

Results from the PACE4 code for fusion evaporation reaction cross-section calculations



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Motivation

- **Lack of Information about cross section calculation**
- **Define the limits of the PACE4 code for different reactions**

LISE++

The program LISE is a kind of simulation program that can be used to produce radioactive beam via disintegration of nuclei or fusion evaporation

Aim of this program;

- Calculate the transmission and yields of disintegrated products.
- The program, can be able to simulate the production of radioactive beams regarding the parameters of the reaction mechanism up to the detection of nuclei that are selected by the fragment separator.

The program LISE++ plays a role in the development of fragment separators as well as the planning of experiments at different laboratories around the World.

The program is constantly expanding and evolving using the feedback of users around the world. Many “satellite” tools have been incorporated into the LISE++ framework, which are accessible with buttons on the main toolbar.

The screenshot displays the LISE++ software interface. On the left, a sidebar contains experimental parameters: Projectile (48Ca²⁰⁺), Fragment (42S¹⁶⁺), Target (9Be, 180 mg/cm²), Stripper, and four degraders (D1-D4) with Brho values of 3.2490 Tm. Below these are FP_PPAC0 and FP_PPAC1 detectors. The main window features a nuclear chart with isotopes color-coded by element and charge state. A 'PROJECTILE FRAGMENT' plot shows a distribution of fragments. The bottom status bar includes: Ncalc=0, Sum=0, No charge states, DG=-0.06mm/%, NP=64, R=0x01.



PACE4

(Projection Angular-momentum Coupled Evaporation)

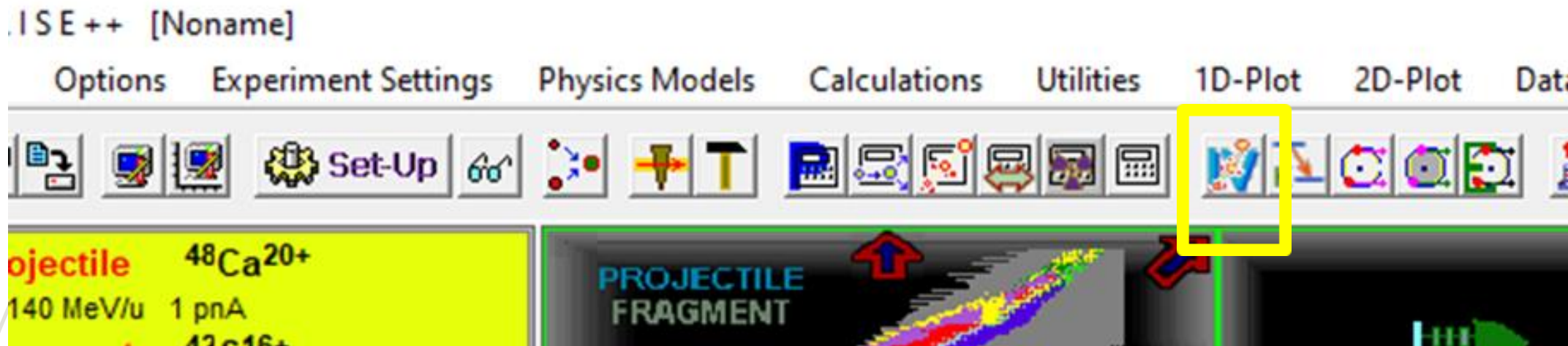
Fusion reactions can be simulated by using PACE4, code which is based on paper by A. Gavron and is advanced edition of JULIAN- the Hillman-Eyal evaporation code in the LISE++ framework.

PACE4

- ▶ The PACE4 code is a statistical model evaporation code
- ▶ By using the Monte-Carlo simulation for de-excitation of compound nucleus, main evaporation channels can be simulated at different beam energies.

The main advantages of Monte-Carlo simulation is that it will provide correlation between various quantities. The code calculates probabilities and decay widths for all the nuclei which are present in the decay chain.

PACE4 in PRACTICE



There is a shortcut for PACE4 in the toolbar of LISE++ program which is marked in figure below.

The first card of the PACE4 code

PACE4 - [Untitled]

File Page Help

Next page **CARD 1** About

NCASC number of cascades. (events in Monte Carlo calculation < 1 000 000)

INPUT =1 projectile + target input. AGRAZ parameter determines diffuseness of partial wave distribution
=2 compound nucleus input for single spin.
=3 compound nucleus input. Spin distribution read in.
=4 compound nucleus input. Spin distribution calculated taking spin-cutoff parameter at given Ex.
=5 triangular (sigma = 2i+1) cross section between LMINN and maximum spin

FYRST parameter determining yrast line to be used. FYRST < 0 provides the G-C yrast line.
< 0 Gilbert-Cameron spin cutoff parameter. EROT = (SPIN)**2/(2.*SIGSQ)
!= 0. EROT = rotating liquid drop rotational energy, multiplied by factor of FYRST.
==0 value changed to FYRST = 1. In both cases level density calculated at E = EX-EROT.

BARFAC The program assumes the A.J.Sierk modified rotating liquid drop barrier if this is equal to 0. If you provide a fission barrier of your own, the Sierk barrier will be renormalized accordingly. If BarFac is positive it will be taken as the desired zero spin fission barrier. If BarFac is negative, its absolute value will be taken as a factor to multiply the Sierk barrier.

ARATIO Ratio of the Fermi gas level density parameter 'LITTLE-A' at the saddle point to the ground state value. The saddle point level density is determined by g.s. 'LITTLE-A' * ARATIO.

FACLA level density parameter = MASS/FACLA if not zero.
if ==0 Gilbert and Cameron value used.

Limits of residual yields (n %) to show angular and energy distributions
Low limit =
High limit =

IDIST
 =0 brief, schematic results of particle spectra and list of evaporated (residual) nuclei
 =1 detailed angular and energy distribution of residual nuclei and evaporated particles.
 =2 detailed(1) + transmission coefficients for particle emission

MDIR
 = 0 Compound nucleus is initially in M=0 states and the Z-axis is the recoil axis.
 = 1 Compound nucleus is initially in M=J states, the Z axis is perpend. to recoil direction.

