Study of the production of superheavy nuclei for S^3 on SPIRAL2

M2-PSA internship defense

Léo Petit-Barande

GANIL
Supervisor: Julien Piot

June 22, 2022

GANIL and SPIRAL2

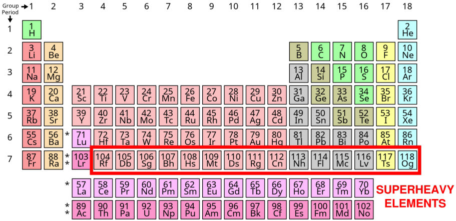
Grand Accélérateur National d'Ions Lourds

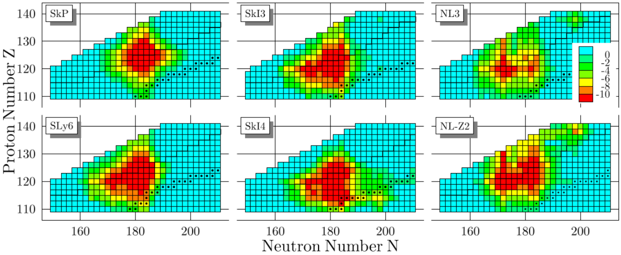
laboratoire commun CEA/DRF CNRS/IN2P3

- Research center in Caen established in 1983 by the CNRS and CEA.
- **Nuclear physics**, astrophysics, atomic physics, material sciences, radiobiology.
- Original complex: 5 cyclotrons to accelerate ^{12}C – ^{238}U beams.
- **SPIRAL2** project: new linear accelerator to accelerate ^{1}H – ^{238}U beams at intensities 10 times larger than the original complex.

Superheavy elements

- Definition may vary but generally $Z \geq 104$
- Existence only possible through shell effects

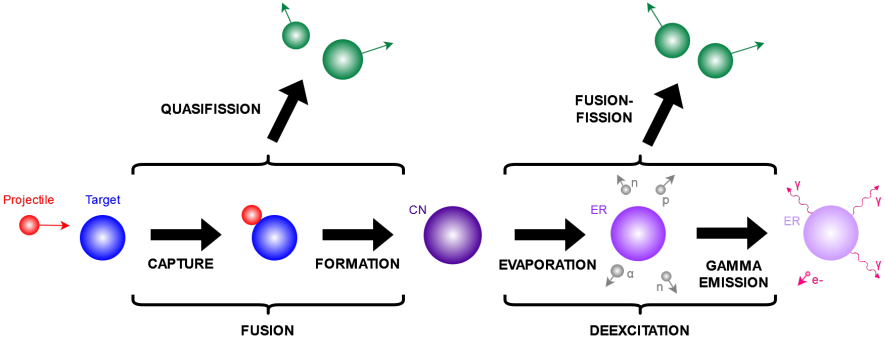




Island of stability (next magic numbers after ^{208}Pb)

