Predicted yields of new neutron-rich isotopes of nuclei with $Z = 64$–80 in the multinucleon transfer reaction ^{48}Ca + ^{238}U

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The production cross sections of new neutron-rich isotopes of nuclei with charge numbers $Z = 64$–80 are estimated for future experiments in the multinucleon transfer reaction ^{48}Ca + ^{238}U at bombarding energy $E_{\mathrm{c.m.}} =$ 189 MeV close to the Coulomb barrier.

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The binary multinucleon transfer reactions have been known for producing exotic nuclei for many years [1–8]. The yields of the quasifission products in the reactions ^{48}Ca + ^{238}U, ^{244}Pu, and ^{248}Cm; ^{58}Fe + ^{208}Pb, ^{232}Th, ^{244}Pu, and ^{248}Cm; and ^{86}Kr + ^{208}Pb at incident energies close to the Coulomb barrier are correctly described within our model [9,10]. As shown in Refs. [9,10], the suggested model is suitable for predicting the mass and charge yields, the total kinetic energy distribution, the neuron multiplicity and the production cross sections for the quasifission products that are identical, in accordance with our model, to the multinucleon transfer products at these energies. In our recent article [10] we demonstrated the possibilities for producing neutron-rich isotopes ^{82,84,86}Zn and ^{86,88,90,92}Ge beyond $N = 50$ in the transfer-type reactions ^{48}Ca + ^{238}U and ^{244}Pu at incident energies close to the Coulomb barrier. Because of the large neutron excess and smaller losses due to the quasifission near the entrance channel, the use of the ^{48}Ca projectile is more preferable than the use of the heavier projectiles to reach the neutron-rich region of nuclide in the actinide-based reactions.

Within the same formalism as in Ref. [10], in the present article we report for future experiments the possibilities for producing new neutron-rich isotopes of nuclei with $Z = 64$–80 as complementary to light fragments in the uranium-based multinucleon transfer reaction with a ^{48}Ca beam at incident energy $E_{\mathrm{c.m.}} = 189$ MeV, the value of the Coulomb barrier for the spherical nuclei. It should be noted that these isotopes cannot be reliably identified among the products of induced fission of actinides and cannot be produced in the complete fusion reaction with available stable beams.

In Ref. [10] the diffusive multinucleon transfer reaction is described as an evolution of the dinuclear system (DNS) that is formed in the entrance channel of the reaction after the capture stage [1,2,9,10]. The multinucleon transfer is considered as a diffusion of the DNS in the charge and mass asymmetry coordinates, which are defined here by the charge and neutron numbers Z and N of the heavy nucleus of the DNS. During the evolution over charge and mass asymmetry coordinates, the excited DNS can decay into two fragments in relative distance R between the centers of the DNS nuclei. The model treats the production of the exotic nucleus as a three-step process. First, the initial DNS with heavy nucleus (Z_i, N_i) is formed in the collision. Second, the DNS with heavy exotic nucleus (Z, N) is produced by nucleon transfers. Then this DNS separates into two fragments. The primary charge and mass yields of the fragments can be expressed by the product of the formation probability $P_{Z,N}(t)$ of the DNS configuration with Z and N ($A = Z + N$ is the mass number of the heavy nucleus) and of the decay probability of this configuration in R proportional to the one-dimensional Kramers rate [10]. $P_{Z,N}(t)$ are found from the solution of the system of master equations with the initial condition $P_{Z,N}(0) = \delta_{Z,Z_i}\delta_{N,N_i}$ [10]. The predicted values of the mass excesses and the neutron separation energies $S_n(Z, N)$ for unknown nuclei are taken from the finite-range liquid drop model [11].

The calculated production cross sections of the primary isotopes in the reaction ^{48}Ca + ^{238}U at $E_{\mathrm{c.m.}} = 189$ MeV are presented in Figs. 1–9. The primary neutron-rich nuclei of interest are excited and transformed into the secondary nuclei with smaller numbers of neutrons. The neutron emission channels are indicated in Figs. 1–9 for primary neutron-rich isotopes. The predictions are done by assuming the excitation energy of the DNS is divided proportionally to the mass numbers of the fragments. As seen, the primary nuclei emit 1–5 neutrons. Because the neutron emission is the dominant deexcitation channel in the neutron-rich isotopes of interest, the production cross sections of the secondary nuclei indicated in Fig. 1–9 are the same as those of the corresponding primary nuclei. This seems to be evident without special statistical treatment.