MDR=1 - it is appropriate for deep inelastic fragment deexcitation

ITRAC - it controls the degree of event traceback
 = 0 produces compact traceback, summed over all residues.
 = 1 detailed traceback leading to each individual isotope separately.

Particle analysis
 Create output file
 neutron
 proton
 alpha
 gamma

Nucleus Gate
 Use
A =
Z =

NOSHL
 =0 uses AME2003 values (A,W&T, NPA 729, 2003, pp.336-676)
 =1 uses Lysekil masses with shell correction

- ▶ NCASC stands for number of cascades for example number of events in Monte-Carlo calculations up to 1000000.
- ▶ INPUT will have values from 1 to 5, 1 for projectile and target input
- ▶ FACLA is level density parameter and in this version of PACE4 is taken as equal to 10 as default
- ▶ The yrast parameter is taken as unity.
- ▶ IDIST should be greater than 0 for particle analysis. Briefly, schematic results of particle spectra and list of evaporated (residual) nuclei

Second card of PACE4

PACE4 - [Untitled]

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Projectile	Target	Compound
A = 48 N = 28	A = 124 N = 74	A = 172 N = 102
Z = 20 Ca	Z = 50 Sn	Z = 70 Yb
Spin (gs) = 0	Spin (gs) = 0	
ME (MeV) = -44.214 DB	ME (MeV) = -88.237 DB	ME (MeV) = -59.260 DB

QCN = 0 Q value of reaction [MeV].
If == 0 it is calculated from mass tables.

Beam Energy (MeV)
Elab = 300 Batch Mode

Calculation
QCN = -73.191
E_CM = 216.279
Ex = 143.089

EXPSIG = 0 experimental fusion cross section if known. TL-S from optical model shifted to reproduce this value if inputted, preserving the L-diffuseness. if == 0 Bass model (PRL 1977) fusion cross section being used.

JCMAX = 0 Maximum J to be used during calculations. (if 0 it is taken from optical model routine)

AGRAZ = 2 To bypass input channel optical model routine (TLOM) specify L-diffuseness of fusion cross section. If == 0 diffuseness will be set to 0.5 which is essentially sharp cutoff.

ELOSS = 0 energy loss of beam thru full target width. (total dE) energies will be distributed between Ebeam & Ebeam-Eloss

LMINN = 0 Lowest partial wave L in calculation. Partial waves from L=0 to LMINN excluded, enabling low-L non-fusion window in reaction calculation.

Transmission probability for a one-dimensional barrier (O.T.)
 Classical (use it above the barrier)
 Quantum-mechanical [D.Hill & J.Wheeler, PhysRev 89(1953) 1105]

Note: If you are running at high bombarding energies for which the grazing angular momentum is above 75 hbar, it is recommended to input AGRAZ > 0, and to specify an arbitrary value for EXPSIG (or 0 = Bass) which corresponds to a fusion cross section with a limiting L-value around 80. This will give you all the evaporation residue data and the fission probabilities you need. For J>80 all nuclei will fission anyway, and you will run out of dimension if you try.

- ▶ A and Z of projectile and target represent for mass number and atomic number respectively.
- ▶ Beam energy is in MeV; E_{lab} stands for energy value for which simulation is to be carried out.
- ▶ AGRAZ parameter should be taken equal to 2 for this version of PACE4
- ▶ classical model at above-barrier energies and quantum mechanically at sub-barrier energies

if calculations are not desired as default, optical model parameters can put on cards from 3A to 3D by manuel

PACE4 - [Untitled]

Previous page **CARD 3A** Next page

Optical model potential
 from systematics
 manuel

neutron

V0D(I) = 47,01 W0D(I) = 9,52 NPD(I) = 250
V01D(I) = -0,267 W01D(I) = -0,053 IMAG(I) = Surface
V02D(I) = -0,002 W02D(I) = 0 IRAD(I) = 1
R0RD(I) = 1,286 R0ID(I) = 1,258
ARD(I) = 0,66 AID(I) = 0,48
R0CD(I) = 0 RMCHD(I) = 0

Depth of real nuclear well $V0=V0D(I)+V01D(I)*ECM+V02D(I)*ECM**2$
Depth of imaginary nuclear well $W0=W0D(I)+W01D(I)*ECM+W02D(I)*ECM**2$

IMAG(I) imaginary well is potential surface or volume

Radial extension of nuclear well

IF IRAD(I)=0	Radius of real nuclear well	R0RD(I)
	Radius of imaginary nuclear well	R0ID(I)
IF IRAD(I)=1	Radius of real well	R0RD(I)*AMT**(1/3)
	Radius of imaginary well	R0ID(I)*AMT**(1/3)
IF IRAD(I)=2	Radius of real well	R0RD(I)*(AMT**(1/3)+AMP**(1/3))

PACE4 - [Untitled]

Previous page **CARD 3B** Next page

Optical model potential
 from systematics
 manuel

proton

V0D(I) = 59,063 W0D(I) = 13,5 NPD(I) = 250
V01D(I) = -0,55 W01D(I) = 0 IMAG(I) = Surface
V02D(I) = 0 W02D(I) = 0 IRAD(I) = 1
R0RD(I) = 1,25 R0ID(I) = 1,25
ARD(I) = 0,65 AID(I) = 0,47
R0CD(I) = 1,25 RMCHD(I) = 0

Depth of real nuclear well $V0=V0D(I)+V01D(I)*ECM+V02D(I)*ECM**2$
Depth of imaginary nuclear well $W0=W0D(I)+W01D(I)*ECM+W02D(I)*ECM**2$

IMAG(I) imaginary well is potential surface or volume

Radial extension of nuclear well

IF IRAD(I)=0	Radius of real nuclear well	R0RD(I)
	Radius of imaginary nuclear well	R0ID(I)
IF IRAD(I)=1	Radius of real well	R0RD(I)*AMT**(1/3)
	Radius of imaginary well	R0ID(I)*AMT**(1/3)
IF IRAD(I)=2	Radius of real well	R0RD(I)*(AMT**(1/3)+AMP**(1/3))

if calculations are not desired as default, optical model parameters can put on cards from 3A to 3D by manual