M. Bender, W. Nazarewicz and P.-G. Reinhard, Phys. Lett. B, 515:42, 2001.

Main mode of production of superheavy elements: fusion-evaporation reactions

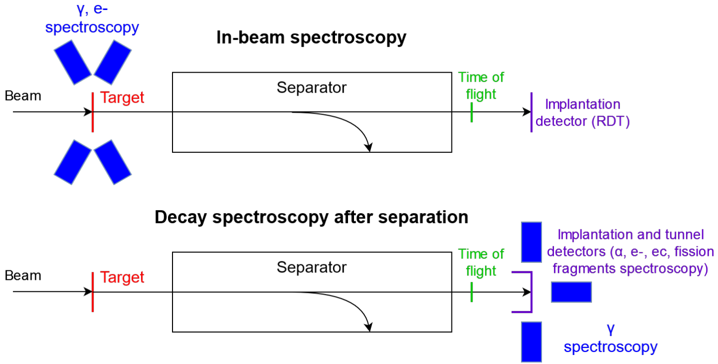


- CN: compound nucleus
- ER: evaporation residue

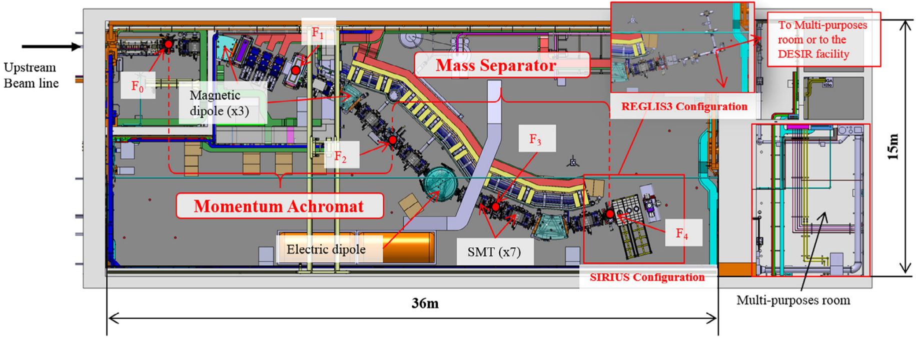
Spectroscopy of superheavy elements

Objective: study the nuclear structure features of superheavy elements.

Two types of spectroscopy:



The Super Separator Spectrometer (S^3)



F. Déchéry et al., Nucl. Instr. Meth. B, 376:125, 2016.

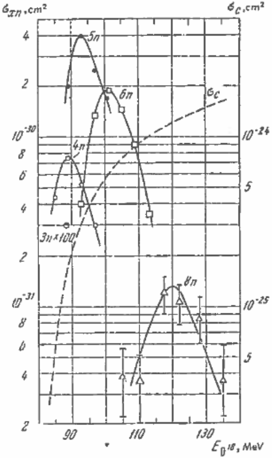
- Separator for fusion-evaporation with very low cross-sections
- Uses the high intensity beams from SPIRAL2
- Synthesis of nuclei in the superheavy and $N = Z$ regions, plasma physics
- Due in 2024

Motivation of the study

Excitation function

ER production cross-section as a function of E^* (excitation energy of the CN), E_{cm} (incident energy in the center-of-mass frame) or E_{lab} (incident energy in the laboratory frame).

- S^3: we want to obtain the best possible ER production rates.
- It is necessary to select the beam energy so as to correspond to the maximum of the excitation function.
- We need to be able to simulate fusion-evaporation reactions → **KEWPIE2** code (2015).



E. D. Donets and V. A. Shchegolev and V. A. Ermakov, Soviet Journal of Nuclear Physics, 2:723, 1966.

Objective of the study

Objective

Study the modeling of the fusion-evaporation mechanism with KEWPIE2 and draw information that will guide the future use of the code in preparing the experiments planned on S^3, by comparing calculation results to experimental measurements.

.

General framework of KEWPIE2

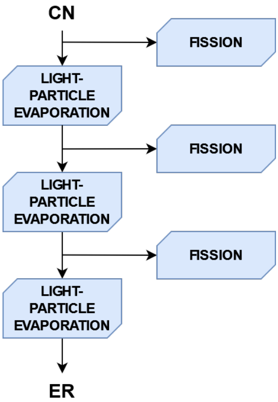
- Code simulating the fusion-evaporation mechanism to obtain excitation functions for ER production.
- Cross-sections are calculated with :

$$\sigma_{ER}(E_{cm}) = \frac{\pi \hbar^2}{2\mu E_{cm}} \sum_{\ell \geq 0} (2\ell + 1) P_{fus}(E_{cm}, \ell) P_{surv}(E^*, \ell)$$

- The fusion and deexcitation phases can be considered independent of each other (Bohr independence hypothesis).
- Two fusion models are available in KEWPIE2 and it is also possible to directly specify fusion cross-sections.

General framework of KEWPIE2 — deexcitation

Dynamical cascade :



