Entrance-channel potentials in the synthesis of the heaviest nuclei

Vitali Yu. DENISOV[1,2] and Wolfgang Nörenberg[1,3]

[1]Gesellschaft für Schwerionenforschung, Darmstadt, Germany

[2]Institute for Nuclear Research, Kiev, Ukraine

[3]Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany

Plan

- Capture is the first decisive step for the fusion
- Definition of a semi-microscopic potential (SMP) in the entrance channel
- SMP for cold-fusion systems
- SMP for hot-fusion systems
- SMP for warm-fusion systems
- Conclusion

Definition of a semi-microscopic potential (SMP) in the entrance channel

The interaction potential $V(R,\vartheta)$

$$V(R,\vartheta) = E_{12}(R,\vartheta) - E_1 - E_2.$$

In the frozen-density approximation these binding energies are determinated by the energy density functional $\mathcal{E}[\rho_p(\mathbf{r}),\rho_n(\mathbf{r})]$, i.e.

$$E_{12}(R,\vartheta) = \int \mathcal{E}[\rho_{1p}(\mathbf{r}) + \rho_{2p}(R,\vartheta,\mathbf{r}), \rho_{1n}(\mathbf{r}) + \rho_{2n}(R,\vartheta,\mathbf{r})]\, d\mathbf{r},$$

$$E_1 = \int \mathcal{E}[\rho_{1p}(\mathbf{r}),\rho_{1n}(\mathbf{r})]\, d\mathbf{r},$$

$$E_2 = \int \mathcal{E}[\rho_{2p}(\mathbf{r}),\rho_{2n}(\mathbf{r})]\, d\mathbf{r},$$

where ρ_{1p}, ρ_{2p}, ρ_{1n} and ρ_{2n} are the frozen proton and neutron densities of the spherical nucleus (index 1) and the deformed nucleus (index 2), respectively.

Energy-density functional:

$$\mathcal{E}[\rho_p(\mathbf{r}),\rho_n(\mathbf{r})] = \frac{\hbar^2}{2m}[\tau_p(\mathbf{r}) + \tau_n(\mathbf{r})] + \mathcal{V}_{\mathrm{Skyrme}}(\mathbf{r}) + \mathcal{V}_{\mathrm{Coul}}(\mathbf{r}).$$

$\rho_{1p}(\mathbf{r}), \rho_{2p}(R,\vartheta,\mathbf{r}), \rho_{1n}(\mathbf{r}), \rho_{2n}(R,\vartheta,\mathbf{r}) \;\Rightarrow$ Hartree-Fock-Bogoliubov (HFB) with Skyrme forces.

The kinetic parts for the protons ($i = p$) and neutrons ($i = n$)

$$\tau_i(\mathbf{r}) = \frac{3}{5}(3\pi^2)^{2/3}\rho_i^{5/3} + \frac{1}{36}\frac{(\nabla\rho_i)^2}{\rho_i} + \frac{1}{3}\Delta\rho_i$$
$$+\frac{1}{6}\frac{\nabla\rho_i\nabla f_i + \rho_i\Delta f_i}{f_i} - \frac{1}{12}\rho_i\left(\frac{\nabla f_i}{f_i}\right)^2$$
$$+\frac{1}{2}\rho_i\left(\frac{2m}{\hbar^2}\frac{W_0}{2}\frac{\nabla(\rho+\rho_i)}{f_i}\right)^2,$$

where W_0 - the strength of the Skyrme spin-orbit interaction, $\rho = \rho_p + \rho_n$,

$$f_i(\mathbf{r}) = 1 + \frac{2m}{\hbar^2}\left(\frac{3t_1 + 5t_2}{16} + \frac{t_2 x_2}{4}\right)\rho_i(\mathbf{r}).$$

The potential part $\mathcal{V}_{\text{sk}}$, Skyrme interaction,

$$\mathcal{V}_{\text{Skyrme}}(\mathbf{r}) = \frac{t_0}{2}[(1+\frac{1}{2}x_0)\rho^2 - (x_0 + \frac{1}{2})(\rho_p^2 + \rho_n^2)]$$
$$+\frac{1}{12}t_3\rho^\alpha[(1+\frac{1}{2}x_3)\rho^2 - (x_3 + \frac{1}{2})(\rho_p^2 + \rho_n^2)]$$
$$+\frac{1}{4}[t_1(1+\frac{1}{2}x_1) + t_2(1+\frac{1}{2}x_2)]\tau\rho$$
$$+\frac{1}{4}[t_2(x_2+\frac{1}{2}) - t_1(x_1+\frac{1}{2})](\tau_p\rho_p + \tau_n\rho_n)$$
$$+\frac{1}{16}[3t_1(1+\frac{1}{2}x_1) - t_2(1+\frac{1}{2}x_2)](\nabla\rho)^2$$
$$-\frac{1}{16}[3t_1(x_1+\frac{1}{2}) + t_2(x_2+\frac{1}{2})]((\nabla\rho_n)^2 + (\nabla\rho_p)^2)$$
$$-\frac{W_0^2}{4}\frac{2m}{\hbar^2}\left[\frac{\rho_p}{f_p}(2\nabla\rho_p + \nabla\rho_n)^2 + \frac{\rho_n}{f_n}(2\nabla\rho_n + \nabla\rho_p)^2\right],$$