PACE4 - [Untitled]

Previous page **CARD 3C** Next page

Optical model potential
 from systematics
 manual

alpha

V0D(I) = W0D(I) = NPD(I) =
V01D(I) = W1D(I) = IMAG(I) =
V02D(I) = W2D(I) = IRAD(I) =
R0RD(I) = R0ID(I) =
ARD(I) = AID(I) =
R0CD(I) = RMCHD(I) =

Depth of real nuclear well $V0=V0D(I)+V01D(I)*ECM+V02D(I)*ECM**2$
Depth of imaginary nuclear well $W0=W0D(I)+W01D(I)*ECM+W02D(I)*ECM**2$

IMAG(I) imaginary well is potential surface or volume

Radial extension of nuclear well
IF IRAD(I)=0 Radius of real nuclear well R0RD(I)
Radius of imaginary nuclear well R0ID(I)
IF IRAD(I)=1 Radius of real well R0RD(I)*AMT**(1/3)
Radius of imaginary well R0ID(I)*AMT**(1/3)
IF IRAD(I)=2 Radius of real well
R0RD(I)*(AMT**(1/3)+AMP**(1/3))

PACE4 - [Untitled]

Previous page **CARD 3D** Next page

Optical model potential
 from systematics
 manual

incoming channel

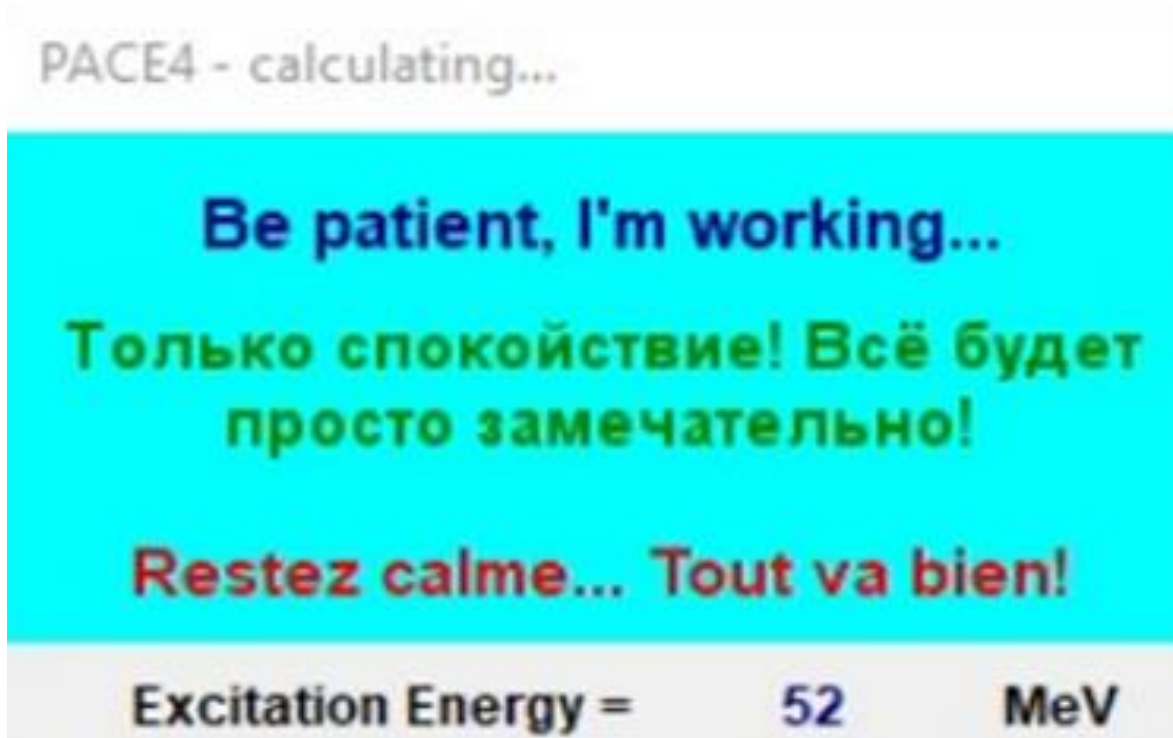
V0D(I) = W0D(I) = NPD(I) =
V01D(I) = W1D(I) = IMAG(I) =
V02D(I) = W2D(I) = IRAD(I) =
R0RD(I) = R0ID(I) =
ARD(I) = AID(I) =
R0CD(I) = RMCHD(I) =

Depth of real nuclear well $V0=V0D(I)+V01D(I)*ECM+V02D(I)*ECM**2$
Depth of imaginary nuclear well $W0=W0D(I)+W01D(I)*ECM+W02D(I)*ECM**2$

