Ca beam. The estimates showed that from 6 to 25% of Ti atoms could form a TiH_2 layer on the foil surface faced to the hydrogen volume of DGFRS.

The estimated yield of U atoms sputtered from UO_2 is quite detectable in our high dose experiments on the synthesis of SHN. In these experiments the integrity of radioactive targets was systematically monitored by counting their α-activities. Thus, the results of such monitoring for the ^{249}Cf oxide target showed that at the beginning of the irradiation, the sputtering yield of Cf atoms corresponded to 0.19 atom/ion and then this value reduced to 0.021 atom/ion. For the total beam dose of 2.48×10^{19} particles accumulated during the experiment, the reduced sputtering yield per unit area was estimated as 6.73×10^{-4} atom/ion/cm^2. In a future experiment on synthesis of the element with Z=120 in the ^{50}Ti+^{249}Cf reaction, as was above mentioned, the beam dose of 2×10^{20} particles may allow us to observe few events of its decay. At the same time, this dose should lead to the loss of 14% for the 0.4 mg/cm^2 target toward the end of the experiment (assuming the same sputtering yield for ^{50}Ti, as was obtained for the ^{48}Ca beam).

4. – Target temperature

Estimates show that the radiation emitted from the surfaces of the target and target backing becomes the main process of heat removal at high temperatures [7]. The differential equation corresponding to the radiation heat exchange [8], was modified to take into account the different thicknesses and specific heat capacities of the target and target backing as well as the emissivity of their surfaces. The same temperature for the target backing and target itself was assumed [7]. The results of the application of this equation are shown in fig. 2 for the temperature of the UO_2 target and Ti target backing. The calculations were performed for a small rotating target wheel and for various ^{48}Ca beam intensities as well as for a large target rotating at different angular velocities and the beam intensity of 7×10^{13} s^{-1}. Main parameters for these calculations are indicated in

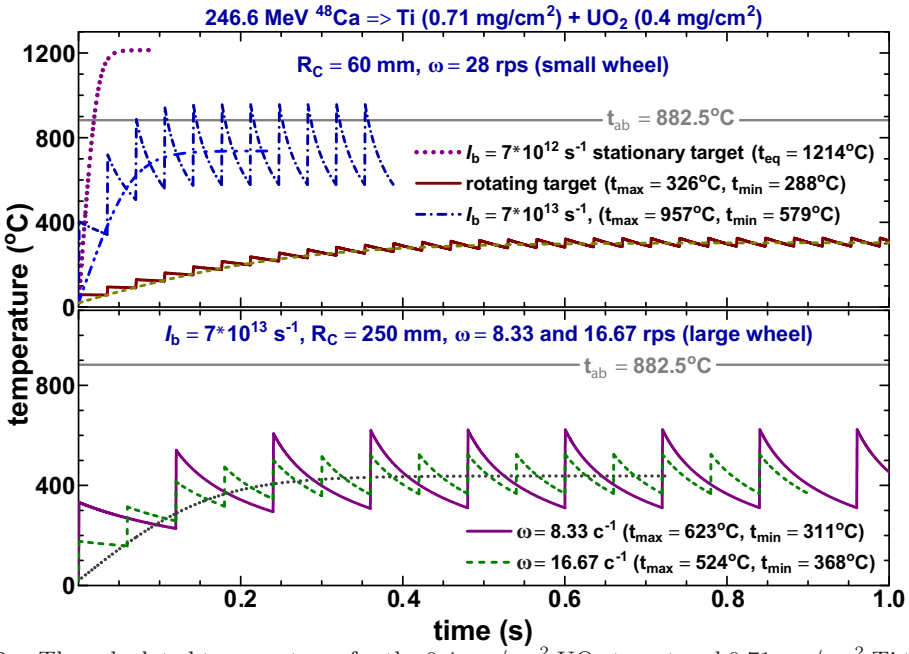

Fig. 2. – The calculated temperatures for the 0.4 mg/cm^2 UO_2 target and 0.71 mg/cm^2 Ti target backing as a whole, which are shown as functions of time for: the small target wheel (central radius R_c=60 mm) rotating at angular velocity ω=28 rps under the ^{48}Ca beam intensities I_b=7×10^{12} and 7×10^{13} s^{-1} (upper panel) and for the large target wheel (R_c=250 mm) rotating at ω=8.33 and 16.67 rps under the ^{48}Ca beam intensity I_b=7×10^{13} s^{-1} (bottom panel).

the figure. More details are presented in [7]. The preference provided by the large target wheel is evidently seen from the figure.

Note that the sputtering yield obtained for the Cf oxide target could be related to the mean temperature of ∼300 °C according to these estimates (see upper panel in fig. 2).

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