where t_0, t_1, t_2, x_0, x_1, x_2, α and W_0 are Skyrme force parameters.

The Coulomb energy density

$$\mathcal{V}_{\text{Coul}}(\mathbf{r}) = \frac{e^2}{2}\rho_p(\mathbf{r})\int\frac{\rho_p(\mathbf{r}\prime)}{|\mathbf{r}-\mathbf{r}\prime|}d\mathbf{r}\prime - \frac{3e^2}{4}\left(\frac{3}{\pi}\right)^{1/3}(\rho_p(\mathbf{r}))^{4/3}.$$

Entrance channel dynamics

The nuclear interaction time $\tau_{\rm coll}$ (collision time)

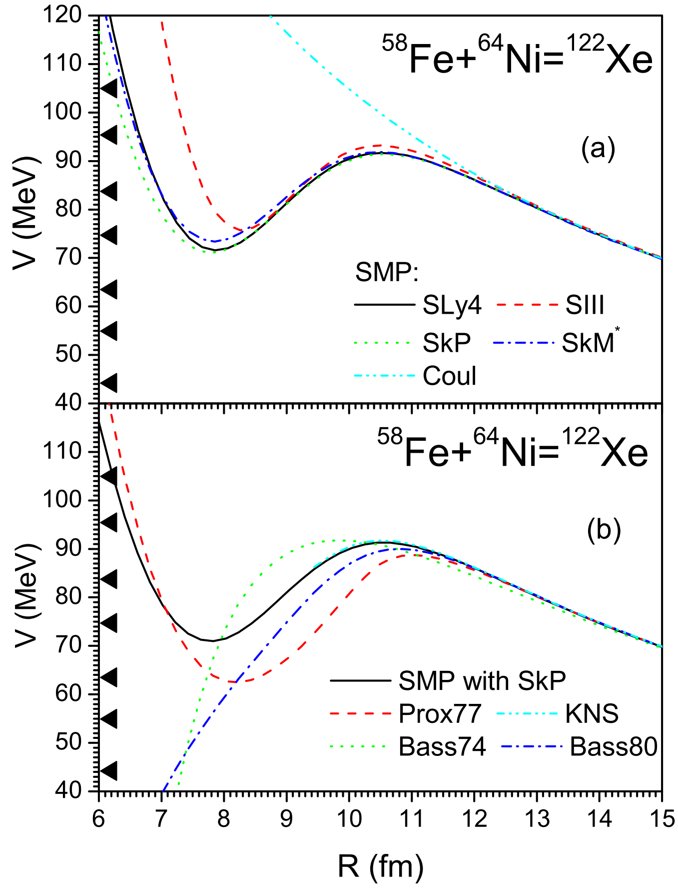
$$\tau_{\rm coll} \approx \frac{\pi}{\omega_{\rm pocket}} = \pi \left[\frac{mA_1A_2}{(A_1+A_2)V''(R_{\rm pocket})}\right]^{1/2} \approx 3\cdot 10^{-22}{\rm s}.$$

The relaxation of the intrinsic nuclear state due to nucleon-nucleon interactions $\tau_{\rm relax}$ (G.F. Bertsch)

$$\tau_{\rm relax} \approx \frac{\epsilon_F}{3.2\sigma v_F \rho_0 E^*} \approx \frac{2\cdot 10^{-22}}{E^*}{\rm s} \approx 3\cdot 10^{-21}{\rm s}.$$