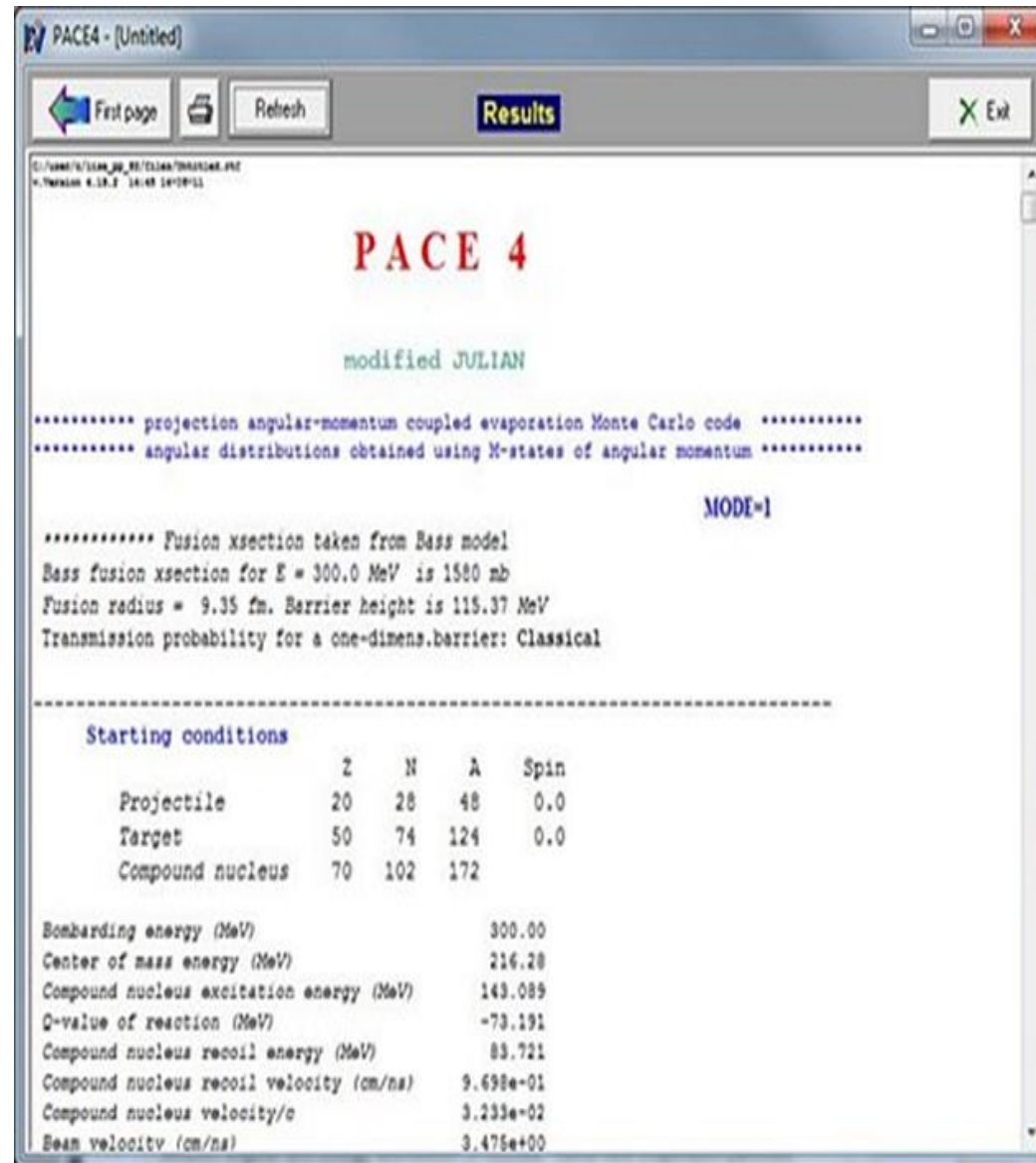
IMAG(I) imaginary well is potential surface or volume

Radial extension of nuclear well
IF IRAD(I)=0 Radius of real nuclear well R0RD(I)
Radius of imaginary nuclear well R0ID(I)
IF IRAD(I)=1 Radius of real well R0RD(I)*AMT**(1/3)
Radius of imaginary well R0ID(I)*AMT**(1/3)
IF IRAD(I)=2 Radius of real well
R0RD(I)*(AMT**(1/3)+AMP**(1/3))

By using nex tab, code start the calculation with other default parameters.



After calculation PACE4 code gives an output file as follows.



The screenshot shows a window titled "PACE4 - (Untitled)" with a toolbar containing "First page", "Refresh", "Results", and "Exit". The main content area displays the following text:

```
PACE 4  
modified JULIAN  
***** projection angular-momentum coupled evaporation Monte Carlo code *****  
***** angular distributions obtained using M-states of angular momentum *****  
  
MODE=1  
  
***** Fusion xsection taken from Bass model  
Bass fusion xsection for E = 300.0 MeV is 1580 mb  
Fusion radius = 9.35 fm. Barrier height is 115.37 MeV  
Transmission probability for a one-dimens.barrier: Classical  
  
-----  
Starting conditions  


|                  | Z  | N   | A   | Spin |
|------------------|----|-----|-----|------|
| Projectile       | 20 | 28  | 48  | 0.0  |
| Target           | 50 | 74  | 124 | 0.0  |
| Compound nucleus | 70 | 102 | 172 |      |

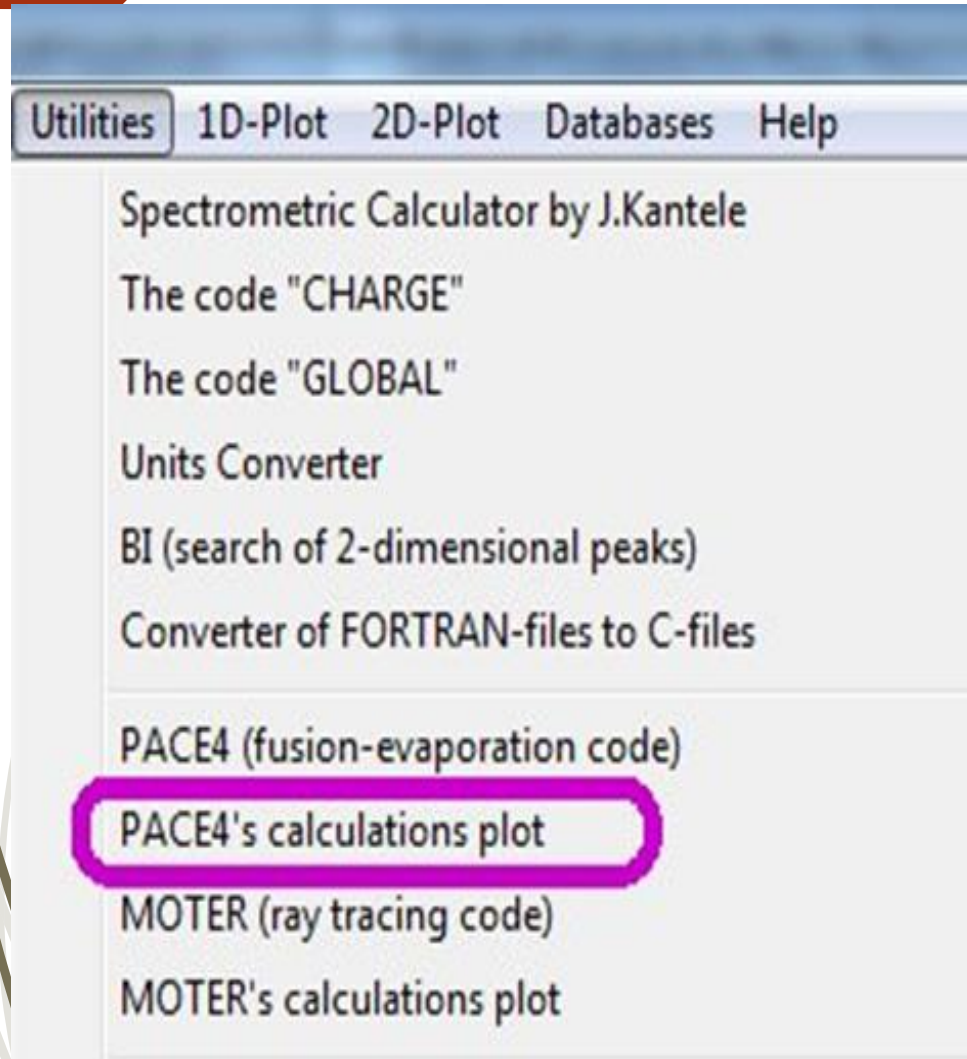
  


|                                          |           |
|------------------------------------------|-----------|
| Bombarding energy (MeV)                  | 300.00    |
| Center of mass energy (MeV)              | 216.28    |
| Compound nucleus excitation energy (MeV) | 143.089   |
| Q-value of reaction (MeV)                | -73.191   |
| Compound nucleus recoil energy (MeV)     | 83.721    |
| Compound nucleus recoil velocity (cm/ns) | 9.698e-01 |
| Compound nucleus velocity/c              | 3.233e-02 |
| Beam velocity (cm/ns)                    | 3.475e+00 |


