Nuclear Reactions: applications and examples

(http://departamento.us.es/famn/tsi08/)

Antonio M. Moro

Universidad de Sevilla

- What is FRESCO?

  Program developed by Ian Thompson since 1983, to perform coupled-reaction channels calculations in nuclear physics.

- Some general features:
  - Multi-platform (Windows, Linux, Unix, VAX)
  - Treats many direct reaction models: elastic scattering (optical model), transfer, inelastic excitation to bound and unbound states, etc
  - Can be run in text mode and graphical mode (XFRESCO interface)
  - FRESCO and XFRESCO can be freely downloaded at `http://www.fresco.org.uk/`
  - SFRESCO: Extension of Fresco, to provide χ^2 searches of potential and coupling parameters.

Essential ingredients of an OM calculation:

- **Physical:**
  - Identify projectile and target (mass, spin, etc)
  - Incident energy
  - Parametrization of the optical potential
- **Numerical:**
  - Radial step for numerical integration (HCM in fresco)
  - Maximum radius R for integration (RMATCH)
  - Maximum angular momentum L. (JTMAX)

RMATCH and JTMAX are linked by: $kR_g\,(1 - 2\eta/kR_g) \approx L_g + 1/2$
(L_g=grazing angular momentum)

Effective potential: $U(R) = U_{\rm nuc}(R) + U_{\rm coul}(R)$

- Coulomb potential: charge sphere distribution

$$U_c(R) = \begin{cases} \frac{Z_1 Z_2 e^2}{2R_c}\left(3 - \frac{R^2}{R_c^2}\right) & \text{if } R \le R_c \\ \frac{Z_1 Z_2 e^2}{R} & \text{if } R \ge R_c \end{cases}$$

- Nuclear potential (complex): Woods-Saxon parametrization

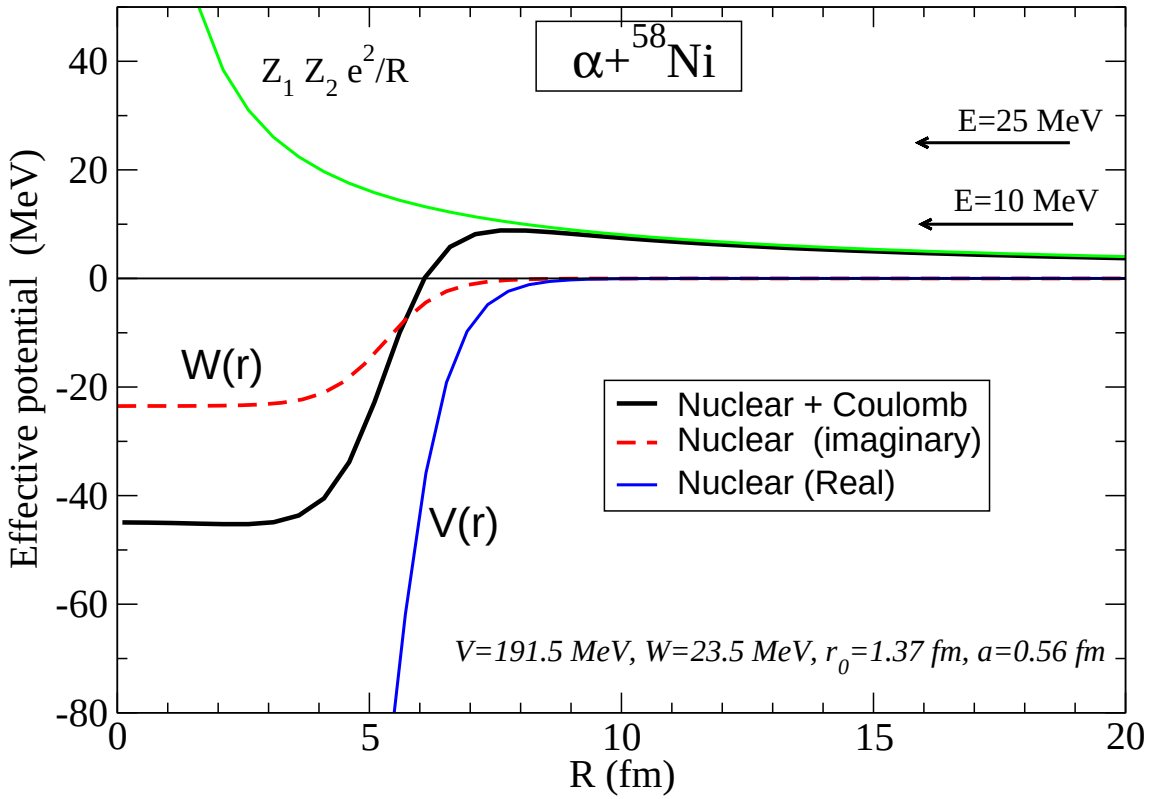
$$U_{\rm nuc}(R) = V(r) + iW(r) = -\frac{V_0}{1+\exp\left(\frac{R-R_0}{a_0}\right)} - i\,\frac{W_0}{1+\exp\left(\frac{R-R_i}{a_i}\right)}$$