Because the predicted production cross sections for new exotic isotopes ^{193}W, ^{195,196}Re, ^{198}Os, and ^{200}Ir are at the microbarn level, they can be easily identified. For these nuclei, the known heaviest isotopes are in the vicinities of the maxima of the primary isotopic distributions (Figs. 2–4). Because the calculated production cross sections for the new exotic isotopes ^{178}Er, ^{180,181}Tm, $^{182-184}$Yb, $^{185-187}$Lu, ^{190}Hf, $^{191-193}$Ta, ^{194,196}W, ^{197,199}Re, ^{199,200}Os, ^{201,202}Ir, and ^{203}Pt (Figs. 2–7) are between microbarn and nanobarn levels, they can also be detected with the present experimental setups. The group of new isotopes, ^{170}Gd, ^{173}Tb, ^{174,176}Dy, ^{176,177,179}Ho, $^{179-182}$Er,

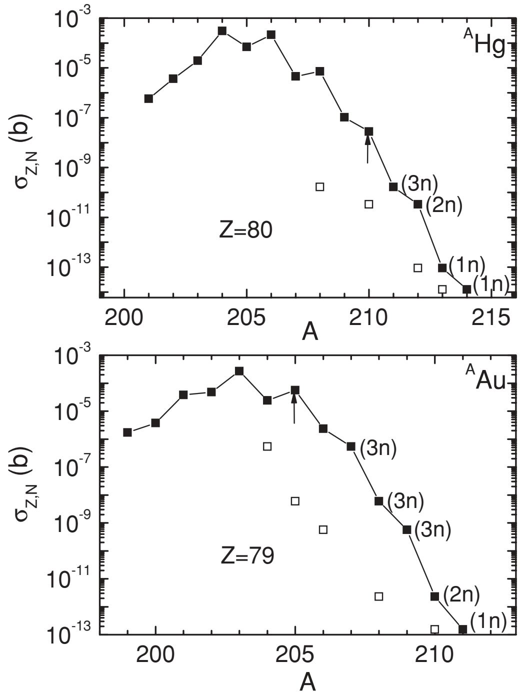

FIG. 1. Calculated production cross sections of the primary (solid squares) Hg and Au isotopes versus the mass number. Neutron evaporation channels for neutron-rich primary isotopes are indicated. The yields of secondary isotopes are shown by open squares. The heaviest known isotopes are marked by arrows.

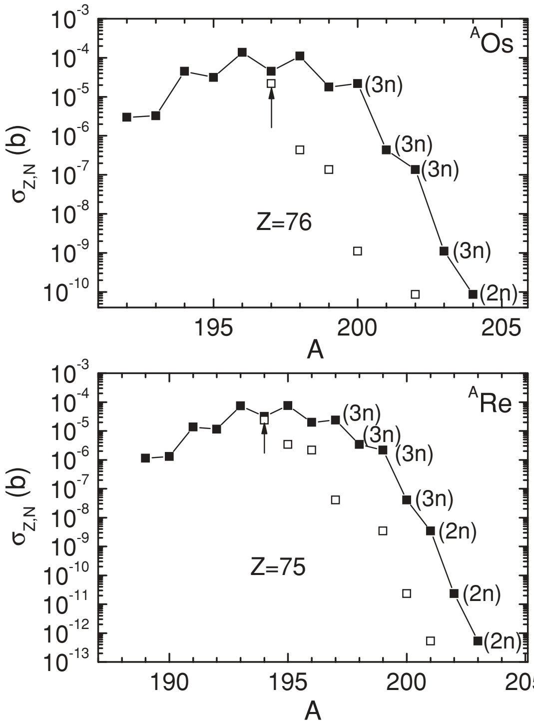

FIG. 3. The same as in Fig. 1, but for the Os and Re isotopes.

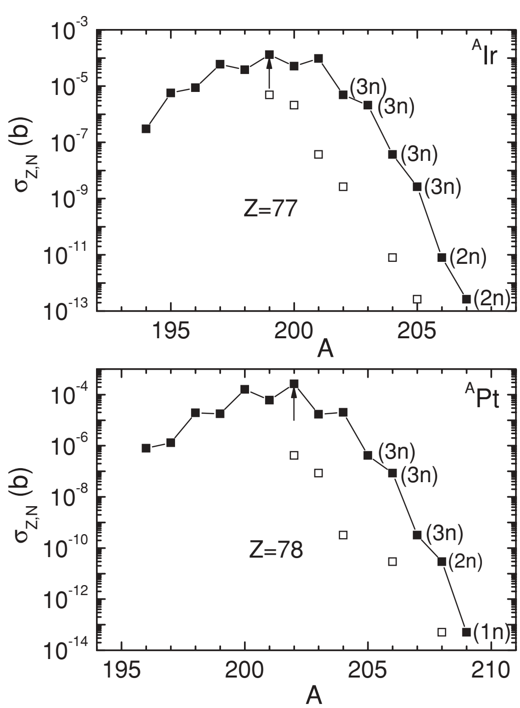

FIG. 2. The same as in Fig. 1, but for the Pt and Ir isotopes.