```


PLOTTING PACE4 RESULTS with LISE++

- Under the Utilities tab in the LISE++ program; the desired results can be obtained graphically with the plotting tab of the PACE4 code

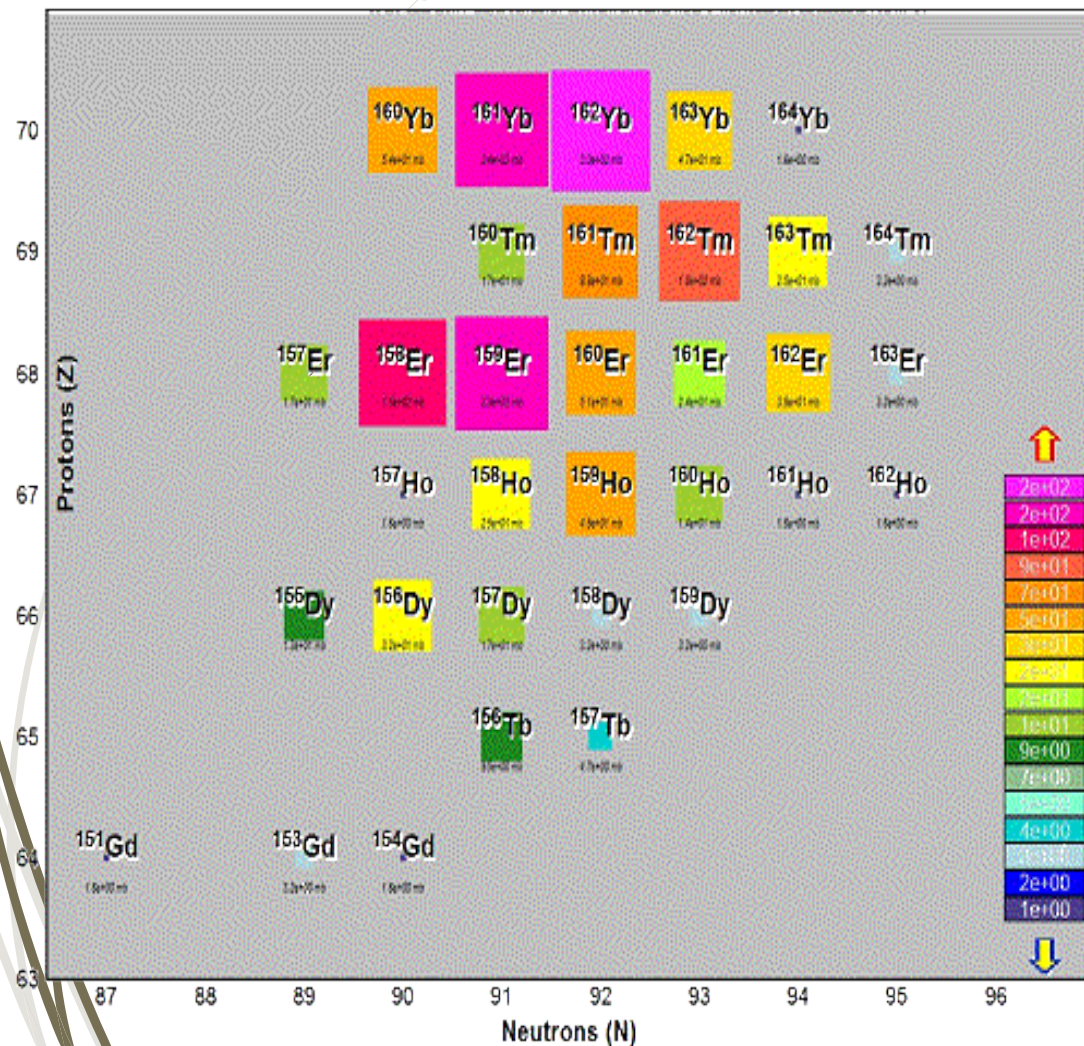


Cross-sections (PACE4)