Typically: $R_0 = r_0(A_p^{1/3} + A_t^{1/3})$

- r_0=reduced radius ($r_0 \sim 1.1 - 1.4$ fm)
- A_p,A_t: projectile, target masses (amu)

Elastic scattering: effective potential

Effective potential: $U(R) = U_{nuc}(R) + U_{coul}(R)$



OM example: $^{4}He+^{58}Ni$

Input example: `4he58ni_e10.in`

```
4he58ni_e10.in: 4He + 58Ni elastic scattering Ecm=10.0 MeV
NAMELIST
&FRESCO hcm=0.1 rmatch=25.0 jtmax=30
      thmin=1.0 thmax=180.0 thinc=2.0
      smats=2 xstabl=1
      elab=10.7 /

&PARTITION namep='ALPHA' massp=4 zp=2 namet='58Ni' masst=58 zt=28 nex=1 /
&STATES jp=0.0 bandp=1 ep=0.0 cpot=1 jt=0.0 bandt=1 et=0.0 /
&partition /

&POT kp=1 at=58 rc=1.4 /
&POT kp=1 type=1
    p1=191.5 p2=1.37 p3=0.56 p4=23.5 p5=1.37 p6=0.56 /
&pot /

&overlap /
&coupling /
```

Elastic scattering example

General variables

```
&FRESCO hcm=0.1 rmatch=25.0 jtmax=30
      thmin=1.00 thmax=180.00 thinc=2.00
      smats=2 xstabl=1
      elab=10.7 /
```

Mass partitions & states

```
&PARTITION namep='ALPHA' massp=4 zp=2 namet='58Ni' masst=58 zt=28
        nex=1 /
&STATES jp=0.0 bandp=1 ep=0.0 cpot=1 jt=0.0 bandt=1 et=0.0 /
&partition /
```

Potentials

```
&POT kp=1 itt=F at=58 rc=1.4 /
&POT kp=1 type=1
    p1=191.5 p2=1.37 p3=0.56 p4=23.5 p5=1.37 p6=0.56 /
&pot /
```

Essential input variables: FRESCO namelist

```
&FRESCO hcm=0.1 rmatch=25.0 jtmax=30
      thmin=1.00 thmax=180.00 thinc=2.00
      smats=2 xstabl=1
      elab=10.7 /
```

- `hcm`: step for integration of radial equations.
- `rmatch`: matching radius (for `R > RMATCH` asymptotic behaviour is assumed)
- `elab`: laboratory energy
- `jtmax`: maximum total angular momentum (projectile+target+relative)
- `smats`: trace variable
  `smats=2` → print elastic S-matrix
- `xstbl`: trace variable
  `xstbl=1` → print cross sections

Essential input variables: partitions and states

```
&PARTITION namep='ALPHA' massp=4 zp=2 namet='58Ni' masst=58 zt=28
         nex=1 /
```