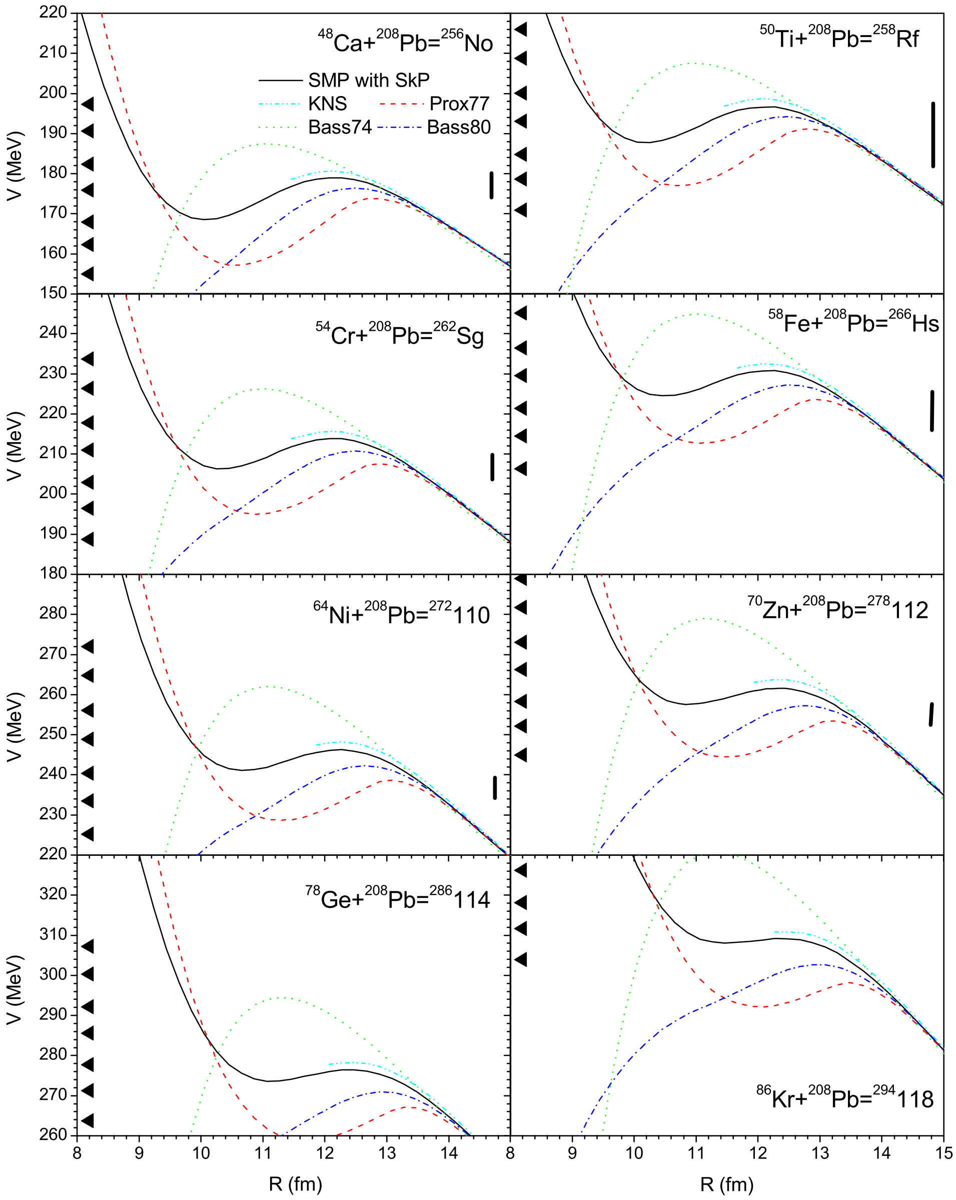
$$\tau_{\rm relax} >> \tau_{\rm coll}.$$

Conclusion: Frozen-densities of nucleons in nuclei can be applied for the evaluation of the nucleus-nucleus potential.