EVAPORATION - Compound nucleus ^{172}Yb ; Mode 1

Excitation energy 143.1 MeV

Compound nucleus formation cross section: $1.58\text{e}+03$ mb

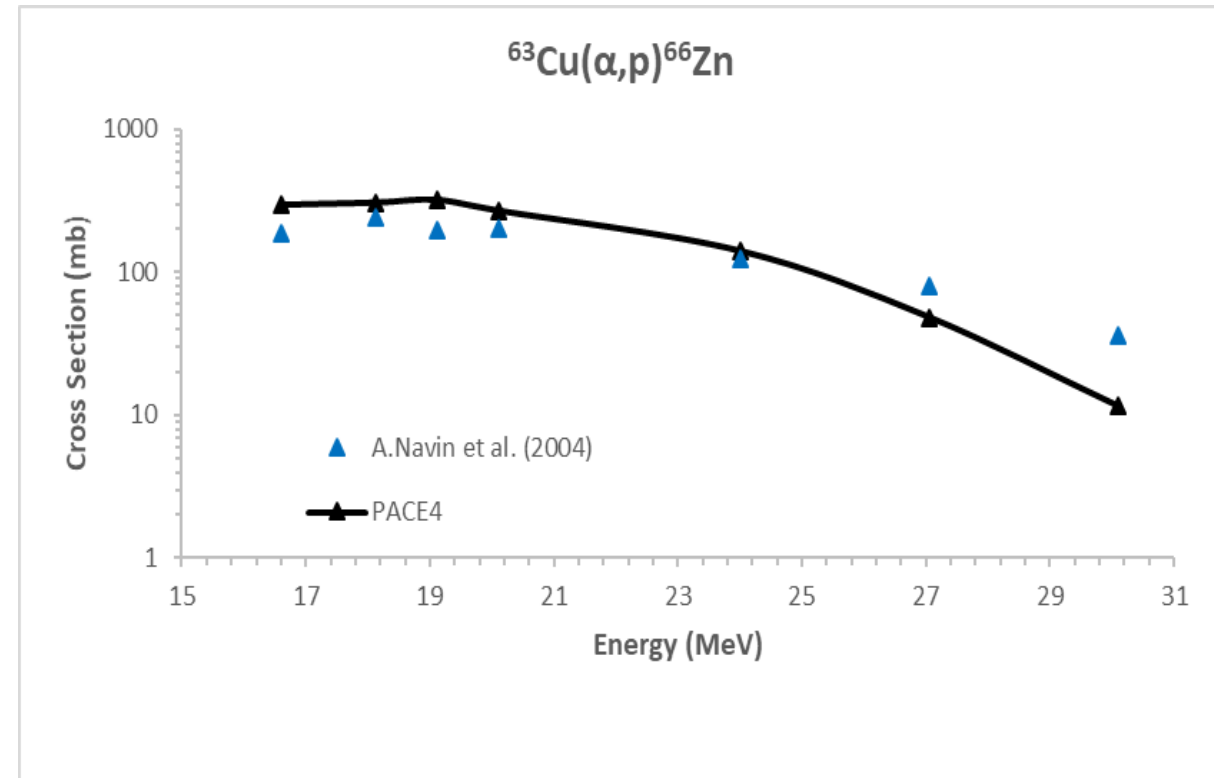


After plotting one can see cross-section values for all residual nuclei in this way.

- If it is interested in only one residual nuclei, an excel worksheet can be created for the cross section values corresponding to different energy values for that nuclei, and as a result, the energy versus effect cross section graph can be drawn.

To give a few examples of the work done with the pace 4 code

- In this experiment reactions induced by radioactive $6,8\text{He}$ beams have been studied on $63,65\text{Cu}$ and they compared to reactions with stable 4He projectiles. All evaporation residues compared with each other with different beam options. (A. Navin et al)
- Example on the right side only one evaporation residue from this experiment. The results for unstable $6,8\text{He}$ beam was not good agreement with calculations of code PACE4. But with stable 4He beam results was good agreement with code.



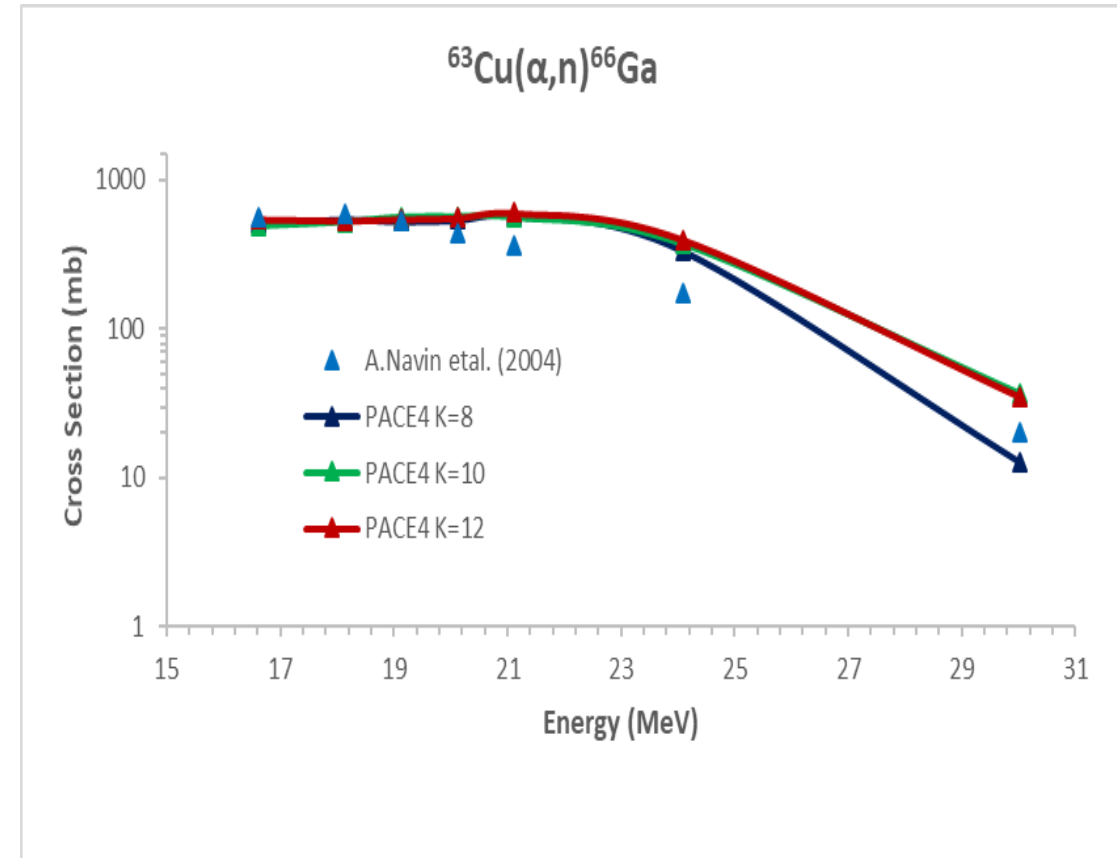
To give a few examples of the work done with the pace 4 code

