Possibilities of production of new isotopes in transfer reactions

G.Adamian, N.Antonenko, Sh.Kalandarov  BLTP, JINR

V.Sargsyan  BLTP, JINR / Uni Giessen

Myeong-Hwan Mun, Youngman Kim  RISP, IBS

S.Lukyanov, Yu.Penionzhkevich  FLNR, JINR

S.Heinz  GSI
Production of new isotopes

- Fusion reactions, particular with radioactive beams.

- Fission of heavy nuclei.

- Multinucleon transfer reactions (V.V.Volkov et al.). The new neutron-rich nuclei in a wide region of the nuclear chart can be reached by multinucleon transfer reactions with radioactive ion beams at incident energies near the Coulomb barrier. $Q_{gg}$-systematic

- Quasifission reactions

- Fragmentation reactions.
The cross section of the production of a primary nucleus $(Z,N)$ in the diffusive nucleon transfer reaction is written as a sum over all partial waves $J$.

$$\sigma_{Z,N}(E_{\text{c.m.}}) = \sum_J \sigma_{Z,N}(E_{\text{c.m.}}, J),$$

$$\sigma_{Z,N}(E_{\text{c.m.}}, J) = \int_0^{\pi/2} \int_0^{\pi/2} d\cos\Theta_1 d\cos\Theta_2$$

$$\times \sigma_c(E_{\text{c.m.}}, J, \Theta_i) Y_{Z,N}(E_{\text{c.m.}}, J, \Theta_i).$$

The primary charge and mass yields of fragments can be expressed by the product of the formation probability $P_{Z,N}(t)$ of the DNS configuration with charge and mass asymmetries given by $Z$ and $N$ and of the decay probability of this configuration in $R$ represented by the rate $\Lambda_{Z,N}^{qf}$

$$Y_{Z,N} = \Lambda_{Z,N}^{qf} \int_0^{t_0} P_{Z,N}(t) dt.$$
\( t_0 \) is the time of reaction

\[
\sum_{Z,N} Y_{Z,N} \approx 0.98.
\]
\[
\frac{d}{dt} P_{Z,N}(t) = \Delta_{Z+1,N}^{(-,0)} P_{Z+1,N}(t) + \Delta_{Z-1,N}^{(+,0)} P_{Z-1,N}(t) \\
+ \Delta_{Z,N+1}^{(0,-)} P_{Z,N+1}(t) + \Delta_{Z,N-1}^{(0,+)} P_{Z,N-1}(t) \\
- \left( \Delta_{Z,N}^{(-,0)} + \Delta_{Z,N}^{(+,0)} + \Delta_{Z,N}^{(0,-)} + \Delta_{Z,N}^{(0,+)} \\
+ \Lambda_{Z,N}^{qf} + \Lambda_{Z,N}^{\text{fis}} \right) P_{Z,N}(t),
\]

\[
P_{Z,N}(0) = \delta_{Z,Z_i} \delta_{N,N_i} \quad \text{- initial condition}
\]

If the primary nucleus is excited, one should take into consideration its survival probability \(W_{\text{sur}}\) in the deexcitation process to obtain the evaporation residue cross section as follows

\[
\sigma_{Z,N-x}^{ER}(E_{\text{c.m.}}) = \sum_J \sigma_{Z,N}(E_{\text{c.m.}}, J) W_{\text{sur}}(E_{\text{c.m.}}, J, x),
\]
In the experiments
S. Heinz et al. EPJ A 38 (2008) 227;
   EPJ A 43 (2010) 181;
V. Comas et al. EPJ A 48 (2012) 48;
   EPJ A 38 (2013) 49;
S. Heinz et al. EPJ A 51 (2015) 140
the clear signatures were observed for the formation of long-living DNS which rotates by large angles.
$Z, N_i \quad N/Z - \text{equilibrium}$

$U(R, Z, N, J) = B_1 + B_2 + V(R, Z, N, J)$,

$B_1$ and $B_2$ are the mass excesses of the light and heavy nuclei, respectively. The nucleus-nucleus interaction potential $V$. 
The calc. (open circles) cross sections of S isotopes are compared with the exp. ones (solid circles) for the $^{40}$Ca + $^{208}$Pb reaction ($E_{c.m.} = 208.8$ MeV) [PRC 71, 044610 (2005)].
In the $^{58}\text{Ni}+^{208}\text{Pb}$ reaction, $^{50}\text{Ti}$ and $^{52}\text{Ti}$ are produced with the cross sections 1 and 0.2 mb, respectively, which are consistent with our calculated cross sections 0.6 and 0.35 mb, respectively. In the $^{64}\text{Ni}+^{238}\text{U}$ reaction the experimental and theoretical production cross sections for $^{52}\text{Ti}$ are 0.5 and 1.6 mb, respectively.

In the $^{48}\text{Ca}(E_{\text{c.m.}} = 274.6 \text{ MeV}) + ^{238}\text{U}$ reaction the experimental [S. Lunardi, *AIP Conference Proceedings* 1120, p. 70.] and calculated ratios of secondary yields $Y(^{62}\text{Fe})/Y(^{58}\text{Cr})$ for the neutron-rich $^{62}\text{Fe}$ and $^{58}\text{Cr}$ isotopes are about 0.2 and 0.3, respectively.
$^{48}\text{Ca} + ^{244}\text{Cm} \ △ \ E_{cm} = 207$ MeV

$^{48}\text{Ca} + ^{246}\text{Cm} \ ● \ E_{cm} = 205.5$ MeV

$^{48}\text{Ca} + ^{248}\text{Cm} \ ● \ E_{cm} = 204$ MeV

PRC 71 (2005) 034603
The possibilities for producing neutron-rich isotopes $^{52,54,56,58}\text{Ca}$ in the transfer reactions with rare-earth targets.

$E_{\text{c.m.}}$ provides the excitations of the isotopes equal to the corresponding threshold for the neutron emission.
$^{48}\text{Ca} + ^{238}\text{U}$ at $E_{\text{c.m.}} = 189$ MeV
The predicted cross sections of the production of neutron-rich isotopes $^{148,150,152}$Xe in the transfer reactions with the radioactive beam of $^{144}$Xe. The cross sections correspond to the maxima of $0n$ evaporation channels.

The expected maximal cross sections of the production of neutron-rich isotopes $^{202,204,206}$Pt in the $0n$ evaporation channels of the listed transfer reactions.
Possibilities of production of neutron-rich Md isotopes in multi-nucleon transfer reactions (suggested by Yu.Oganessian, G.Ter-Akopian, R.Wolski)
$^{48}$Ca$^{+}$ $^{244-248}$Cm at 5.625MeV/A

with $^{40}$Ca at $L_{\text{max}} = 20$

Th

$^{208}$Th with $^{40}$Ca at $L_{\text{max}} = 20$

$^{244-248}$Cm at 5.625MeV/A

Pa

L=80-100

with $^{40}$Ca at $L_{\text{max}} = 20$

L=80-100

exp. S.Heinz et al.
Summary

1) The production of neutron-rich nuclei in multinucleon transfer reactions is possible at incident energies close to the Coulomb barrier.

2) Multinucleon transfer reactions could be the only way to produce some unknown isotopes of actinides and transactinides.
Thank you.