UNIVERSITY OF SURREY

Superheavy Dynamics with Time-Dependent Hartree-Fock

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Overview

- Would like to learn about reactions involving ^{254}Es
- Use techniques based on Static and Time-Dependent Hartree-Fock
- & Skyrme forces
- For recent work:
- How assumed force affects heavy-ion reactions:
  - P. D. Stevenson & M. C. Barton, Prog. Part. Nucl. Phys. **104**, 142 (2019)
- Friction effects in fusion:
  - Kai Wen, M. C. Barton, Arnau Rios Huguet, and P. D. Stevenson, *Phys. Rev.* **C 98**, 014603 (2018)
- Effect of symmetry energy & other nuclear matter properties on fusion:
  - P.-G. Reinhard, A. S. Umar, P. D. Stevenson, J. Piekarewicz, J. A. Maruhn, and V. E. Oberacker, *Phys. Rev.* **C 93**, 044618 (2016)
- Fission from TDHF point of view
  - P. M. Goddard, P. D. Stevenson and A. Rios, Phys. Rev. C **92**, 054610 (2015)

Input: Skyrme-type density functional

$$\mathcal{E}_{\text{Skyrme}} = \int d^3r \sum_{t=0,1} \Big\{ C_t^\rho[\rho_0]\,\rho_t^2 + C_t^s[\rho_0]\,\mathbf{s}_t^2 + C_t^{\Delta\rho}\rho_t\Delta\rho_t + C_t^\tau(\rho_t\tau_t - \mathbf{j}_t^2)$$
$$+C_t^T\left[\mathbf{s}_t\cdot\mathbf{T}_t - \tfrac{1}{3}(J^{(0)})^2 - \tfrac{1}{2}(J^{(1)})^2 - (J^{(2)})^2\right] + C_t^{\Delta s}\mathbf{s}_t\cdot\Delta\mathbf{s}_t$$
$$+C_t^F\left[\mathbf{s}_t\cdot\mathbf{F}_t - \tfrac{2}{3}(J^{(0)})^2 + \tfrac{1}{4}(J^{(1)})^2 - \tfrac{1}{2}(J^{(2)})^2\right] + C_t^{\nabla s}(\nabla\cdot\mathbf{s}_t)^2$$
$$+C_t^{\nabla\cdot J}(\rho_t\nabla\cdot\mathbf{J}_t + \mathbf{s}_t\cdot\nabla\times\mathbf{j}_t)\Big\}$$

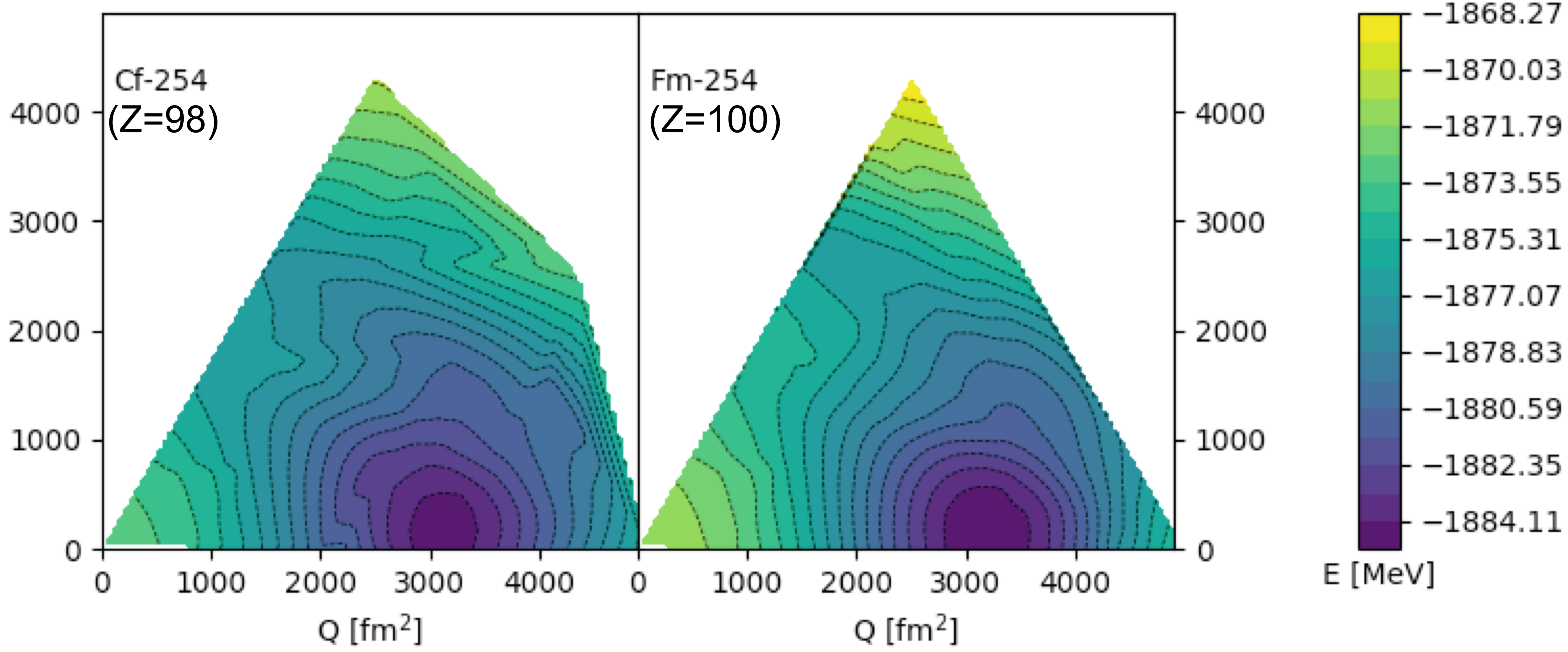
The C coefficients are our unknown force coefficients. Can derive from Skyrme parameters or fit directly