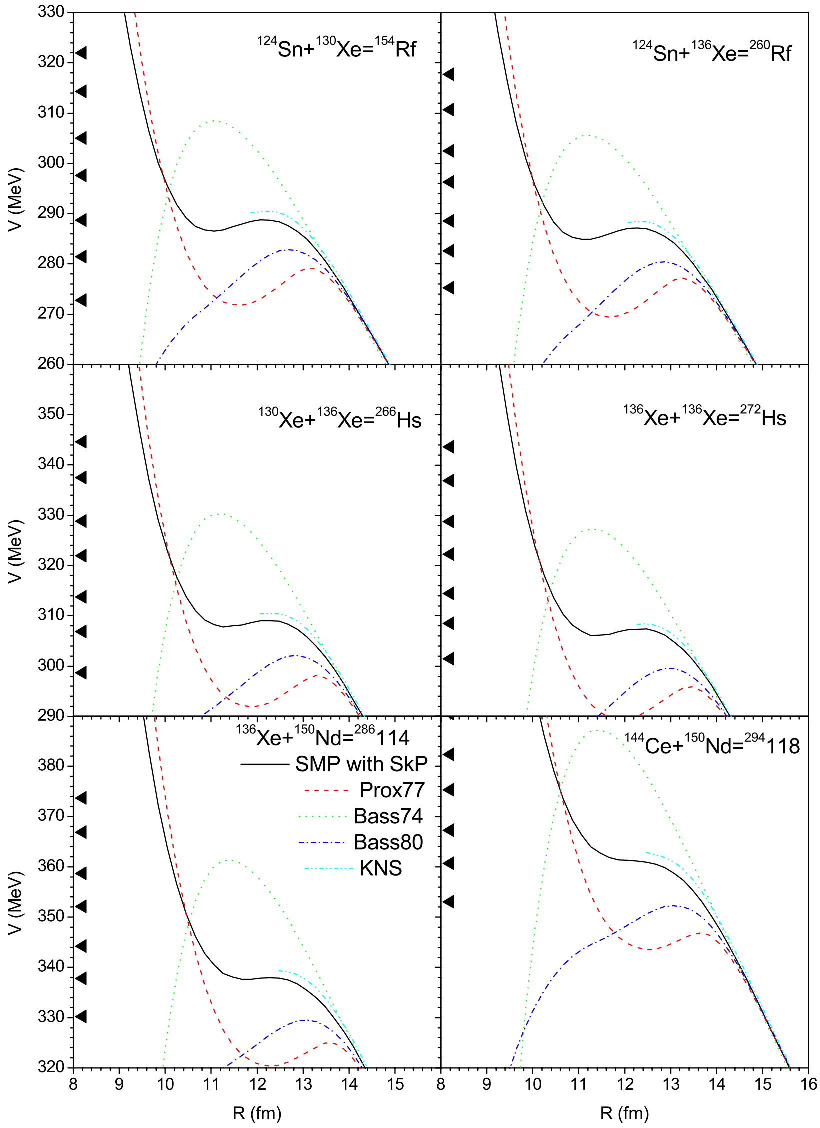
Main features of SMP in light systems:

- Deep pocket inside the barrier
- Light ions easily fuse after tunneling through or passing over the barrier
- The barrier height and the potential pocket are well above the ground-state energy
- The potential surface exhibits large gradients in the fusion direction driving the system into the compound-nucleus shape
- The barriers obtained with the help Bass-74, Bass-80, Proximity-77 and Krappe-Nix-Sierk (KNS) potentials are spread over a wide interval



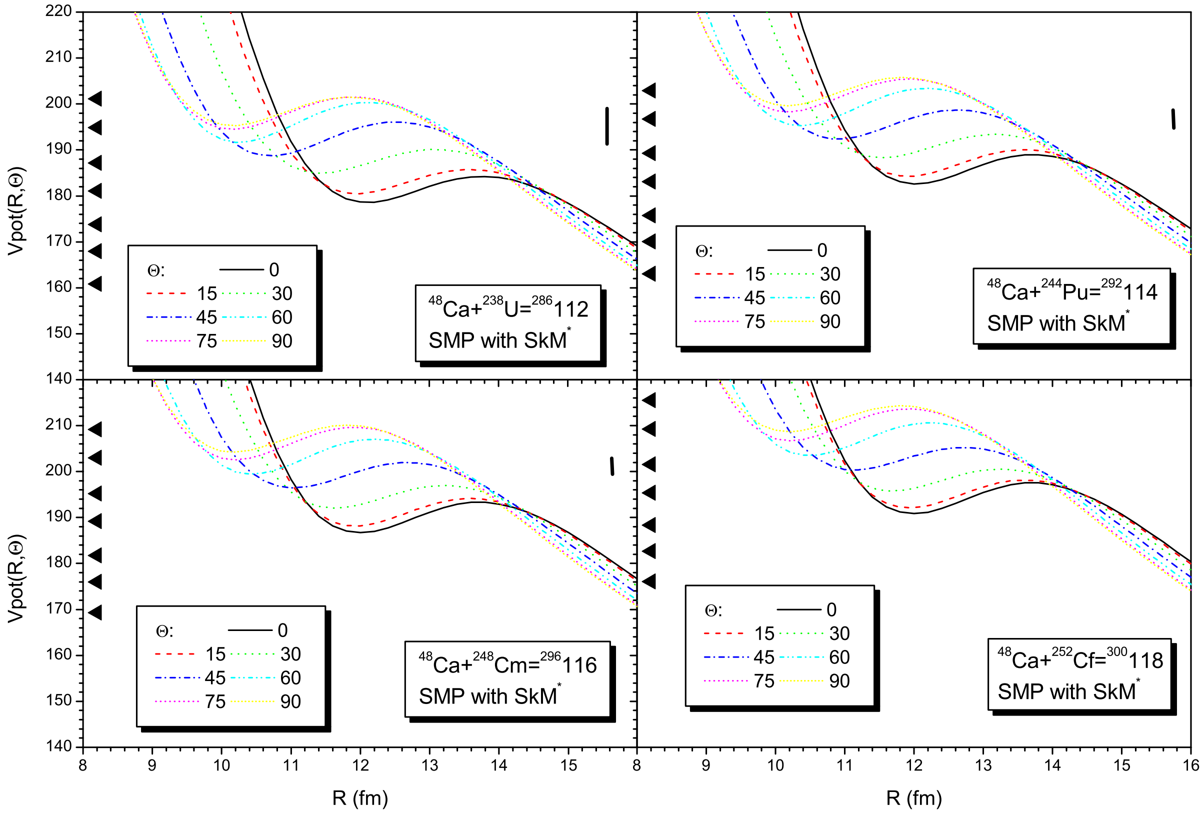
- The Bass-74, -80, Prox-77 and KNS interaction potentials are spread over even larger intervals for heavier systems as compared to light system
- The potential pockets are much shallower than for lighter systems and tend to vanish with increasing size of the projectile
- We attribute the observed reduction of the SHE formation with increasing size of the projectile, at least partially, to decreasing pocket depth
- The observed fusion windows lie about 5 to 10 MeV below SMP barriers.
- There is a correlation between the width of fusion window and the depth of potential pocket (cases ^{50}Ti+^{208}Pb, ^{58}Fe+^{208}Pb and ^{64}Ni+^{208}Pb)