- `namep` / `namet`: projectile / target name
- `massp` / `masst`: projectile / target mass (amu)
- `zp` / `zt`: projectile / target charge
- `nex`: number of (pairs) of states in this partition

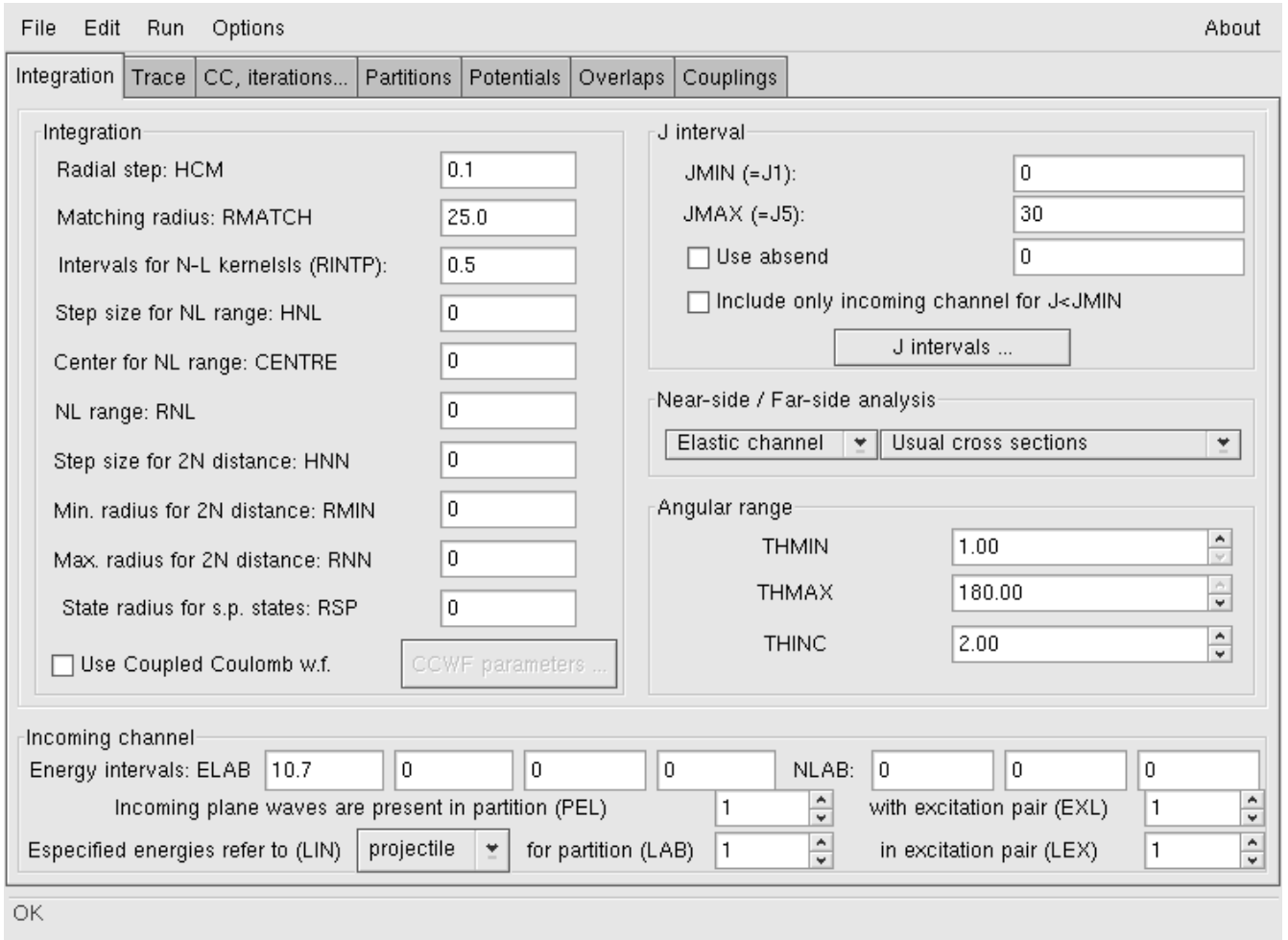
```
&STATES jp=0.0 bandp=1 ep=0.0 cpot=1 jt=0.0 bandt=1 et=0.0 /
```