Bateman equations:

$$\frac{dP_{0,0}}{dt} = -\Gamma_{tot}^{0,0} P_{0,0}$$

$$\frac{dP_{1,0}}{dt} = \Gamma_{n}^{0,0} P_{0,0} - \Gamma_{tot}^{1,0} P_{1,0}$$

$$\frac{dP_{0,1}}{dt} = \Gamma_{p}^{0,0} P_{0,0} - \Gamma_{tot}^{0,1} P_{0,1}$$

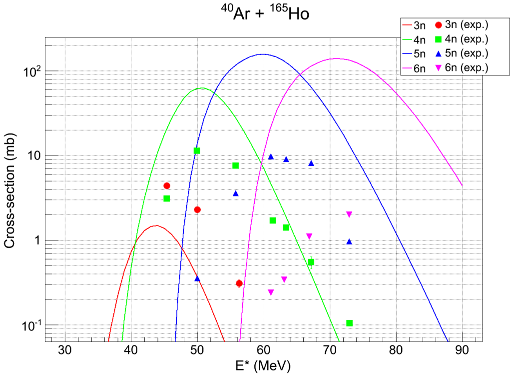
$$\vdots$$

$$\frac{dP_{2,2}}{dt} = \Gamma_{p}^{2,1} P_{2,1} + \Gamma_{n}^{1,2} P_{1,2} + \Gamma_{\alpha}^{0,0} P_{0,0} - \Gamma_{tot}^{2,2} P_{2,}$$

$$\vdots$$

Comparison of KEWPIE2 results with experimental data

We start by studying reactions using a ^{40}Ar projectile. A number of experimental excitation functions have been published in *D. Vermeulen et al., Z. Phys. A, 318:157, 1984*.



There is a large difference (up to several orders of magnitude) bewteen the KEWPIE2 results and the experimental measurements.

Fission barriers in KEWPIE2

Such a large discrepancy could result from a bad estimation of the fission barriers, which is a parameter the cross-sections are very sensitive to.

$$B_f = B_{LDM} - \Delta E_{sh}$$

$$\Delta E_{sh} = f \cdot \Delta E_{MN}$$

- The liquid drop fission barrier B_{LDM} can be calculated with 2 different modeles : Thomas-Fermi (TF) model (default) and Lublin-Strasbourg Drop (LSD) model.
- The shell-correction factor f can be adjusted (between 0 and 1).

Other parameters of interest — fission

The fission decay width Γ_f^{BW} calculated with the Bohr-Wheeler model can be multiplied by a correction factor (Kramers-Strutinsky factor) to account for viscosity:

$$\Gamma_f = K \cdot S \cdot \Gamma_f^{BW}$$

$$K = \sqrt{1 + \left(\frac{\beta}{2\omega_{sd}}\right)^2} - \frac{\beta}{2\omega_{sd}}$$

$$S = \frac{\hbar\omega_{gs}}{T_{gs}}$$

β: **reduced friction coefficient** (5 zs^{-1} by default) — *free parameter*

Other parameters of interest — level density

- The nuclear level density plays an important role in the calculation of the various decay widths.
- Level-density parameter a.
- Four different expressions for a: Fermi gas model (a_0), Tōke and Świątecki (a_1), Reisdorf (a_2), Nerlo-Pomorska et al. (a_3).
- Ignatyuk's prescription:

$$a_{gs}(E^*) = a\left[1 + (1 - e^{-E^*/E_d})\frac{\Delta E_{sh}}{E^*}\right]$$

- E_d: **shell-damping energy** (19 MeV by default) — *free parameter*

χ^2 analysis

Procedure

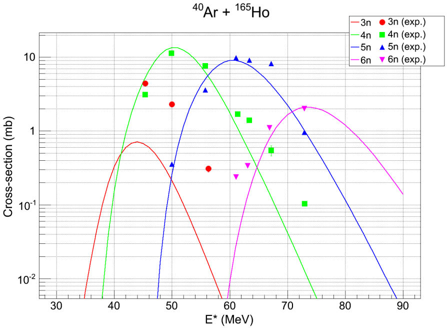
To adjust the model we proceed to do a χ^2 analysis. The χ^2 value is to be compared to the number of degrees of freedom, equal here to the number of experimental values N. We can define a reduced χ^2 that is to be compared to 1 : $\chi_r^2 = \frac{\chi^2}{N}$.