$$\rho(\boldsymbol{r},\boldsymbol{r}') = \sum_{\sigma,q}\rho_q(\boldsymbol{r}\sigma,\boldsymbol{r}'\sigma) = \sum_{i,\sigma,q}\phi_i^*(\boldsymbol{r}',\sigma,q)\phi_i(\boldsymbol{r},\sigma,q),$$
$$\boldsymbol{S}(\boldsymbol{r},\boldsymbol{r}') = \sum_{\sigma,\sigma',q}\rho_q(\boldsymbol{r}\sigma,\boldsymbol{r}'\sigma')\langle\sigma'|\hat{\boldsymbol{\sigma}}|\sigma\rangle = \sum_{i,\sigma,\sigma',q}\phi_i^*(\boldsymbol{r}',\sigma',q)\hat{\boldsymbol{\sigma}}\phi_i(\boldsymbol{r},\sigma,q),$$

All other coloured symbols are derivatives of these two densities

Ground state properties around ^{254}Es

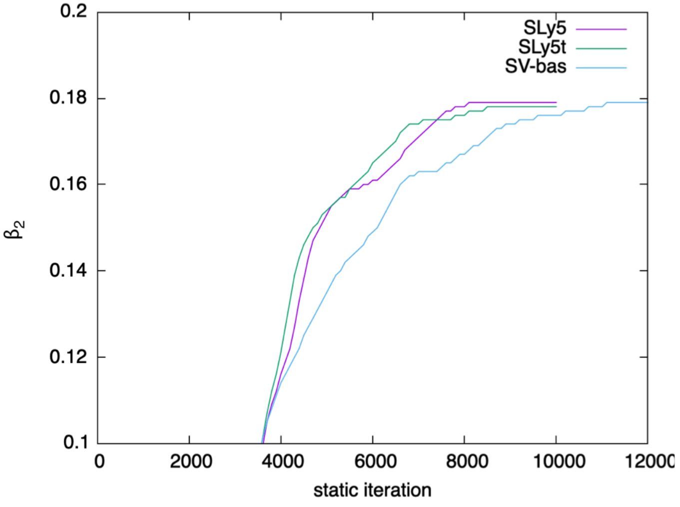
Constrained HF+BCS Calculation with SLy4 interaction. Using ev8 code from W. Ryssens et al. Comp. Phys. Commun. **187**, 175 (2015)