- `jp` / `jt`: projectile / target spins
- `bandp` / `bandt`: projectile / target parities ($\pm$ 1)
- `cpot`: index of potential for this pair of states.

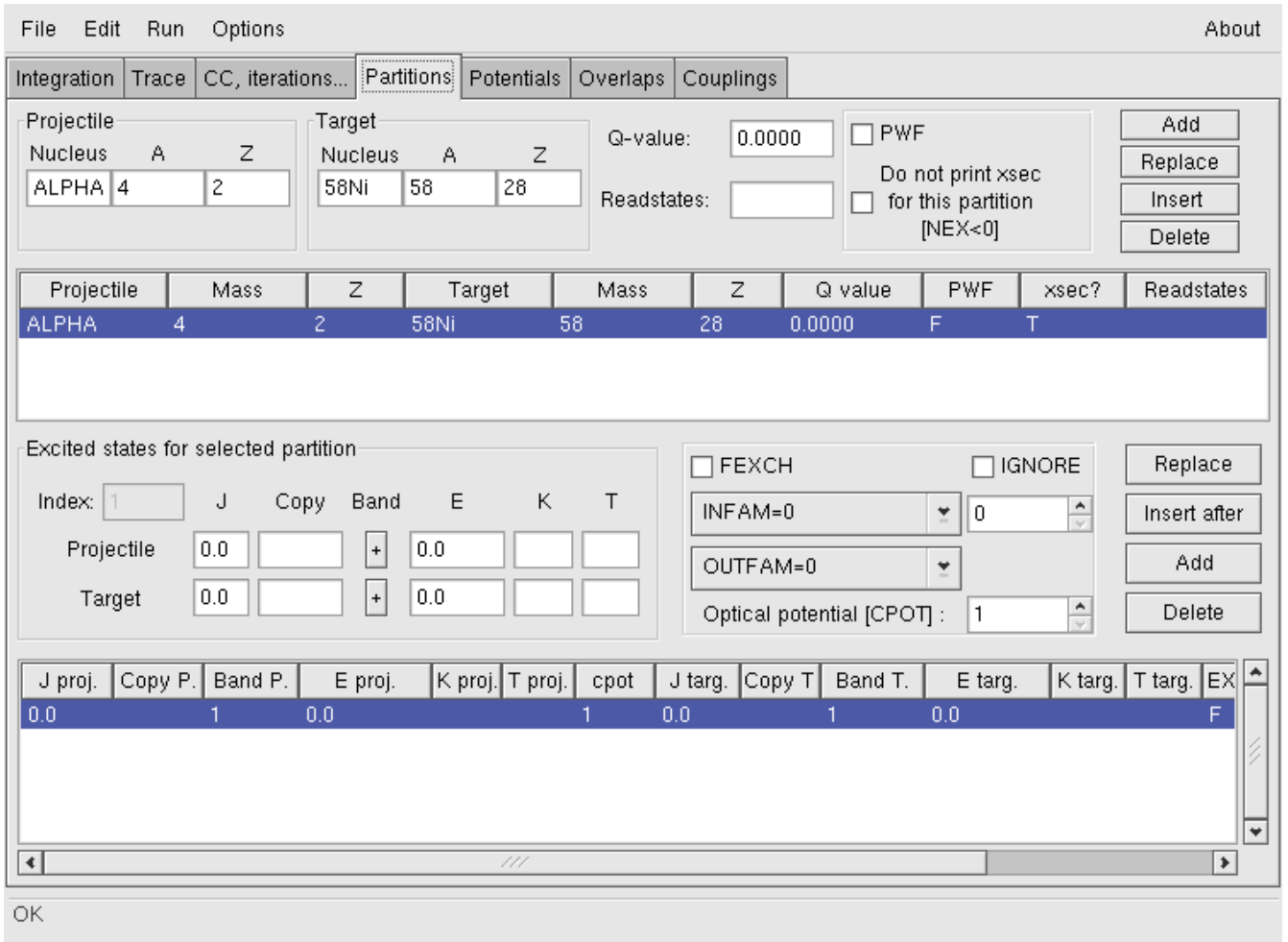
```
&POT kp=1 type=0 ap=0 at=58 rc=1.4 /
&POT kp=1 type=1 shape=0
    p1=191.5 p2=1.37 p3=0.56 p4=23.5 p5=1.37 p6=0.56 /
&pot /
```