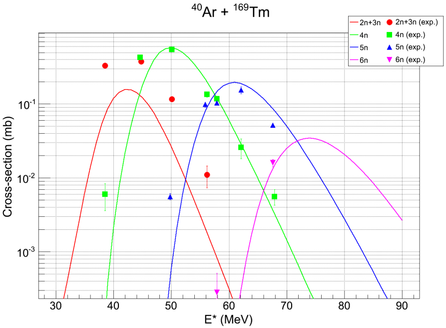
KEWPIE2 configuration	χ_r^2	RMSE (mb)
Default	8089877.74	63.960
$f = 0,5$	697661.67	25.130
$f = 0,1$	35251.76	4.024
LSD	1525.57	2.411
LSD + a_2	1393.55	2.401
LSD + a_2 + $\beta = 4$ zs^{-1}	619.75	1.713
LSD + a_2 + $\beta = 3$ zs^{-1}	1353.48	2.310
LSD + a_2 + $E_d = 16$ MeV	598.32	1.634
LSD + a_2 + $E_d = 15$ MeV	517.25	1.576
LSD + a_2 + $E_d = 14$ MeV	520.48	1.642

$^{40}Ar + ^{165}Ho$

Results for ^{40}Ar + ^{165}Ho and ^{40}Ar + ^{169}Tm

"LSD + a_2 + E_d = 15 MeV" configuration

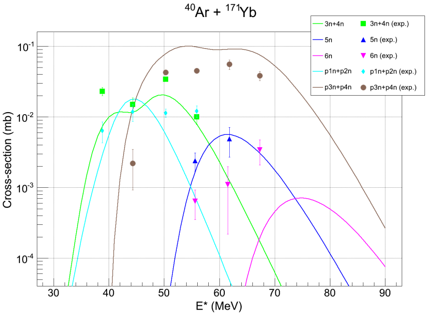


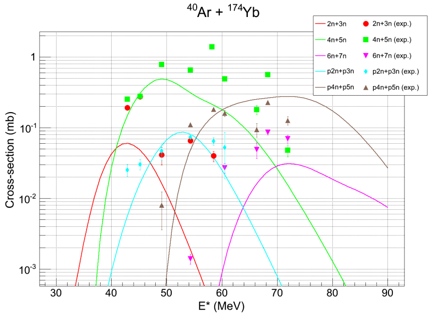


The amplitudes and positions of the maxima of the excitation functions are indeed well reproduced. However, the 3n / 2n + 3n channels appear to still be underestimated.

Results for $^{40}Ar + {}^{171}Yb$ and $^{40}Ar + {}^{174}Yb$

"LSD + a_2 + $E_d = 15$ MeV" configuration





The positions of the maxima are well reproduced, and so are the orders of magnitude except for the 2n+3n channel as before, as well as for the 6n / 6n+7n channels.

Taking γ emission into account

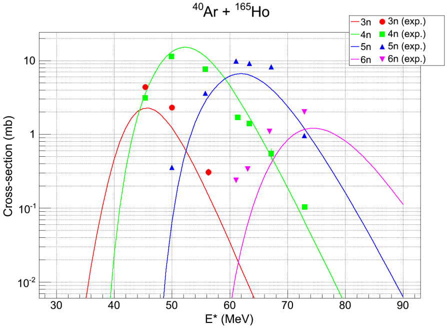
The 2n / 2n+3n channels may be underestimated because until now γ emission, which would compete with fission, has not been taken into account. We can do so in KEWPIE2 with the SMLO model.

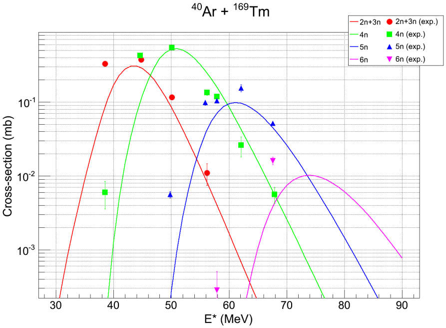
Configuration KEWPIE2		χ_r^2	RMSE (mb)
LSD	3n	1263.79	2.579
	4n	877.88	1.648
	5n	1873.70	3.676
	6n	2171.63	0.638
	Total	**1525.56**	**2.411**
LSD + a_2 + E_d = 15 MeV	3n	1170.87	2.482
	4n	687.23	1.347
	5n	293.10	1.861
	6n	156.10	0.196
	Total	**517.25**	**1.576**
LSD + SMLO	3n	360.21	1.38
	4n	259.21	1.628
	5n	682.72	2.441
	6n	1221.88	0.520
	Total	**623.85**	**1.709**
LSD + SMLO + E_d = 20 MeV	3n	293.70	1.248
	4n	486.70	2.227
	5n	534.47	2.045
	6n	981.15	0.476
	Total	**590.50**	**1.768**