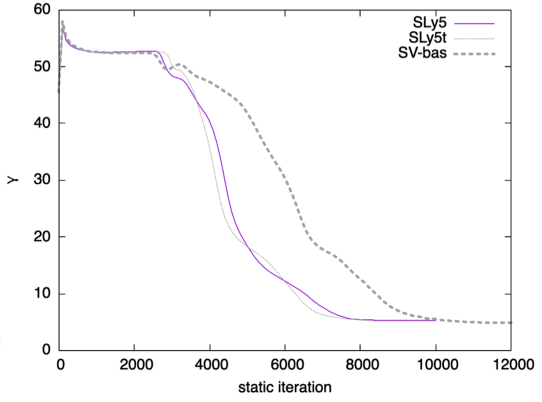
β_{20}=0.279
γ= 3.2º

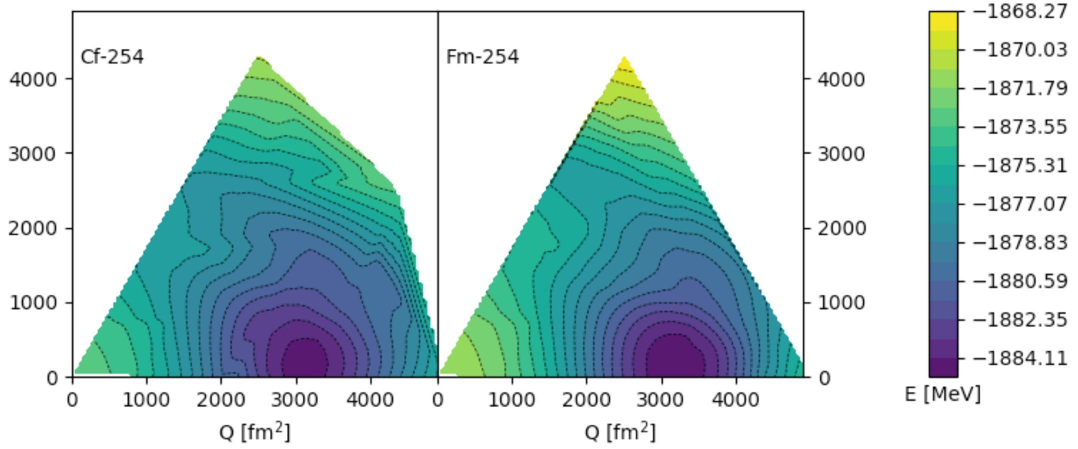
Ground states of odd-odd ^{254}Es

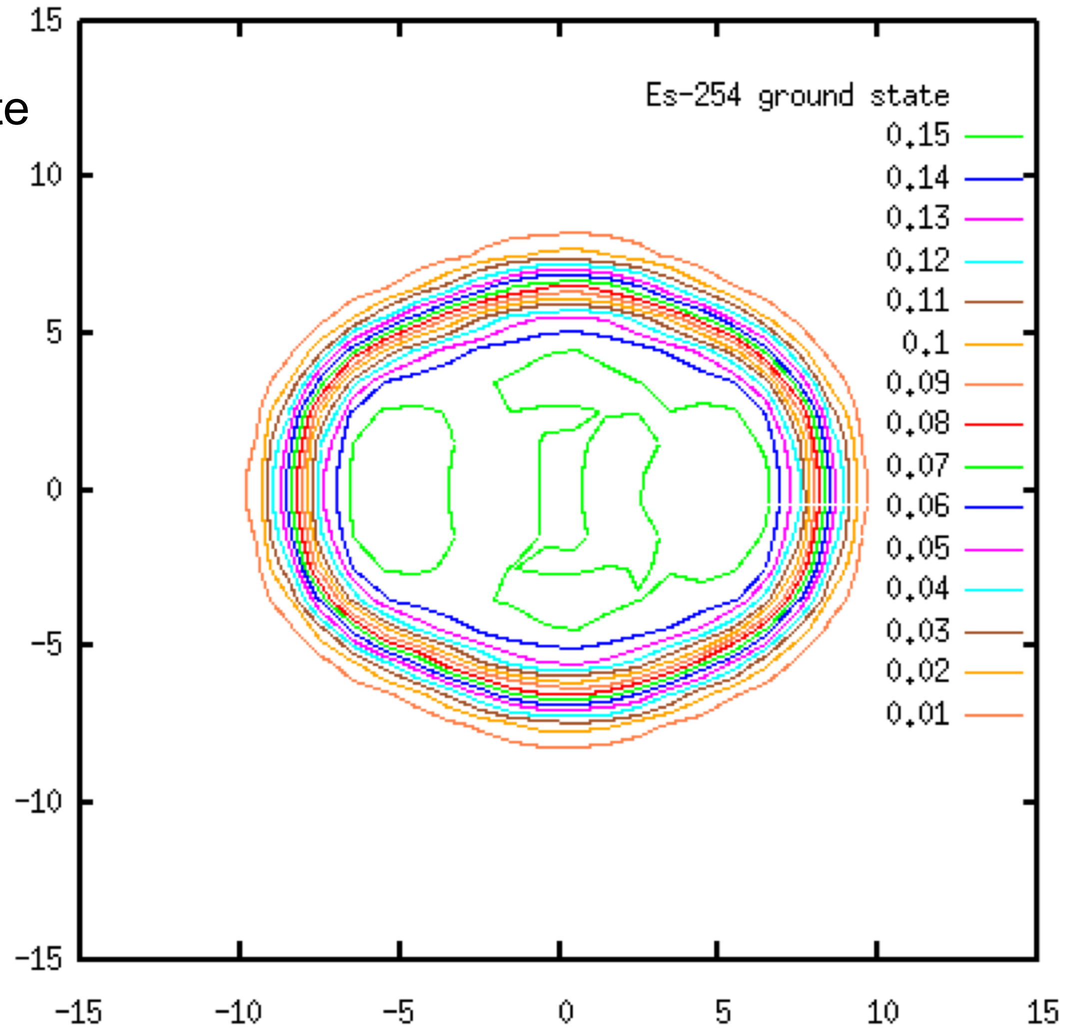
Weakly triaxial; reasonably rigid deformation



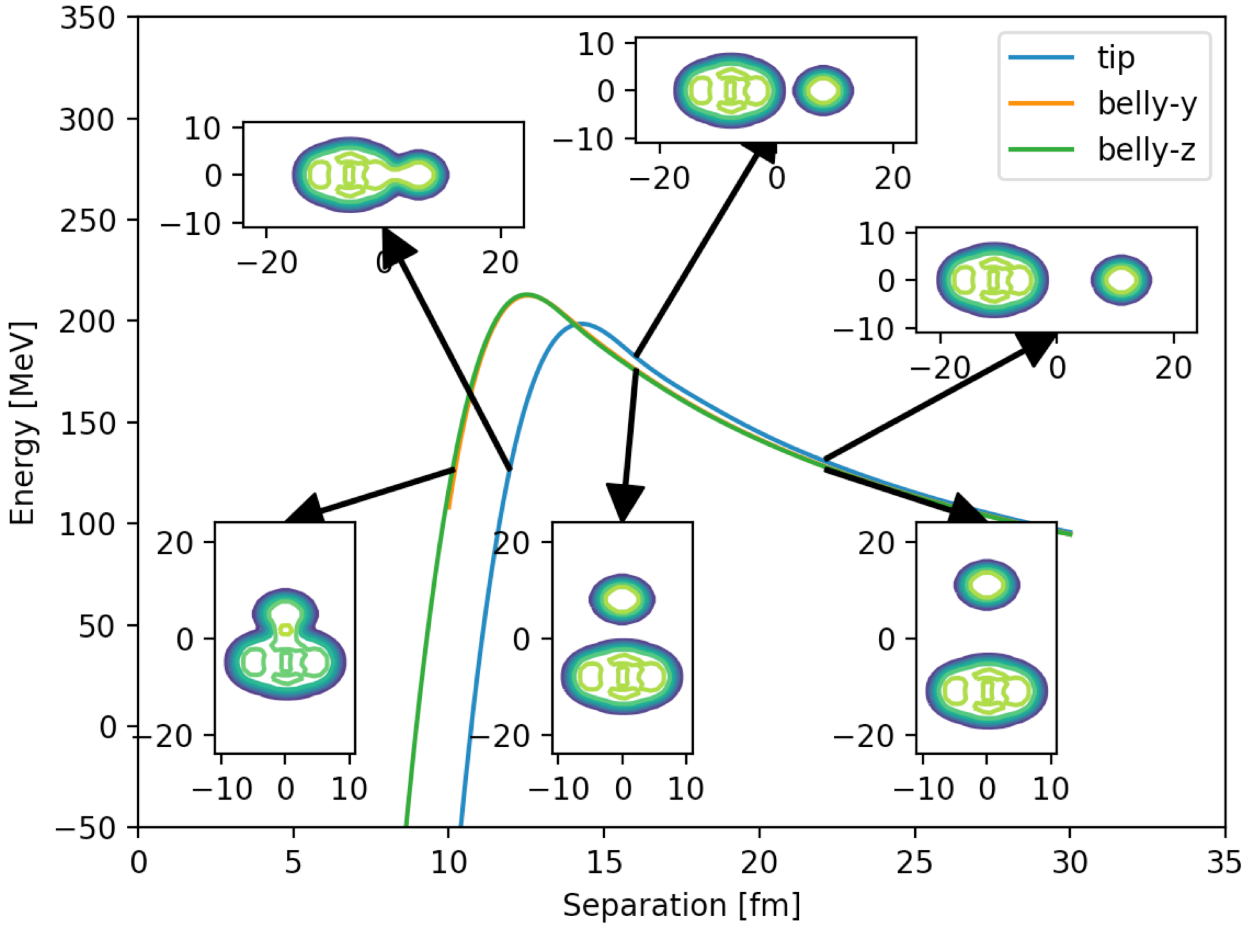
Odd-mass ^{254}Es ground state
With SLy5 + tensor terms