- The difference between the barrier position and the ground-state Q-value for fusion decreases with increasing charge of the projectile



Symmetric systems

- The capture process is suppressed by the shallowness of the potential pocket
- The shape of the system at capture is less compact, and hence a longer shape evolution is needed to reach the compound-nucleus shape.
  $\Rightarrow$ the formation probability of compound nucleus is reduced due to the larger competition of other decays



Large distances between spherical and prolate nuclei $\Rightarrow \vartheta = 90°$ due to the Coulomb interaction ($\vartheta = 90°$ $\Leftrightarrow$ side position)

The time for the rotating the deformed nucleus by 90°

$$\tau_{\rm rot} \approx \frac{\pi}{2\omega_{\rm rot}} = 2 \cdot 10^{-20}\ \mathrm{s},$$

where $\hbar\omega_{\rm rot} \approx 50$ keV. Typical collision times on the approaching part of the Coulomb trajectory are order $2 \cdot 10^{-21}$ s.

- Strong orientation effect on the barrier and pocket, strongly deformed plolate target
- High excitation energy of compound nucleus
- Fusion relates with side orientation ($\vartheta \approx 90°$)
- Fusion suppressed for tip position ($\vartheta \approx 0°$)
- The height of the barrier reduces with increasing neutron number

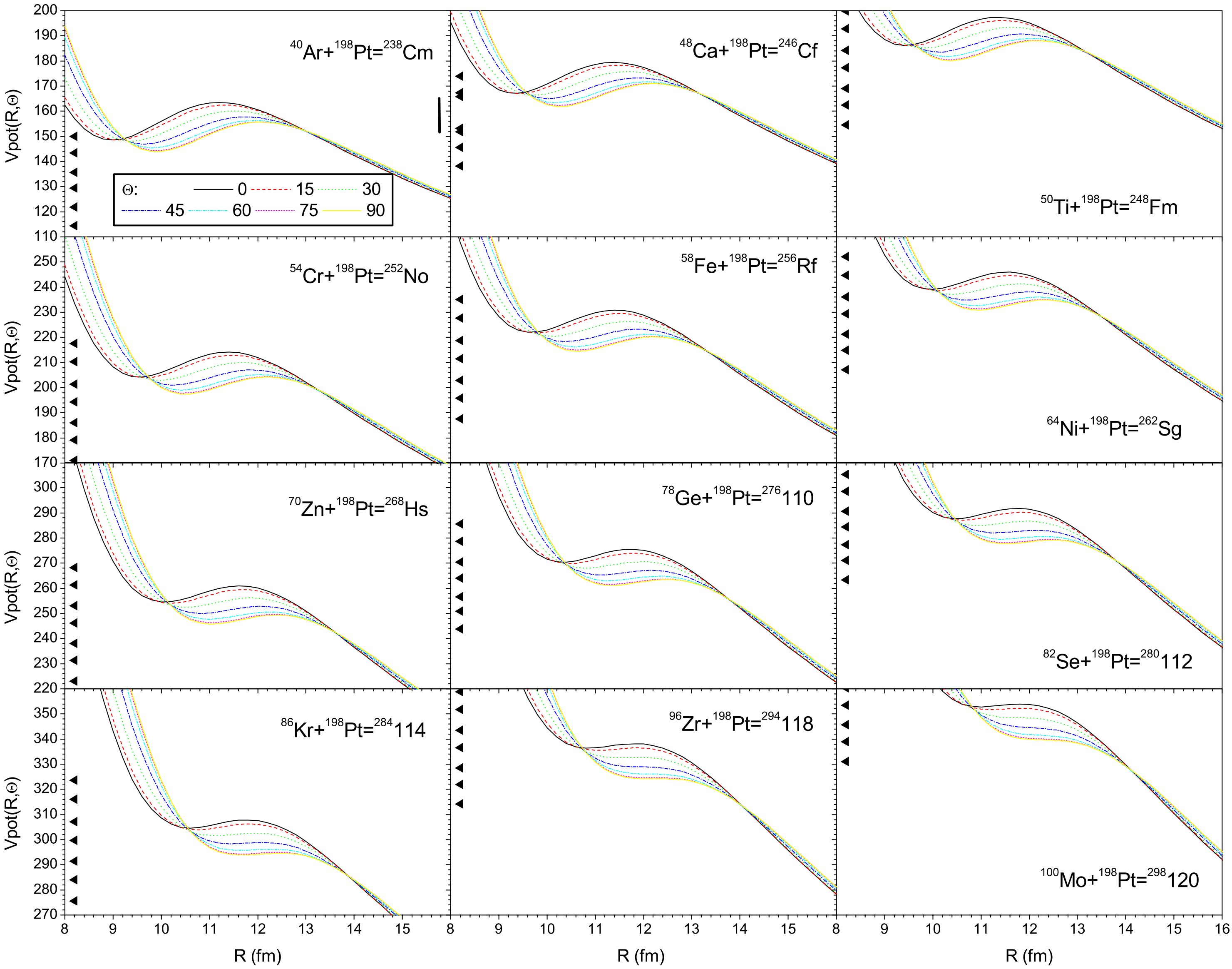
Warm-fusion systems

^{198}Pt - oblate -$\beta_2 = -0.10$

Recent GSI experiment: ^{40}Ar,^{50}Ti+^{198}Pt.

The cross sections for reaction ^{50}Ti+^{198}Pt is comparable with the one for cold-fusion reaction ^{40}Ar+^{208}Pb.

Large distances between spherical and oblate nuclei $\Rightarrow \vartheta = 0°$ due to the Coulomb interaction ($\vartheta = 0° \Leftrightarrow$ 'tip' position)



Conclusion

Rules for the determination of the best candidates for the synthesis of SHEs

- The SMP barrier should lie about 5 to 15 MeV above the 1n fusion threshold, but not above the 2n fusion threshold to avoid the reduction of the fusion cross-section by an additional factor Γ_n/Γ_f
- The deeper the pocket $\Rightarrow$ the larger the capture window $\Rightarrow$ better the chance of synthesis
- It is best to have a most compact capture configuration

The synthesis of 118 with **hot-**, **cold-** and **warm-**fusion systems

- The cold-fusion system ^{86}Kr+^{208}Pb has its capture window below the 1n-fusion channel and shallow pocket, and hence is not expected to be a good candidate
- The symmetric system ^{144}Ce+^{150}Nd has no pocket and hence no capture window at all
- The hot-fusion system ^{48}Ca+^{252}Cf has nice capture properties, however needs to emit about 3 to 4 neutrons, which reduce the survival probability by several orders due to factor $\Gamma_n/\Gamma_f << 1$
- The hot-fusion system ^{40}Ca+^{252}Cf has less attractive capture properties (as compared to the ^{48}Ca case) and needs to emit even 5 to 6 neutrons
- The system ^{58}Fe+^{238}U has only a tiny pocket and needs to emit about 3-4 neutrons
- the warm-fusion system ^{96}Zr+^{198}Pt has also a tiny tip-positioned pocket but needs to emit only 1n