$^{40}Ar + ^{165}Ho$

Results for $^{40}Ar + ^{165}Ho$ and $^{40}Ar + ^{169}Tm$

"LSD + SMLO" configuration



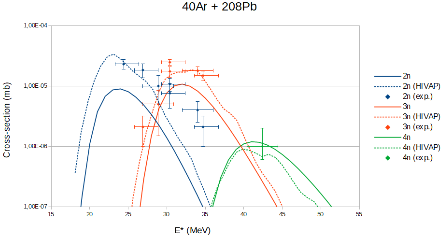


The amplitudes for the 2n / 2n+3n channels are no longer underestimated in a substantial manner.

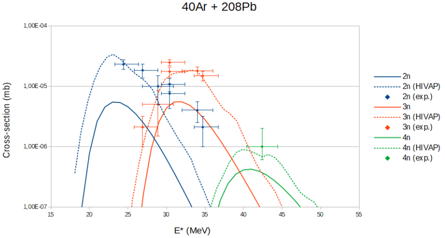
Results for $^{40}Ar + ^{208}Pb$

We now consider a significantly heavier target (^{208}Pb) and compare the KEWPIE2 results with experimental values from *D. Ackermann, Diplomarbeit, Technische Hochschule Darmstadt, 1989*, as well as results from the HIVAP code.

"LSD + a_2 + E_d = 15 MeV" configuration



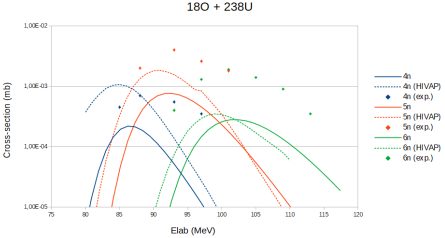
"LSD + SMLO" configuration



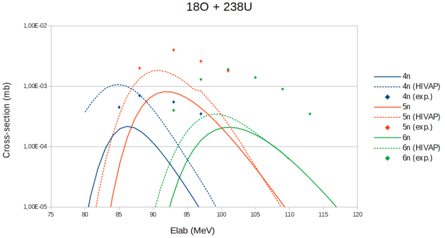
Results for $^{18}O + ^{238}U$

We now change both projectile and target and compare the KEWPIE2 results with experimental values from *E. D. Donets, V. A. Shchegolev, V. A. Ermakov, Soviet Journal of Nuclear Physics, 2:723, 1966*, as well as results from the HIVAP code.

"LSD + a_2 + E_d = 15 MeV" configuration



"LSD + SMLO" configuration



Conclusion

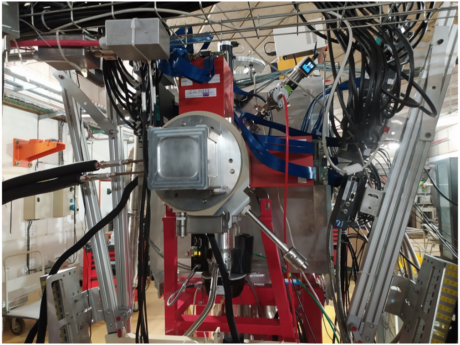
- We could successfully reproduce the positions of the maxima and the orders of magnitude of excitation functions for reactions with a ^{40}Ar projectile and a range of targets. However the 6n channel was sometimes underestimated.
- The results were not as good when changing target and projectile (^{18}O + ^{238}U reaction).
- Taking γ emission into account and using the LSD fission barriers generally lead to better results.
- There is still much to do, the next step is to simulate reactions with various mass numbers to get a better global picture of KEWPIE2's ability to model fusion-evaporation reactions.
- **Globally the simulation works relatively well, but the extrapolation power is low since we need to adjust for different reactions.**

Thank you for your attention!