Frozen Hartree Fock Calculation of potential



^{254}Es + ^{48}Ca

$$V_{FHF}(\hat{\mathbf{R}}) = \int d\mathbf{r} \;\; \mathcal{H}[\rho_1(\mathbf{r}) + \rho_2(\mathbf{r} - \hat{\mathbf{R}})] - E[\rho_1] - E[\rho_2] \; ,$$

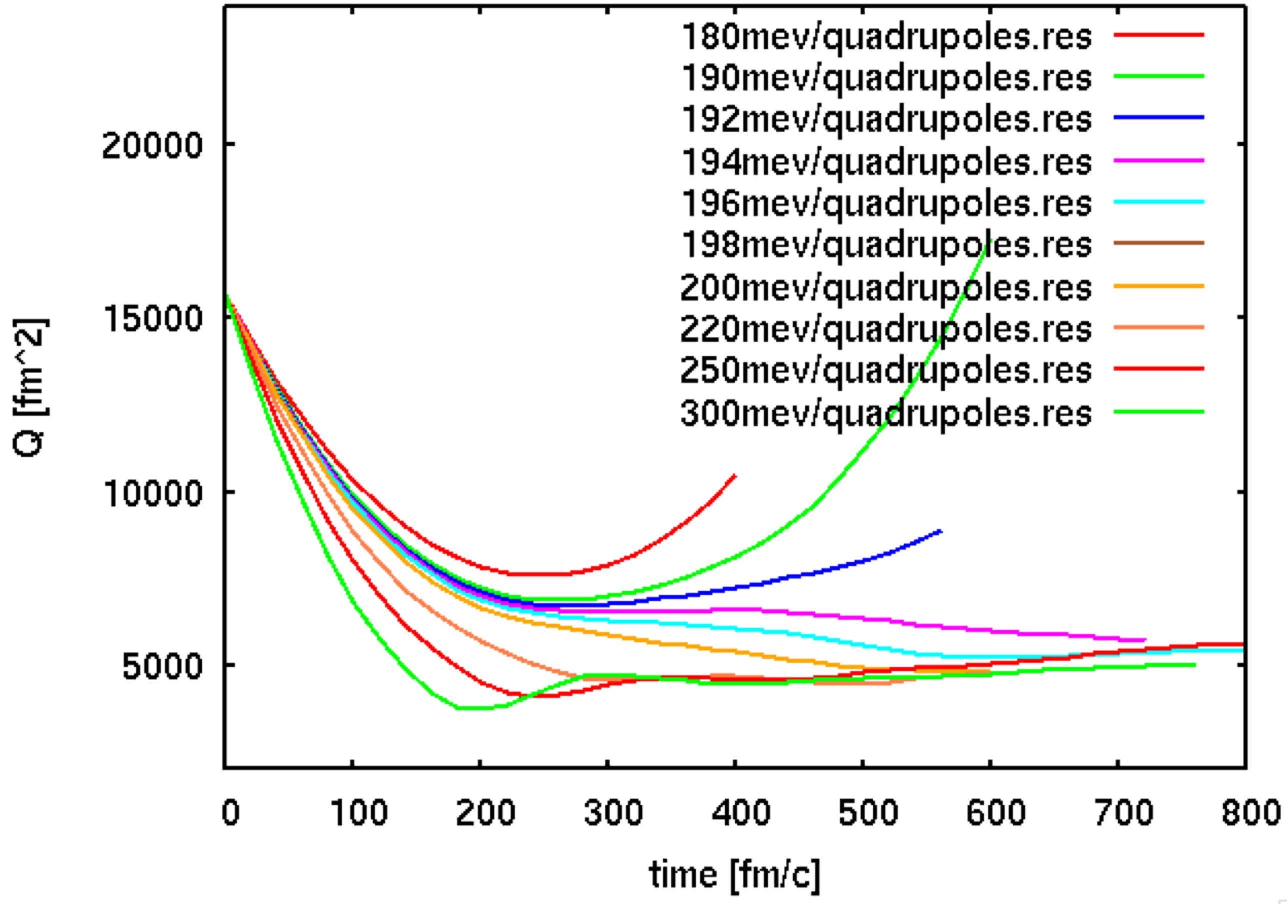
See review by C. Simenel and A. S. Umar, Prog. Part. Nucl. Phys. **103**, 19 (2019)

From Frozen HF
Barrier in tip direction: 198.6 MeV
Barrier in belly direction: 213.0 MeV