- `kp`: index to identify this potential
- `ap, at`: projectile and target mass, for conversion from reduced to physical radii: $R = r(\mathrm{ap}^{1/3} + \mathrm{at}^{1/3})$
- `type, shape`: potential cathegory and shape: $\Rightarrow$
  - `type=0`: Coulomb potential
    `shape=0`: uniform charge sphere
  - `type=1`: volume nuclear potential
    `shape=0`: Woods-Saxon shape
- `rc`: reduced radius for charge distribution
- `p1,p2,p3`: V_0, r_0, a_0 (real part)
- `p4,p5,p6`: W_0, r_i, a_i (imaginary part)

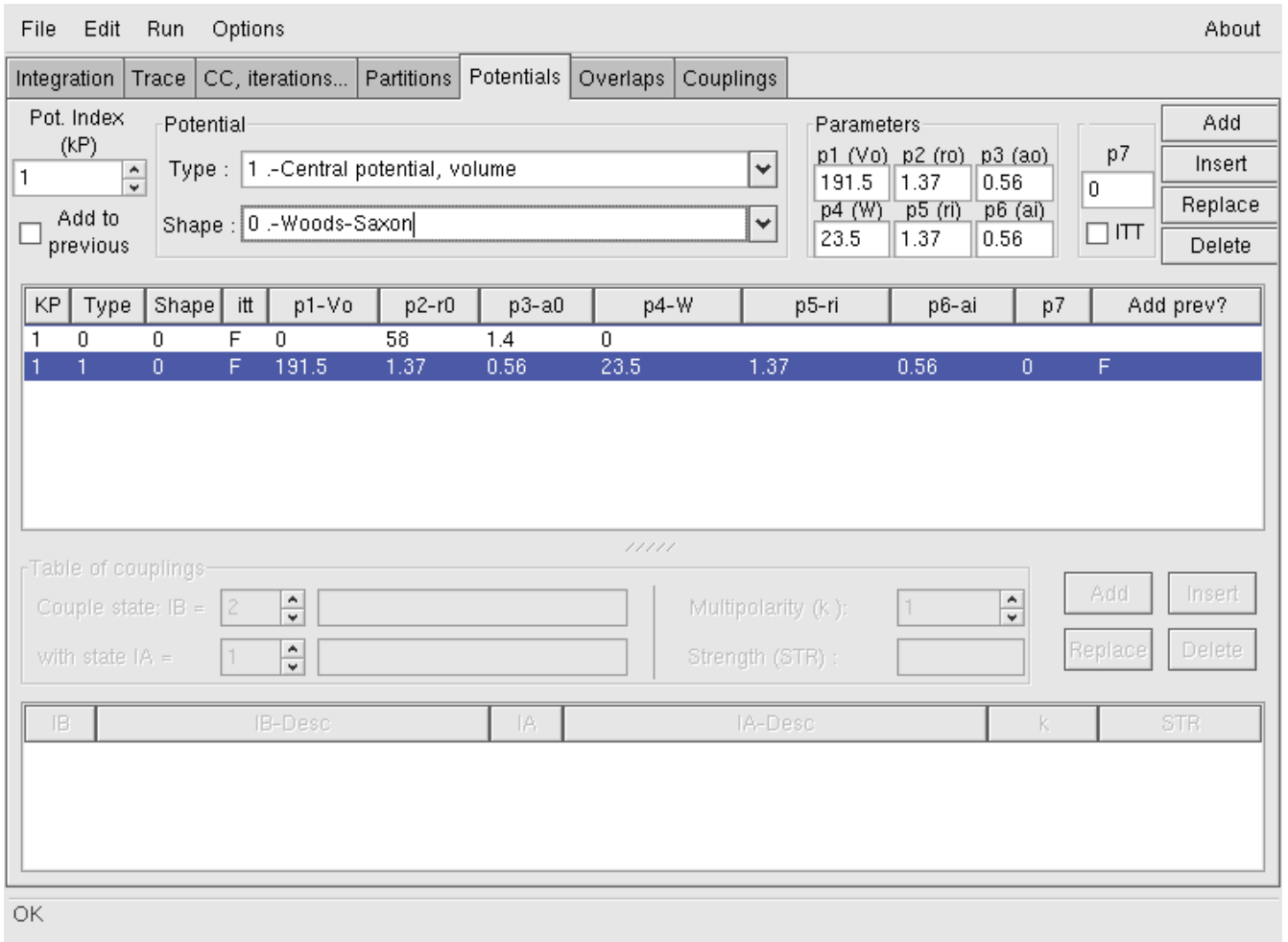
General variables:



Partitions & states:



Potentials:


File
Edit
Run
Options
About
Integration
Trace
CC, iterations...
Partitions
Potentials
Overlaps
Couplings
Pot. Index (kP)
1
Add to previous
Potential
Type : 1 .-Central potential, volume
Shape : 0 .-Woods-Saxon
Parameters
p1 (Vo) p2 (ro) p3 (ao)
191.5 1.37 0.56
p4 (W) p5 (ri) p6 (ai)
23.5 1.37 0.56
p7
0
ITT
Add
Insert
Replace
Delete
KP Type Shape itt p1-Vo p2-r0 p3-a0 p4-W p5-ri p6-ai p7 Add prev?
1 0 0 F 0 58 1.4 0
1 1 0 F 191.5 1.37 0.56 23.5 1.37 0.56 0 F
Table of couplings
Couple state: IB = 2
with state IA = 1
Multipolarity (k): 1
Strength (STR) :
Add
Insert
Replace
Delete
IB IB-Desc IA IA-Desc k STR
OK

Useful output files:

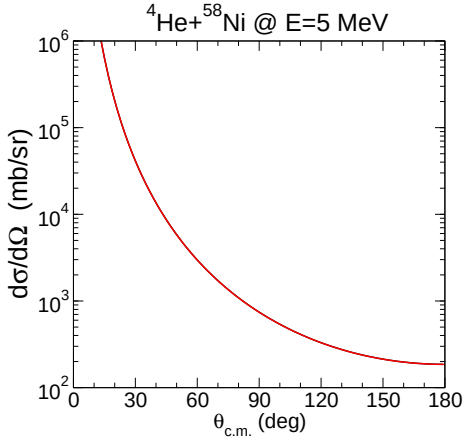
- Main output file (stdout)
- `fort.201` : Elastic scattering angular distribution
  - `thmax > 0`: relative to Rutherford.
  - `thmax < 0`: absolute units (mb/sr).
- `fort.7`: Elastic S-matrix (real part, imaginary part, angular momentum)
- `fort.56`: Fusion (absorption), reaction and inelastic cross section for each angular momentum