The SIRIUS detection system

Spectroscopy and Identification or Rare Isotopes Using S^3
(detection system for decay spectroscopy after separation)

- Implantation detector: 10×10 cm^2 DSSD (*Double-sided Silicon Strip Detector*)
- 4 10×10 cm^2 Si tunnel detectors
- 5 Ge clover detectors (EXOGAM)



Currently: only the DSSD and 1 tunnel detector

Thomas-Fermi (TF) model (fission barriers)

$$B_{LDM} = P \cdot F(X)$$

$$F(X) = \begin{cases} 0.595553 - 0.124136(X - X_1) & \text{for } 30 \leq X \leq X_1 \\ 1.99749 \cdot 10^{-4}(X_0 - X)^3 & \text{for } X_1 \leq X \leq X_0 \end{cases}$$

$$X = \frac{Z_C^2}{A_C(1 - k_s I_c^2)}$$

$$X_0 = 48.5428$$

$$X_1 = 34.15$$

$$P = A_C^{2/3}(1 - k_s I_c^2)$$

$$k_s = 1.9 + (Z_C - 80)/75$$

Lublin-Strasbourg Drop (LSD) model (fission barriers)

$$B_{LDM} = B_{max} \exp\left[-\left(\frac{I_C - I_0}{\Delta_I}\right)^2\right]$$

$$B_{max} = a_0 + a_1 Z_C + a_2 Z_C^2 10^{-2} + a_3 Z_C^3 10^{-4}$$

$$I_C = (A_C - 2Z_C)/A_C$$

$$I_0 = a_4 + a_5 Z_C 10^{-4}$$

$$\Delta_I = a_6 + a_7 Z_C 10^{-2} + a_8 Z_C^2 10^{-4}$$

Level-density parameter (1)

- Tōke and Świątecki:

$$a_1 = \frac{A}{14.61}\left(1 + 3.114\frac{\mathcal{B}_s}{A^{1/3}} + 5.626\frac{\mathcal{B}_k}{A^{2/3}}\right)\left(1 - \frac{I^2}{9}\right)$$

- Reisdorf:

$$a_2 = A\left(0.04543 r_0^3 + 0.1355 r_0^2\frac{\mathcal{B}_s}{A^{1/3}} + 0.1426 r_0\frac{\mathcal{B}_k}{A^{2/3}}\right)$$

- Nerlo-Pomorska et al.:

$$a_3 = 0.092A + 0.036A^{2/3}\mathcal{B}_s + 0.275A^{1/3}\mathcal{B}_k - 0.00146\frac{Z^2}{A^{1/3}}\mathcal{B}_c$$

Level-density parameter (2)

- Surface term:

$$\mathcal{B}_s = 1 + \frac{2}{5}\alpha_2^2 - \frac{4}{105}\alpha_2^3 - \frac{66}{175}\alpha_2^4$$

- Curvature term:

$$\mathcal{B}_k = 1 + \frac{2}{5}\alpha_2^2 + \frac{16}{105}\alpha_2^3 - \frac{82}{175}\alpha_2^4$$

- Coulomb term:

$$\mathcal{B}_c = 1 - \frac{1}{5}\alpha_2^2 - \frac{4}{105}\alpha_2^3 + \frac{51}{245}\alpha_2^4$$

Ground state:

$$\alpha_2 = \sqrt{\frac{5}{4\pi}}\beta_2$$

Saddle point:

$$\alpha_2 = \frac{7}{3}y - \frac{938}{765}y^2 + 9.499768y^3 - 8.050944y^4$$

Empirical Barrier Distribution (EBD) model (fusion)

$$\sigma_{cap} = \int_0^{E_{cm}} \sigma_{cap}(E_{cm}, B) D(B) \, \mathrm{d}B$$

$$\sigma_{cap}(E_{cm}, B) = \pi R^2 \left(1 - \frac{B}{E_{cm}}\right)$$

$$D(B) = \frac{1}{\sqrt{2\pi} w} \exp\left[-\frac{(B - B_0)^2}{2w^2}\right]$$

Wentzel-Kramers-Brillouin (WKB) approximation (fusion)

$$P_{cap}(E_{cm}, J_C) = \frac{1}{1 + \exp(2\Omega)}$$

$$\Omega = \int_{r_{int}}^{r_{out}} \mathrm{d}r \sqrt{\frac{2\mu}{\hbar^2}[V(r) - E_{cm}]}$$

$$V(r) = V_N(r) + V_{coul}(r) + V_{cent}(r)$$