Potential curves interpolated with cubic b-splines

Barrier from TDHF

Tip configuration

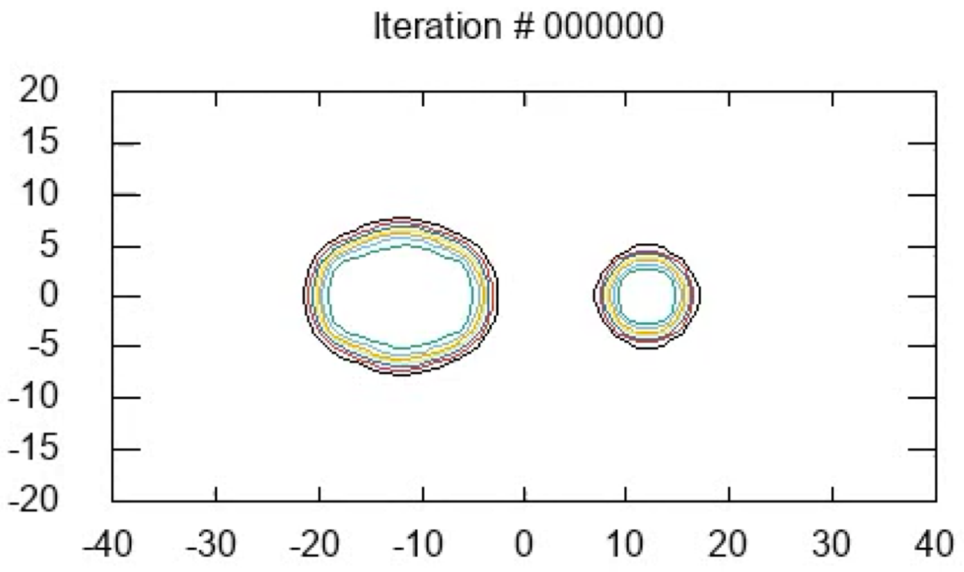


TDHF dynamical changes in densities upon approach give lower barrier:

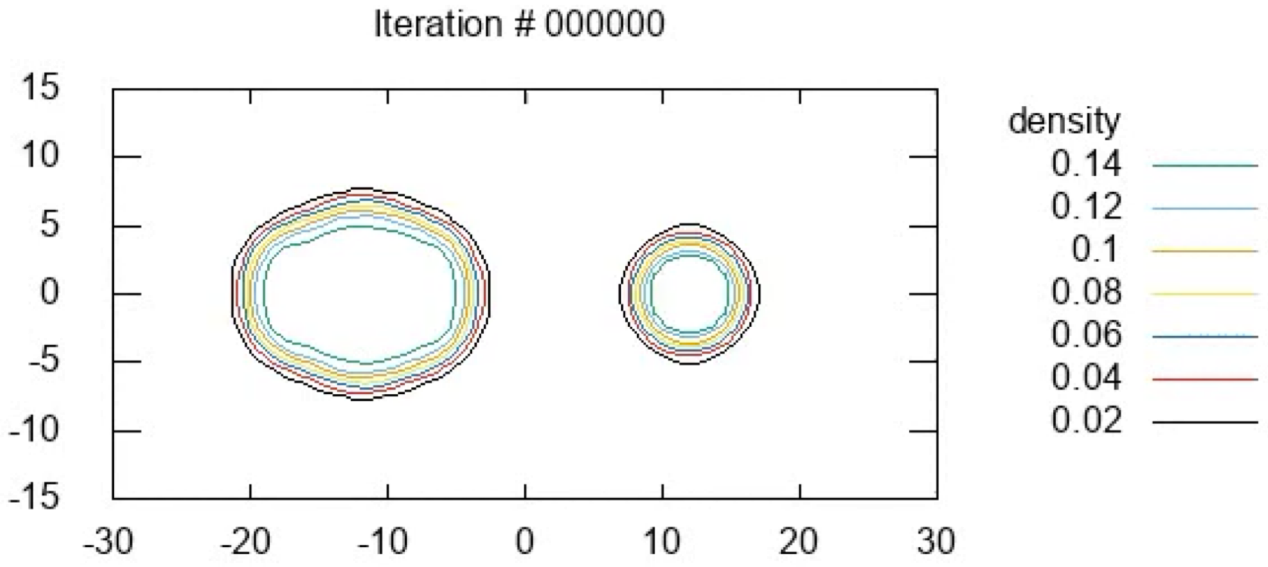
Tip configuration barrier @ 193±1 MeV (cf 199 MeV FHF)

Belly configuration not much lowered (<2 MeV)

