



Nuclear Reactions: applications and examples

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

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Fresco, Xfresco and Sfresco

- 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)

Elastic scattering: optical model

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

- Coulomb potential: charge sphere distribution

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

- Nuclear potential (complex): Woods-Saxon parametrization

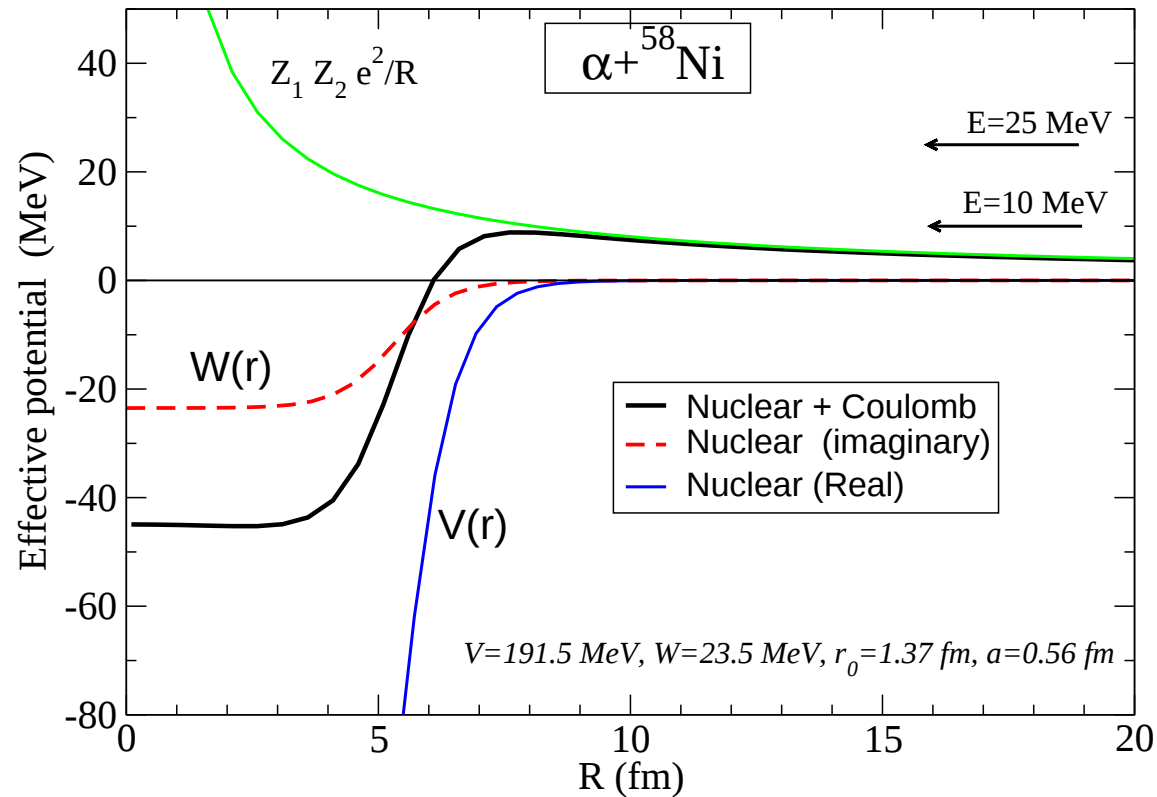
$$U_{\text{nuc}}(R) = V(r) + iW(r) = -\frac{V_0}{1 + \exp\left(\frac{R-R_0}{a_0}\right)} - i \frac{W_0}{1 + \exp\left(\frac{R-R_i}{a_i}\right)}$$

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: ${}^4\text{He} + {}^{58}\text{Ni}$

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 /
```

Elastic scattering example

Essential input variables: FRESKO namelist

```
&FRESKO 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 $R > R_{MATCH}$ asymptotic behaviour is assumed)
- **elab**: laboratory energy
- **jtmax**: maximum total angular momentum (projectile+target+relative)
- **smats**: trace variable
smats=2 → print elastic S-matrix
- **xstabl**: trace variable
xstabl=1 → print cross sections

Elastic scattering with Fresco

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 (± 1)
- **cpot**: index of potential for this pair of states.