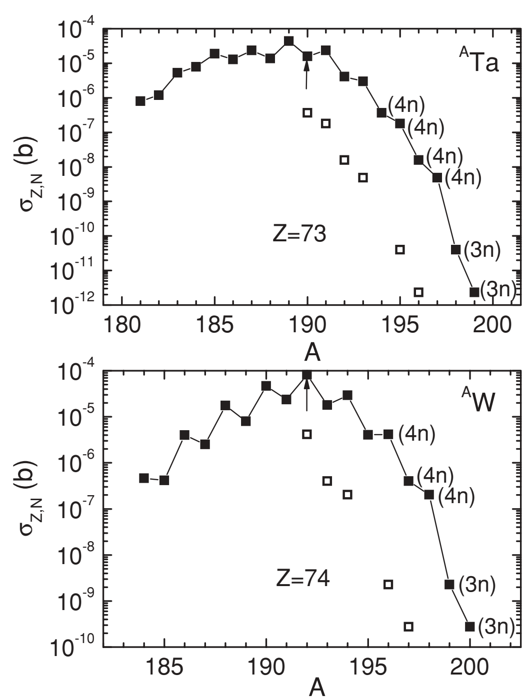

FIG. 4. The same as in Fig. 1, but for the W and Ta isotopes.

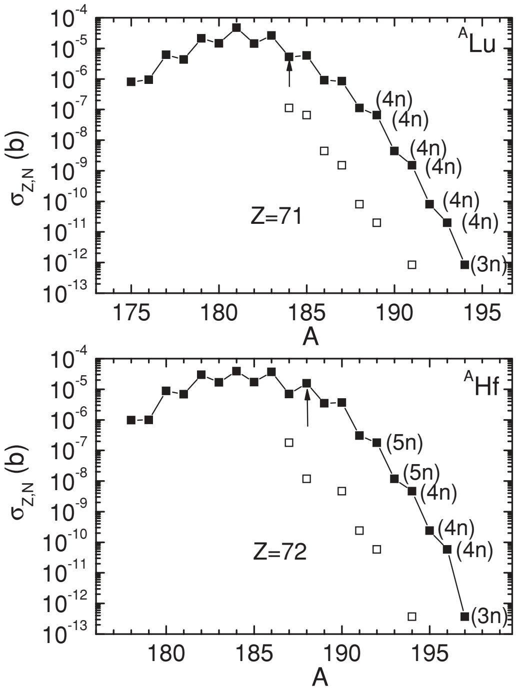

FIG. 5. The same as in Fig. 1, but for the Hf and Lu isotopes.

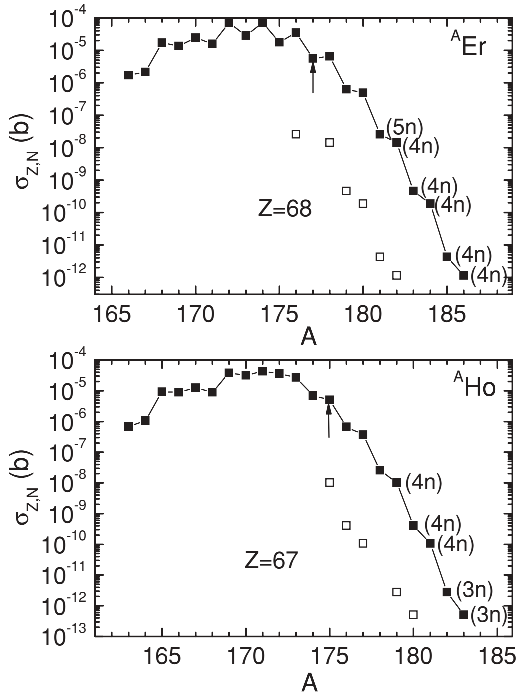

FIG. 7. The same as in Fig. 1, but for the Er and Ho isotopes.