^{254}Es + ^{48}Ca tip configuration



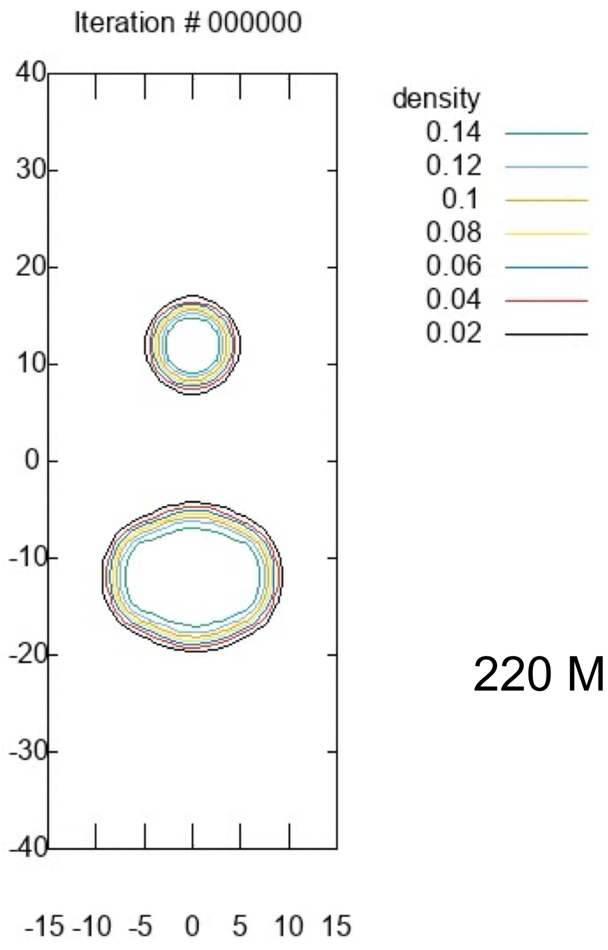
196 MeV CM energy



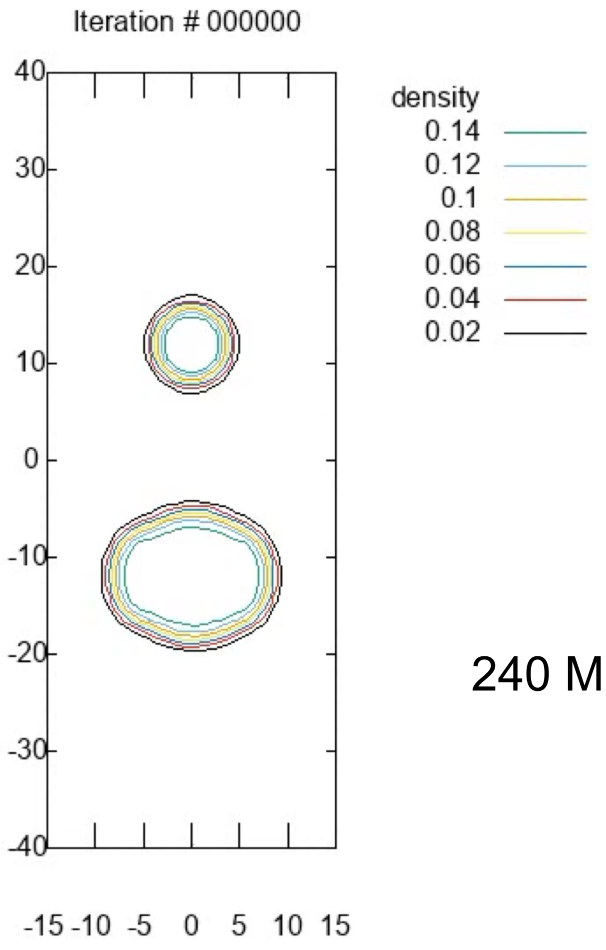
300 MeV CM energy

X<-4.5: Z=79 (Au), N=124
X>-4.5: Z=40 (Zr), N= 60
Tmax = 16000 iter = 3200 fm/c = 1 x 10^{-21} s = 1 zs