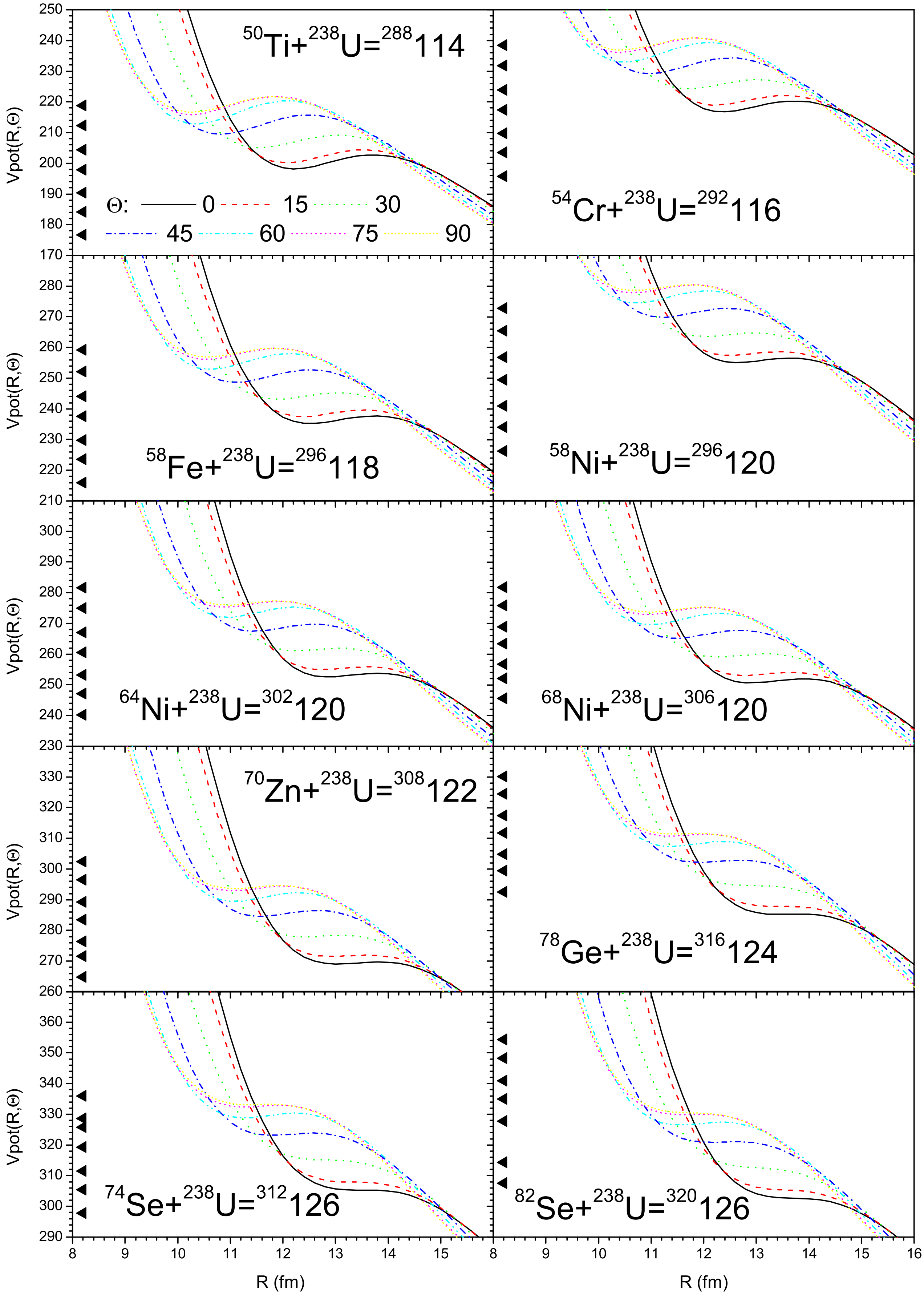
The most attractive projectile-target are:

$$^{48}\mathrm{Ca}+^{252}\mathrm{Cf} \text{ at } E_{\mathrm{coll}} \approx 206 \text{ MeV}$$