Code has been modified to take into account the excitation energy dependence of the level density parameter using the prescription Kataria *etal.*

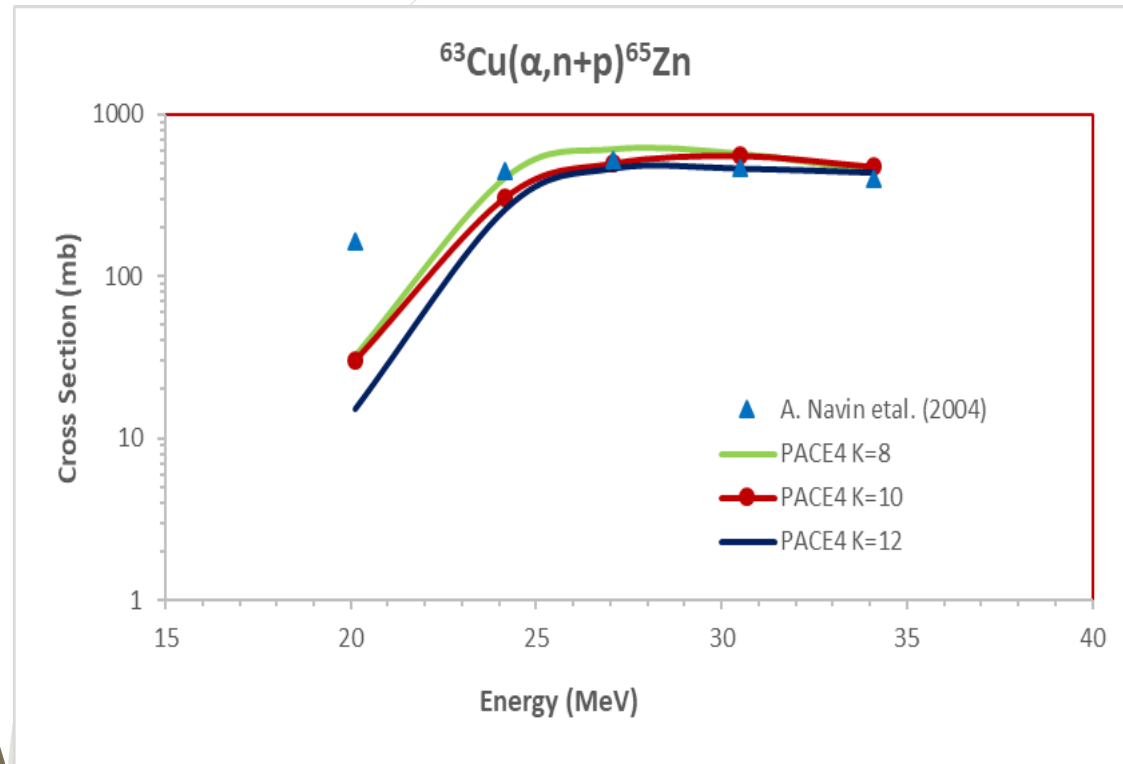
In this code the level density parameter a , which largely affects the equilibrium state components of a cross section is calculated from the expression;

$a = A/K \text{ MeV}^{-1}$, where A is the nucleon number of a compound system and K is an adjustable constant, which may be varied to match the experimental data.

The example on the right side ; calculations were done with different level density parameters.