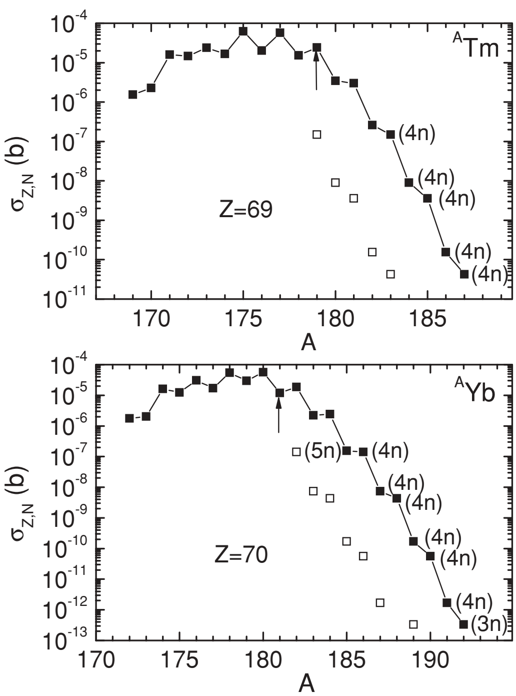

FIG. 6. The same as in Fig. 1, but for the Yb and Tm isotopes.

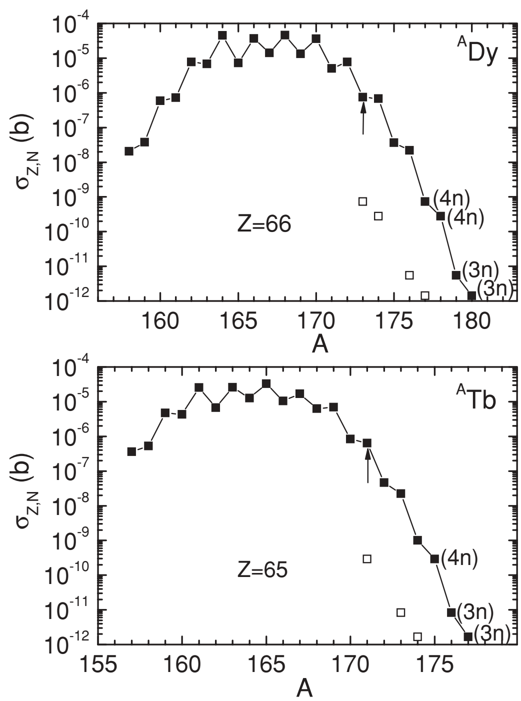

FIG. 8. The same as in Fig. 1, but for the Dy and Tb isotopes.

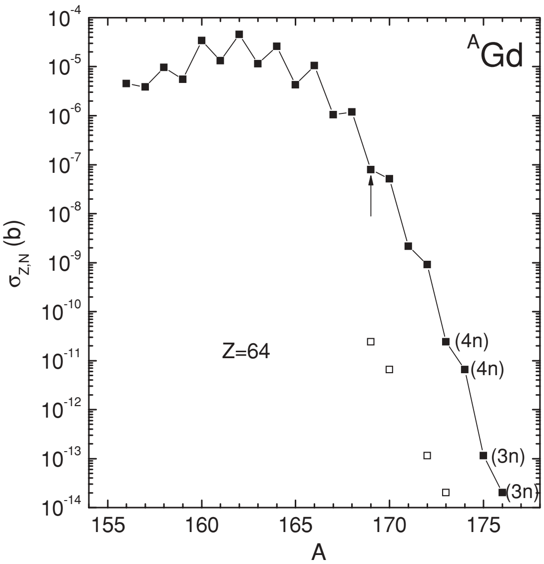

FIG. 9. The same as in Fig. 1, but for the Gd isotopes.

^{182,183}Tm, $^{185-187}$Yb, ^{188,189,191}Lu, ^{191,192}Hf, ^{195,196}Ta, ^{197}W, ^{200}Re, ^{202}Os, ^{204}Ir, ^{204,206}Pt, and ^{206,208}Au (Figs. 1–9), is produced with the cross sections in the interval between nanobarn and picobarn. The unknown neutron-rich isotopes of Hg can be produced in the reaction treated with the cross sections less than 1 pb. In this case the known heaviest isotope, ^{210}Hg, is far to the right side of the maximum of the calculated isotopic distribution (see Fig. 1).

In conclusion, the calculated results indicate that the multinucleon transfer reaction ^{48}Ca ($E_{\rm c.m.} = 189$ MeV) + ^{238}U provides a very efficient tool for producing new neutron-rich nuclei with $Z = 64$–79. One can propose such type of the experiment. Note that in this experiment one can study the odd-even effects that are clearly observed in Figs. 1–9. It is apparent that through the use of the heavier actinide target, for example, ^{244}Pu or ^{248}Cm, with a ^{48}Ca beam at energies near the Coulomb barrier one can reach a more neutron-rich region of nuclide. By irradiating the heavier actinide targets with the ^{48}Ca beam to produce neutron-rich isotopes, we gain in the Q value and the known heaviest isotopes are closer to the maxima of isotopic distributions.

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