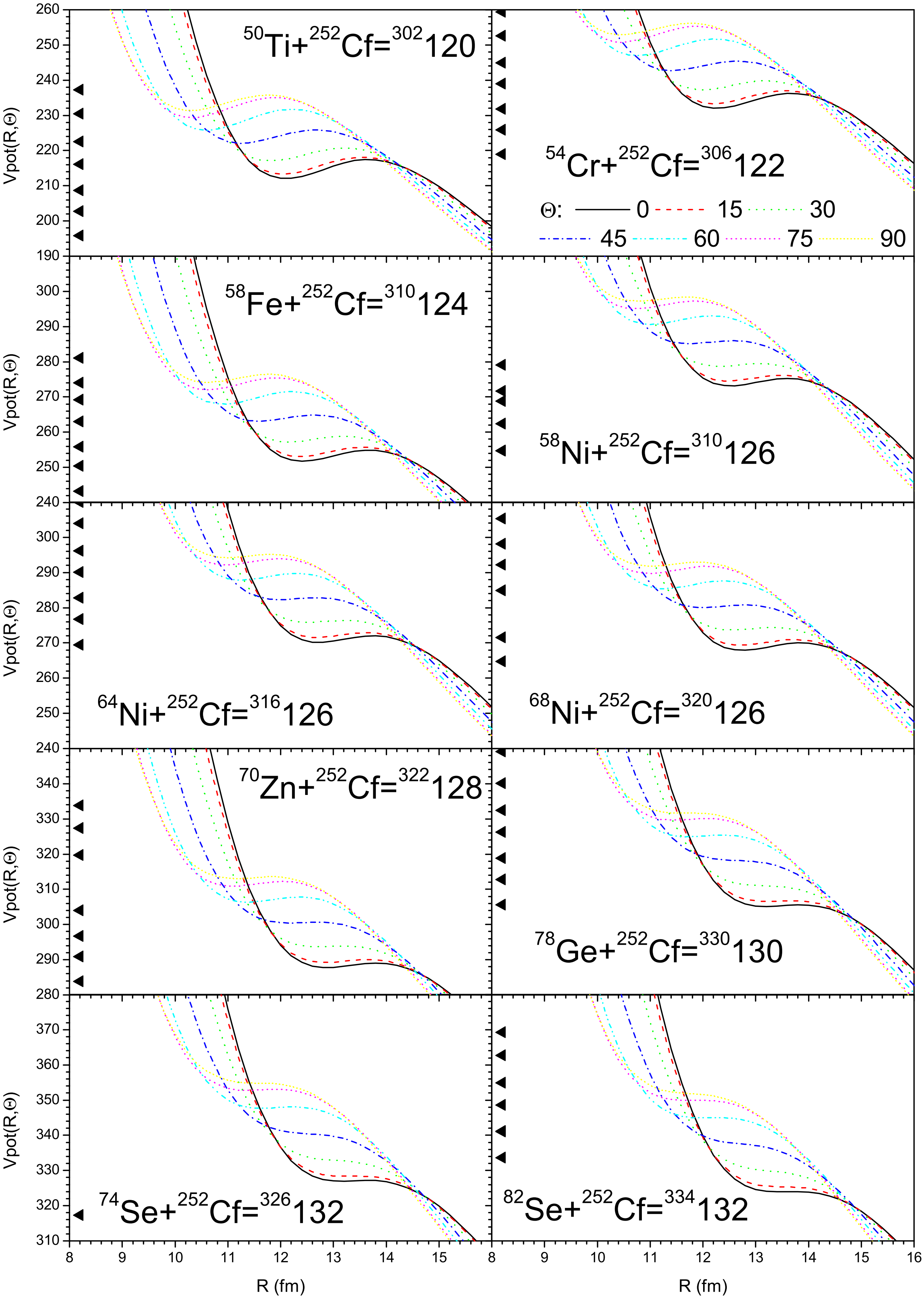
$$^{96}\mathrm{Zr}+^{198}\mathrm{Pt} \text{ at } E_{\mathrm{coll}} \approx 330 \text{ MeV}.$$

While ^{48}Ca+^{252}Cf is more compact, ^{96}Zr+^{198}Pt needs to emit only 1 neutron.

It is hard to judge which of these features are more important



$^{50}Ti+^{238}U=^{288}114$
$^{54}Cr+^{238}U=^{292}116$
$^{58}Fe+^{238}U=^{296}118$
$^{58}Ni+^{238}U=^{296}120$
$^{64}Ni+^{238}U=^{302}120$
$^{68}Ni+^{238}U=^{306}120$
$^{70}Zn+^{238}U=^{308}122$
$^{78}Ge+^{238}U=^{316}124$
$^{74}Se+^{238}U=^{312}126$
$^{82}Se+^{238}U=^{320}126$
Θ: 0 15 30 45 60 75 90
Vpot(R,Θ)
R (fm)



$^{50}Ti+^{252}Cf=^{302}120$
$^{54}Cr+^{252}Cf=^{306}122$
Θ: 0 15 30 45 60 75 90
$^{58}Fe+^{252}Cf=^{310}124$
$^{58}Ni+^{252}Cf=^{310}126$
$^{64}Ni+^{252}Cf=^{316}126$
$^{68}Ni+^{252}Cf=^{320}126$
$^{70}Zn+^{252}Cf=^{322}128$
$^{78}Ge+^{252}Cf=^{330}130$
$^{74}Se+^{252}Cf=^{326}132$
$^{82}Se+^{252}Cf=^{334}132$
Vpot(R,Θ)
R (fm)