Belly Configuration



220 MeV CM

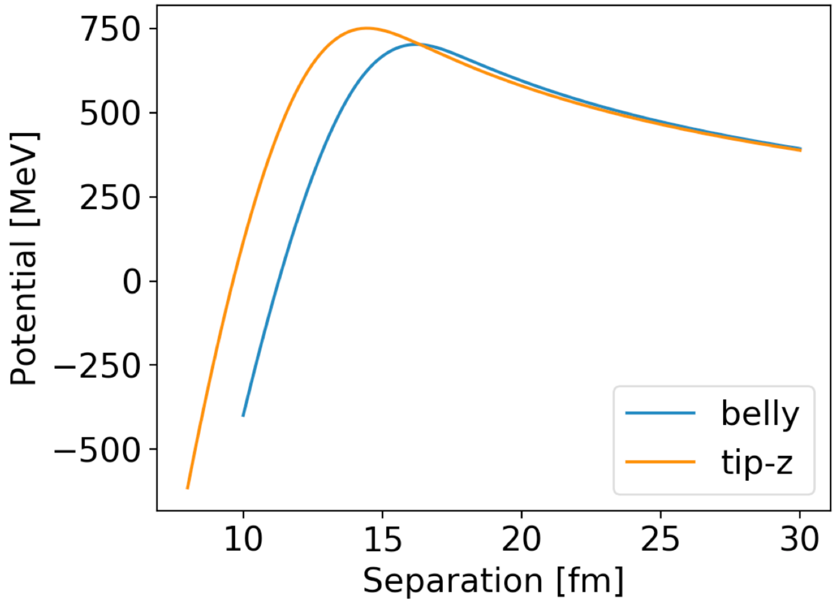


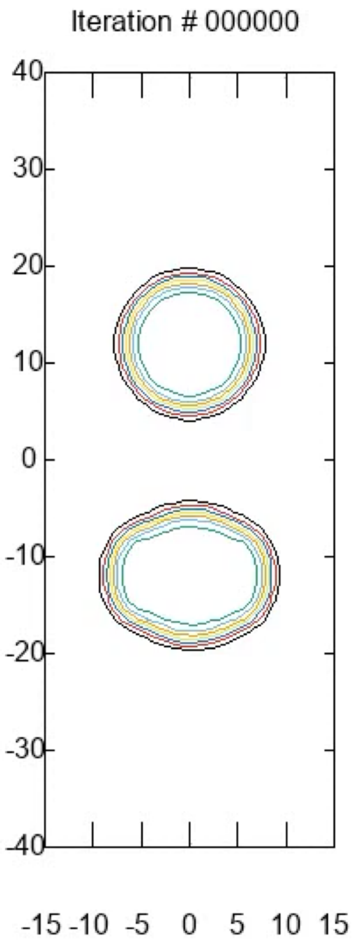
240 MeV CM

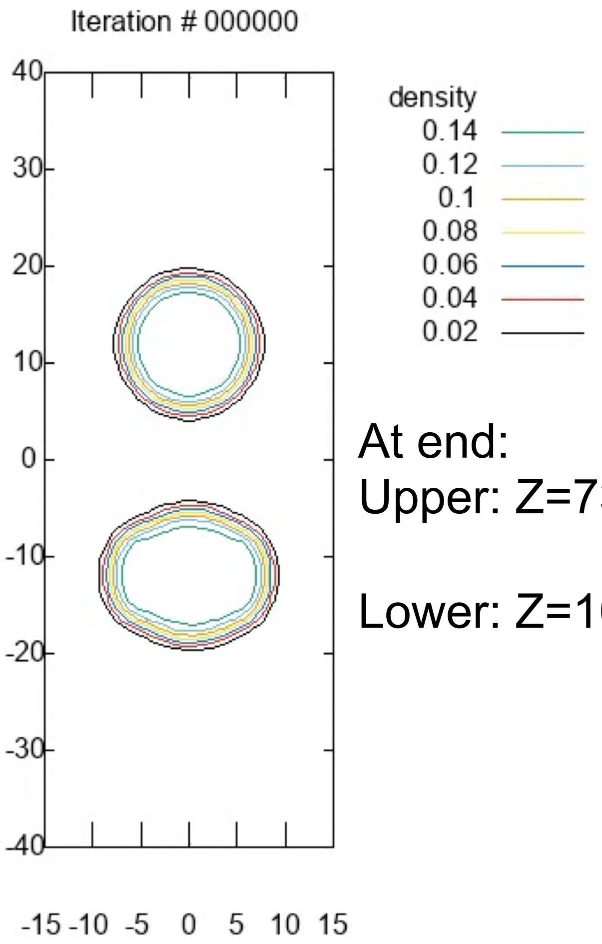
N.B structure lasting 1 zs has width ~70 keV

$^{254}Es + {}^{208}Pb$: Heavier beam

Belly configuration
@ 800 MeV CM energy
& 1200 MeV



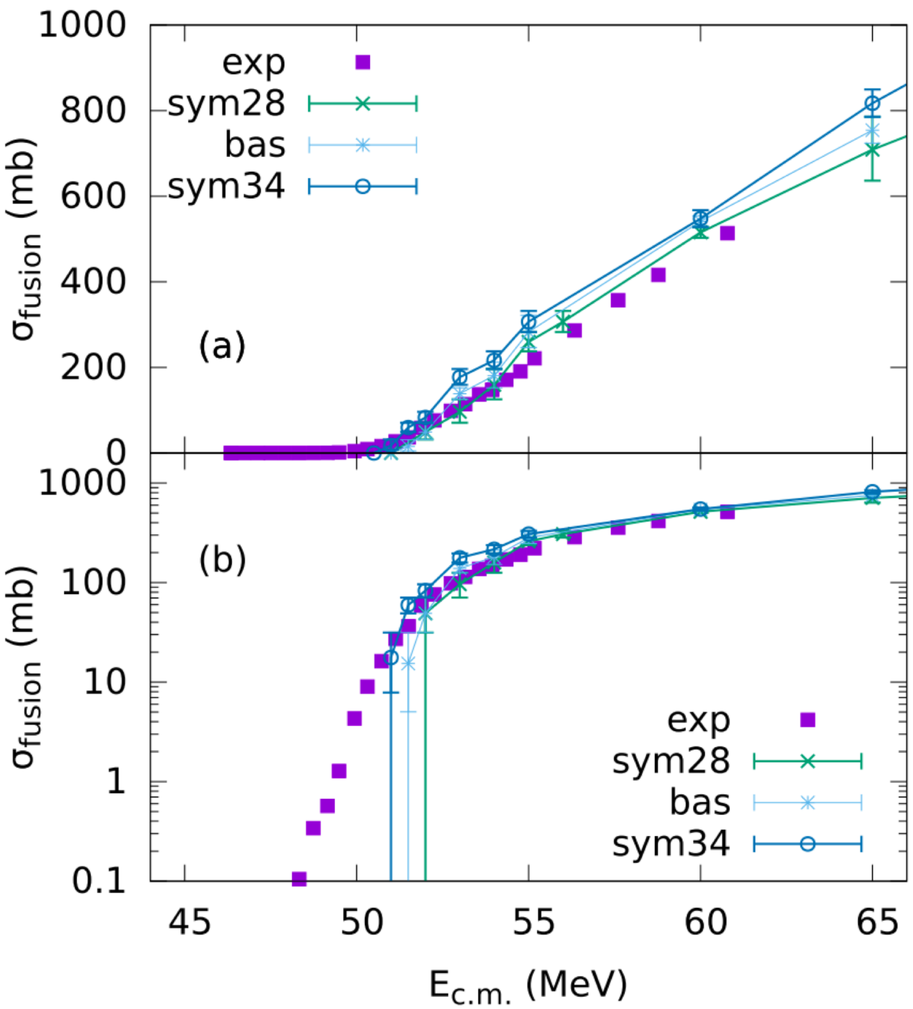




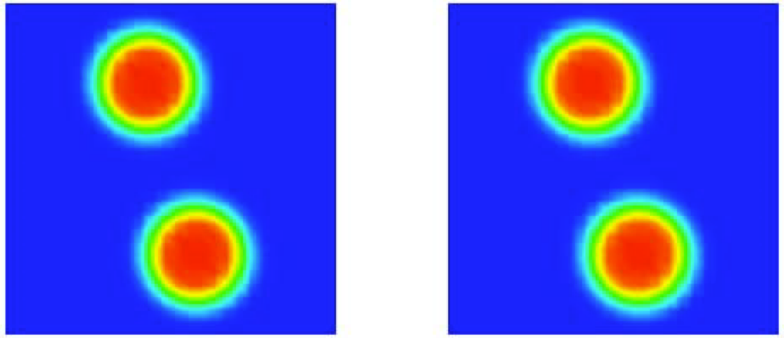
At end:
Upper: Z=73 (Ta), N=112

Lower: Z=108 (Hs), N=169

Role of symmetry energy (for $^{48}Ca+^{48}Ca$)