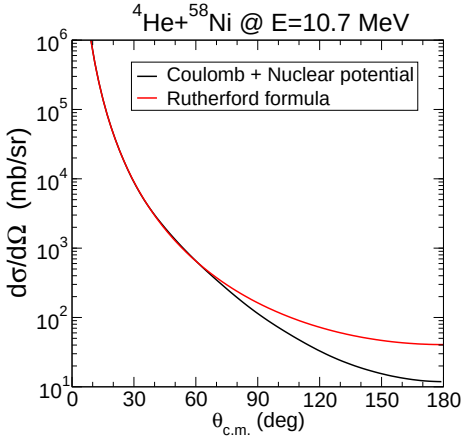
Dynamical effects: ^{4}He+^{58}Ni at E=5, 10.7, 25 and 50 MeV

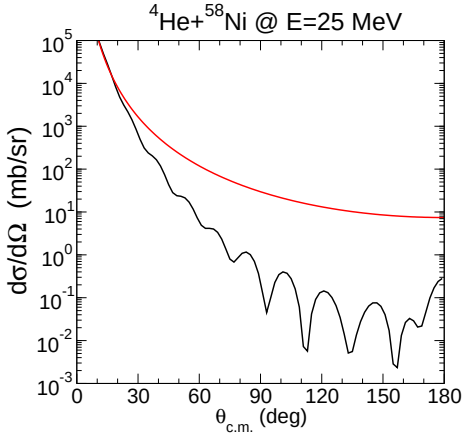
$E_{\rm lab}$ (MeV)	η	k (fm^{-1})	$\bar{\lambda} = 1/k$ (fm)	$2a_0$ (fm)
5	7.95	0.920	1.087	17.2
10.7	5.62	1.34	0.746	8.06
25	3.55	2.06	0.485	3.44
50	2.51	2.91	0.343	1.69

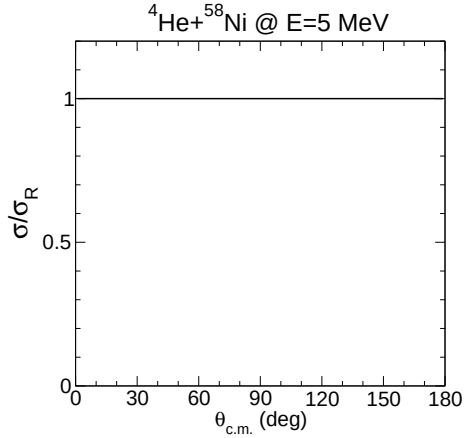
- $\eta \ggg 1$: Rutherford scattering: $\sigma(\theta) \propto 1/\sin^4(\theta/2)$
- $\eta \gg 1$: Fresnel scattering (rainbow)
- $\eta \leq 1$: Fraunhofer scattering (oscillatory behaviour):

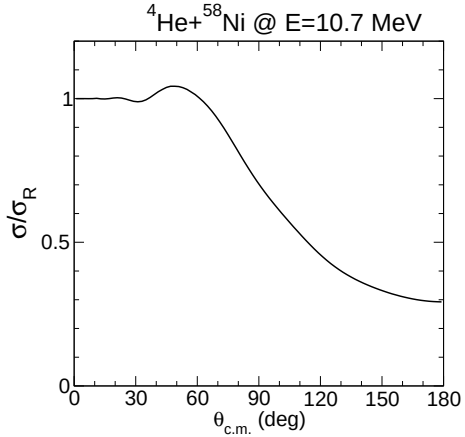
Elastic scattering: energy dependence

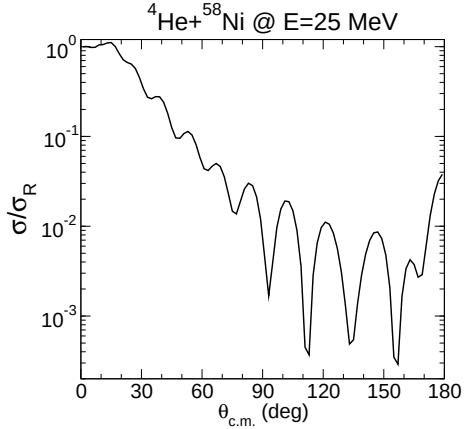












Rutherford scattering

Fresnel

Fraunhöfer