Elastic scattering with fresco

```
&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:
$$R = r(ap^{1/3} + at^{1/3})$$
- **type, shape**: potential category 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:

File Edit Run Options About

Integration Trace CC, iterations... Partitions Potentials Overlaps Couplings

Integration

Radial step: HCM 0.1

Matching radius: RMATCH 25.0

Intervals for N-L kernels (RINTP): 0.5

Step size for NL range: HNL 0

Center for NL range: CENTRE 0

NL range: RNL 0

Step size for 2N distance: HNN 0

Min. radius for 2N distance: RMIN 0

Max. radius for 2N distance: RNN 0

State radius for s.p. states: RSP 0

☐ Use Coupled Coulomb w.f. CCWF parameters ...

J interval

JMIN (=J1): 0

JMAX (=J5): 30

☐ Use absend 0

☐ Include only incoming channel for J<JMIN

J intervals ...

Near-side / Far-side analysis

Elastic channel Usual cross sections

Angular range

THMIN 1.00

THMAX 180.00

THINC 2.00

Incoming channel

Energy intervals: ELAB 10.7 0 0 0 NLAB: 0 0 0

Incoming plane waves are present in partition (PEL) 1 with excitation pair (EXL) 1

Specified energies refer to (LIN) projectile for partition (LAB) 1 in excitation pair (LEX) 1

OK

Optical model with XFRESKO

Partitions & states:

File Edit Run Options About

Integration Trace CC, iterations... **Partitions** Potentials Overlaps Couplings

Projectile

Nucleus	A	Z
ALPHA	4	2

Target

Nucleus	A	Z
58Ni	58	28

Q-value: 0.0000

Readstates:

☐ PWF

Do not print xsec
☐ for this partition
[NEX<0]

Add

Replace

Insert

Delete

Projectile	Mass	Z	Target	Mass	Z	Q value	PWF	xsec?	Readstates
ALPHA	4	2	58Ni	58	28	0.0000	F	T	

Excited states for selected partition

Index: 1 J Copy Band E K T

	J	Copy	Band	E	K	T
Projectile	0.0		+	0.0		
Target	0.0		+	0.0		

☐ FEXCH ☐ IGNORE

INFAM=0 0

OUTFAM=0

Optical potential [CPOT] : 1

Replace

Insert after

Add

Delete

J proj.	Copy P.	Band P.	E proj.	K proj.	T proj.	cpot	J targ.	Copy T	Band T.	E targ.	K targ.	T targ.	EX
0.0	1	0.0			1	0.0		1	0.0				F

OK

Optical model with XFRESKO

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
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OK

Useful output information in OM calculations

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

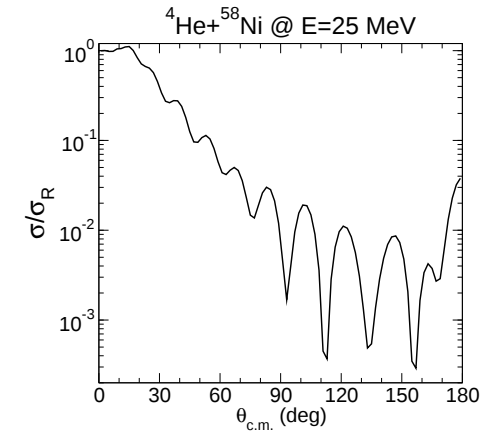
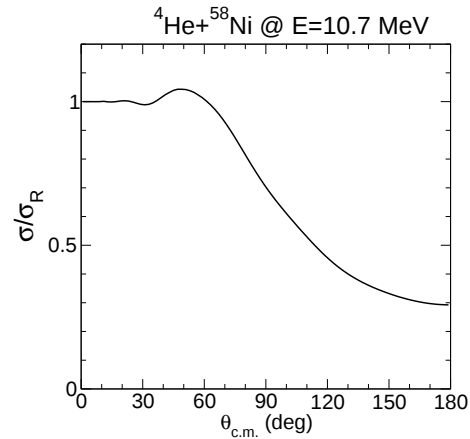
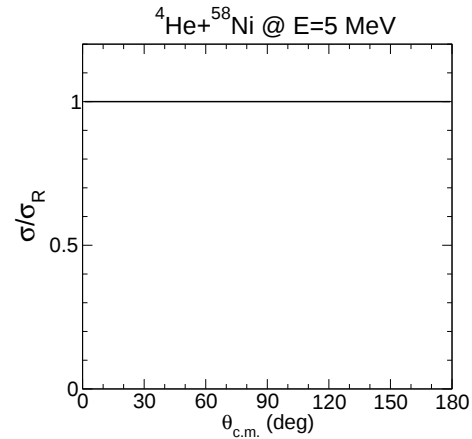
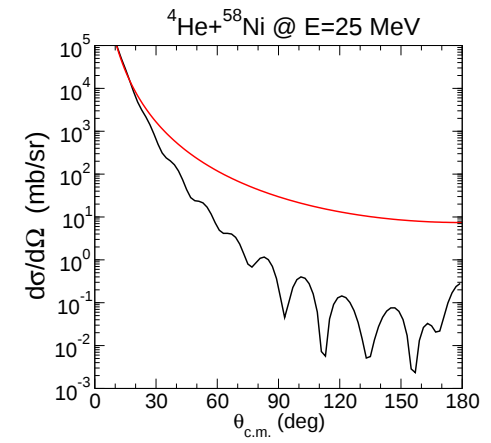
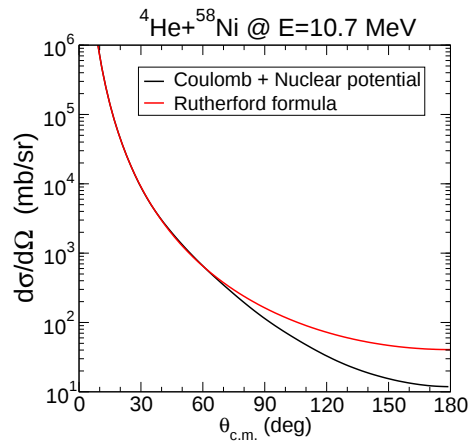
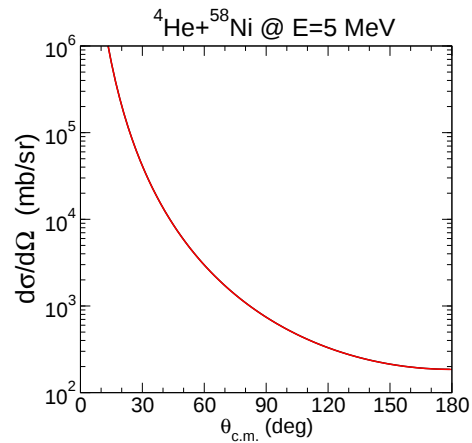
Elastic scattering: optical model

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

E_{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

- $\eta \gg 1$: 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

Fraunhofer