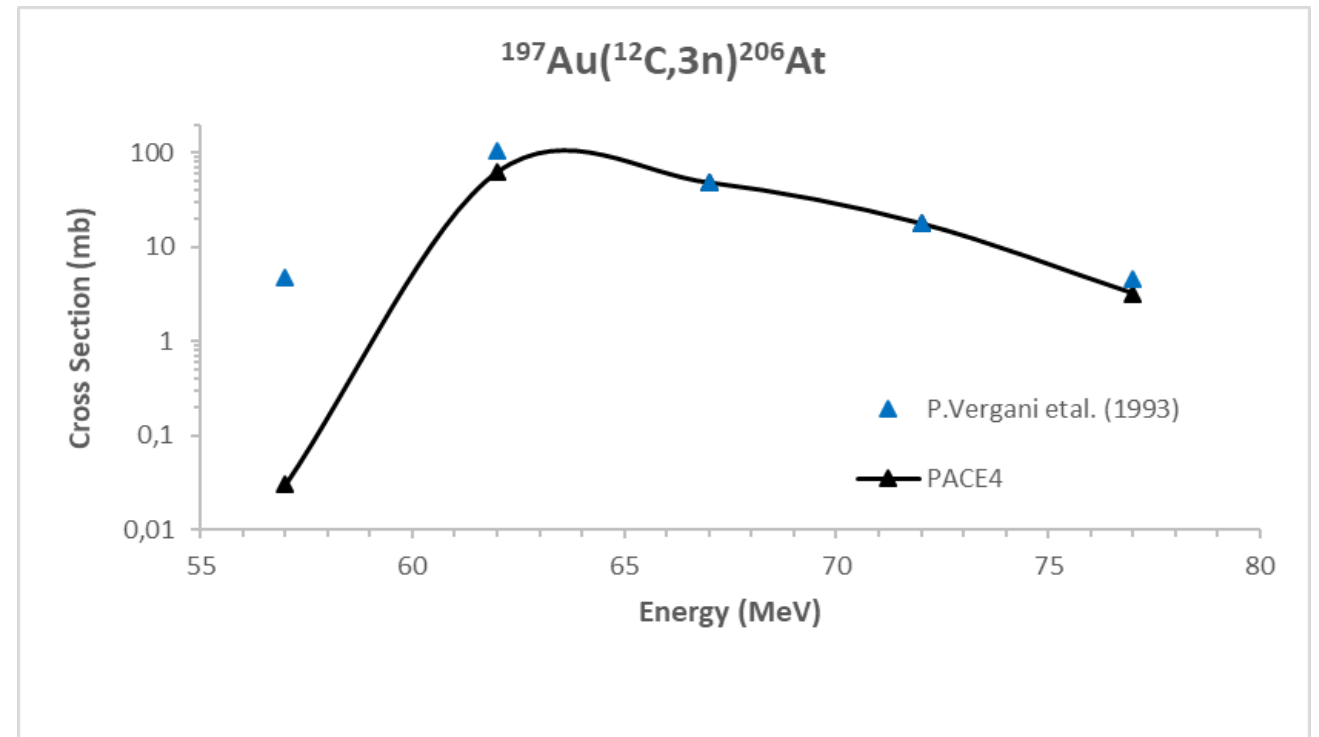
To give a few examples of the work done with the pace 4 code



This evaporation residue also from same experiment with different level density parameters.

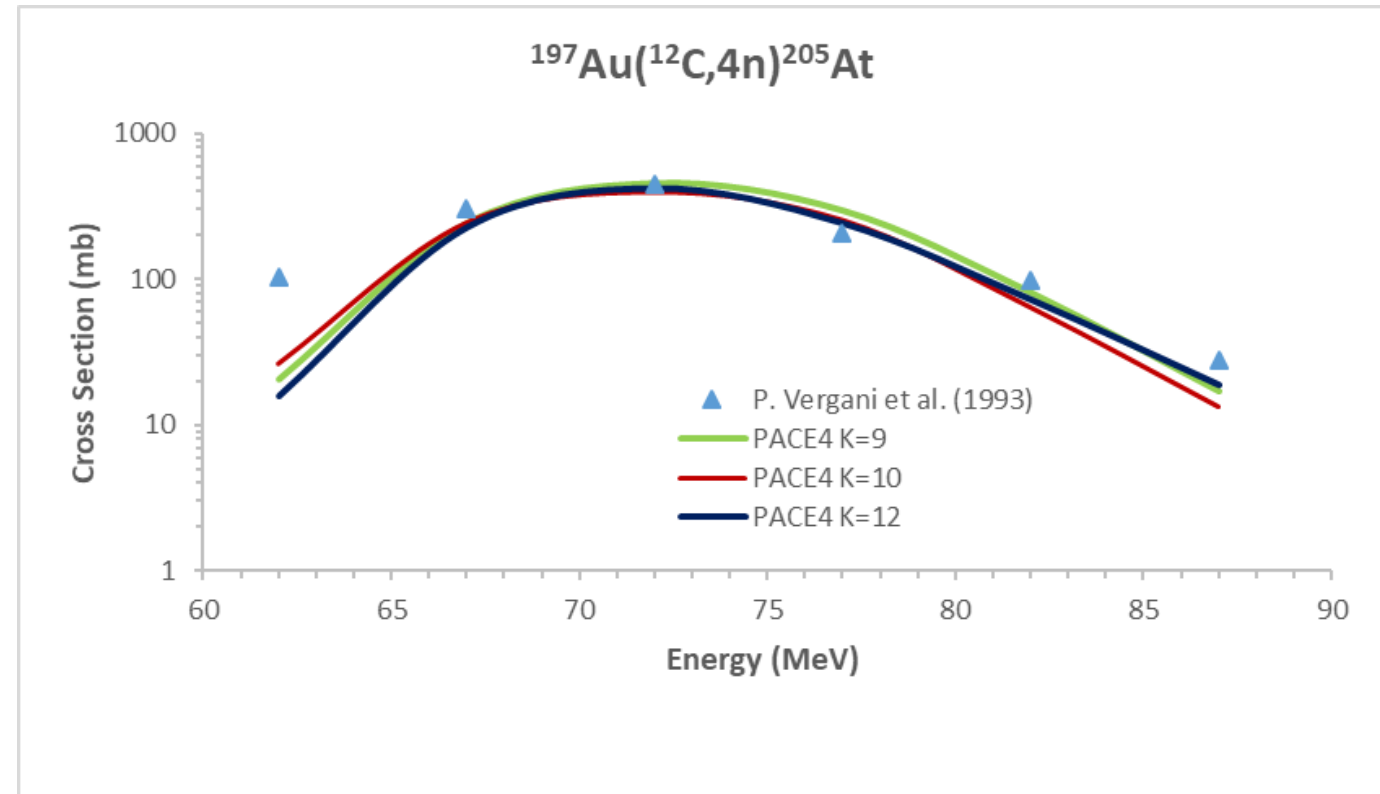
To give a few examples of the work done with the pace 4 code

- On this example; experiment has been done for "Complete and incomplete fusion and emission of preequilibrium nucleons in the interaction of ^{12}C with ^{197}Au below 10 MeV/nucleon" by P.Vergani et al



To give a few examples of the work done with the pace 4 code

➤ Result for $^{197}\text{Au}(^{12}\text{C},4n)^{205}\text{At}$ reaction with different level density parameters



REFERENCES

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Thanks for listening