Left frame below = head-on (b=0) collision with SV-sym28 @ 51MeV CM energy.
Right frame is same but for SV-sym32

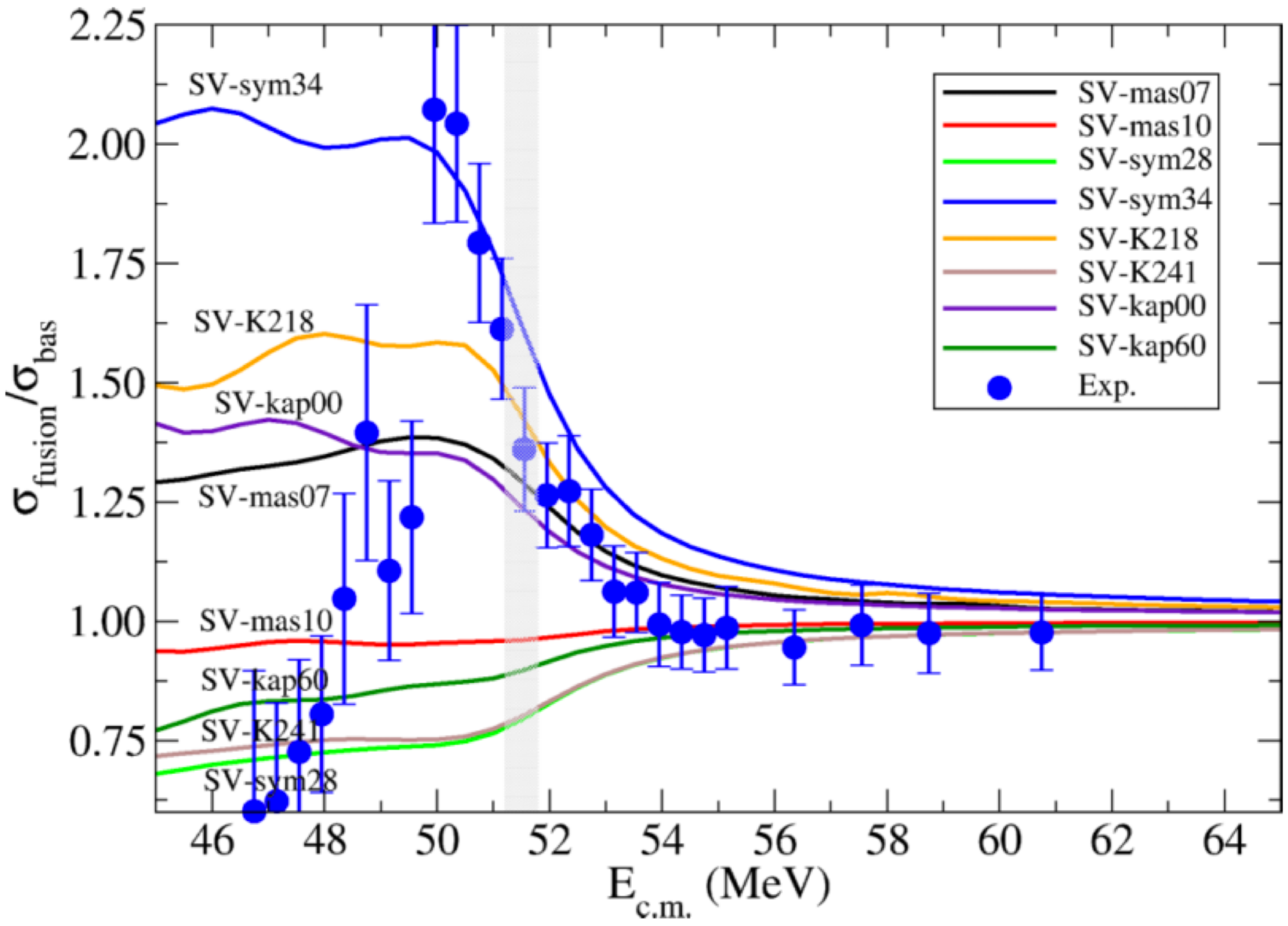


P.-G. Reinhard, A. S. Umar, P. D. Stevenson, J. Piekarewicz, J. A. Maruhn, and V. E. Oberacker, *Phys. Rev.* **C 93**, 044618 (2016)

Variation in Cross-Section

» Compared with the "basic" SV-bas

Exp. Data from A. M. Stefanini, G. Montagnoli, R. Silvestri, L. Corradi, S. Courtin, E. Fioretto, B. Guiot, F. Haas, D. Lebhertz, P. Mason, F. Scarlassara, and S. Szilner, Phys. Lett. B 679, 95 (2009)



Different forces with different nuclear matter parameters follow the experimental data as the CM energy changes

But around barrier, symmetry energy of 32-34 works best

Conclusions & Acknowledgements

- Density functionals predict slight static triaxiality in even-even neighbours of ^{254}Es
- Estimate of Ion-ion potential through Frozen Hartree-Fock Approximation
- Allowing dynamic changes of the density as nuclei approach in TDHF produces modest changes to FHF prediction of barrier height
- reactions with Ca along tip of Es give fusion-fission close above barrier
- reactions Ca into belly of Es give (quasi-)stable triangular configurations lasting O(zs) or longer
- heavy beam particle + Es => transfer, fusion fission
- need Particle Number Projection for more details
- Can learn about symmetry energy of nuclear force from fusion reactions

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