united nations educational, scientific and cultural organization

international atomic energy agency

the **abdus salam** international centre for theoretical physics

ICTP 40th Anniversary

SMR.1555 - 32

Workshop on
Nuclear Reaction Data and Nuclear Reactors:
Physics, Design and Safety

16 February - 12 March 2004

Coupled-Channels

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COUPLED CHANNEL vs SINGLE CHANNEL OMPs

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Workshop on Nuclear Reaction Data and Nuclear Reactors - Physics, Design and Safety

ICTP, Trieste, Italy, 16 February – 12 March 2004

OVERVIEW

- Spherical OMP for applications
- Coupled channel method
- EMPIRE optical model calculations

SINGLE CHANNEL EQUATION

$$\left\{ \frac{d^2}{dr^2} - \frac{l(l+1)}{r^2} + k^2 - \frac{2\mu}{\hbar^2} \left(U(r) + d_l^j \, U_{so}(r) \right) \right\} \psi_l^j(r) = 0$$

$$d_l^j = d_{so} \left(j(j+1) - l(l+1) - s(s+1) \right) / 2$$

Neutron-nucleus spherical OMP

$$U(r) = V(r) + i \cdot W(r)$$

$$V(r) = -V_v \cdot f_{WS}(r) - V_s \cdot g_{WS}(r)$$
$$W(r) = -W_v \cdot f_{WS}(r) - W_s \cdot g_{WS}(r)$$

$$\left(\frac{\hbar}{m_\pi c}\right)^2 (V_{so} + iW_{so}) \cdot \frac{1}{r} \cdot \frac{df_{WS}}{dr} (\vec{l} \cdot \vec{\sigma})$$

Spherical Optical Model

Energy dependence (I)

Functional form of the real and imaginary potentials:

$$V_{HF}(E) = V_0 \cdot exp(-\alpha_{HF}(E - E_F))$$

$$W_V(E) = A_V \frac{(E - E_F)^4}{(E - E_F)^4 + (B_V)^4}$$

$$W_S(E) = A_S \frac{(E - E_F)^4}{(E - E_F)^4 + (B_V)^4} \cdot exp(-C_S|E - E_F|)$$

Spherical Optical Model

Energy dependence (II)

$$W_V(E)=\begin{cases} 0 & E_F < E < E_P \\ A_V \dfrac{(E-E_P)^n}{(E-E_P)^n+(B_V)^n} & E > E_P \end{cases}$$

$$W_S(E)=\begin{cases} 0 & E_F < E < E_P \\ A_S\, e^{-C_S|E-E_P|} \dfrac{(E-E_P)^m}{(E-E_P)^m+(B_S)^m} & E > E_P \end{cases}$$

with the symmetry condition:

$$W(2E_F-E)=W(E)$$

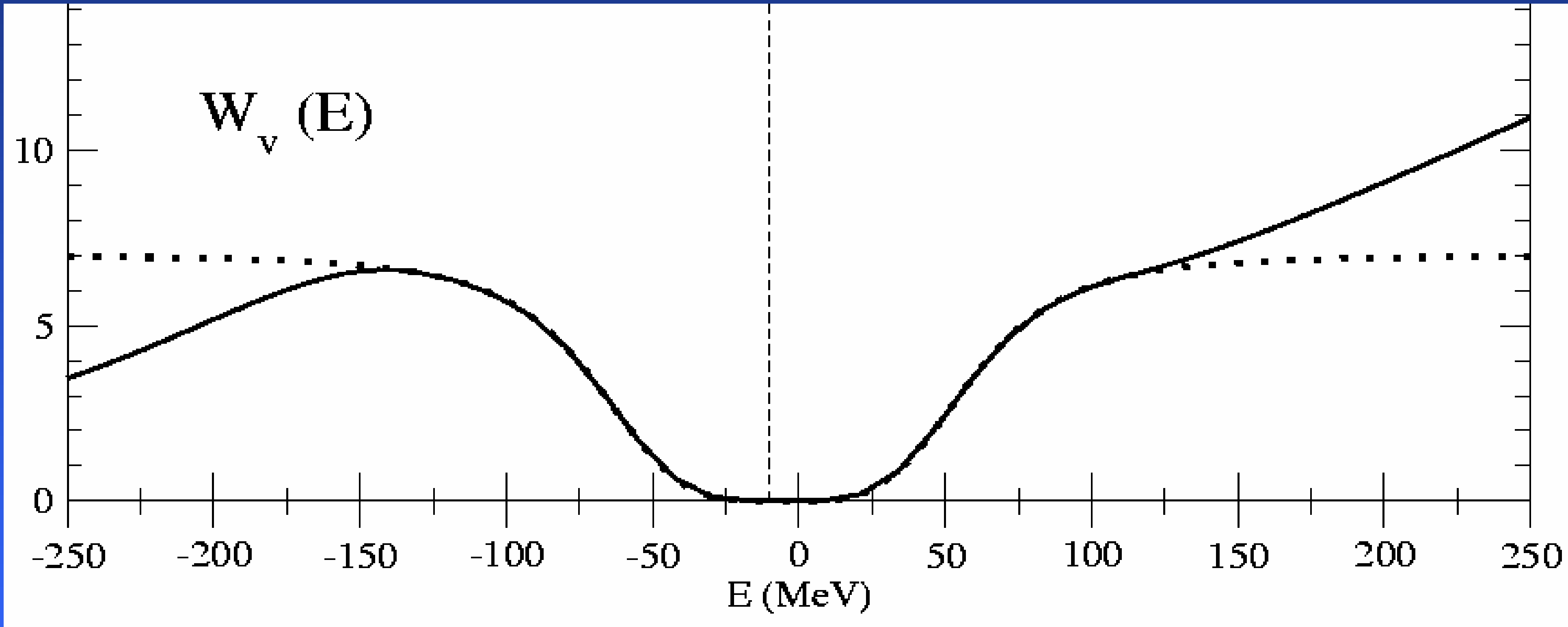
Spherical Optical Model

Non-locality corrections

$$\begin{cases} W_V(E)\left[1-\dfrac{(E_F-E-E_a)^2}{(E_F-E-E_a)^2+E_a^2}\right] & E \quad <E_F-E_a \\ \\ W_V(E)+\alpha_V\cdot\left[\sqrt{E}+\dfrac{(E_F+E_a)^{3/2}}{2E}-\frac{3}{2}\sqrt{(E_F+E_a)}\right] & E \quad >E_F+E_a \end{cases}$$

$$W_S(E)+\alpha_S\cdot\left[\sqrt{E}+\dfrac{(E_F+E_a)^{3/2}}{2E}-\frac{3}{2}\sqrt{(E_F+E_a)}\right] \quad E \quad >E_F+E_a$$

Imaginary potential extended to negative energies



Dispersive Optical Model

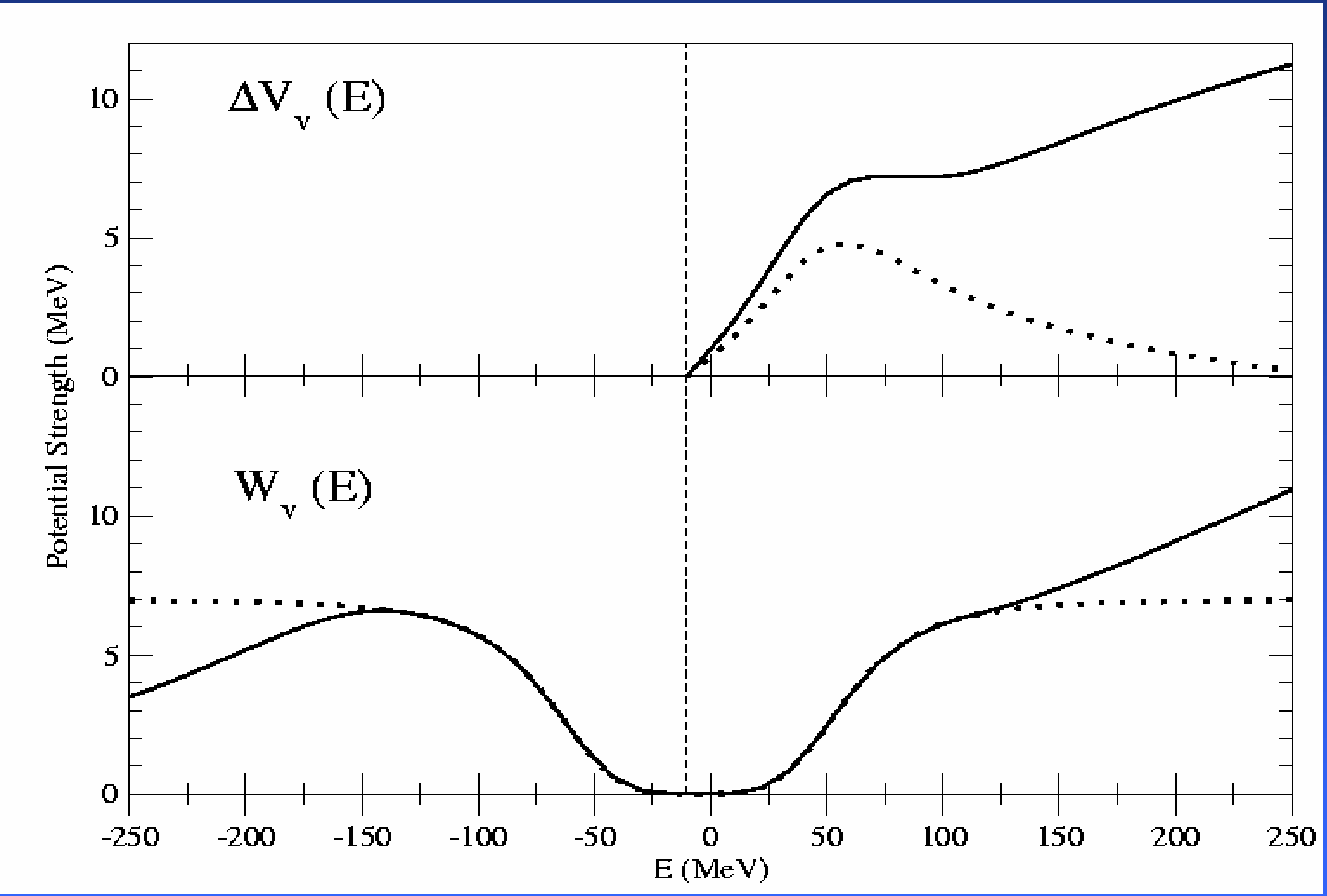
$$\Delta V(E) = \frac{\mathcal{P}}{\pi}\int_{-\infty}^{\infty} \frac{W(E')}{E' - E} dE'$$

$$V_V(E) = V_{HF}(E) + \Delta V_V(E) + \Delta V_<(E) + \alpha_V \Delta V_>(E)$$

$$V_S(E) = \Delta V_S(E) + \alpha_S \Delta V_>(E)$$

$W(E)$ must be defined in the interval $-\infty < E < \infty$

Imaginary potential W and dispersive contribution



Spherical Optical Model

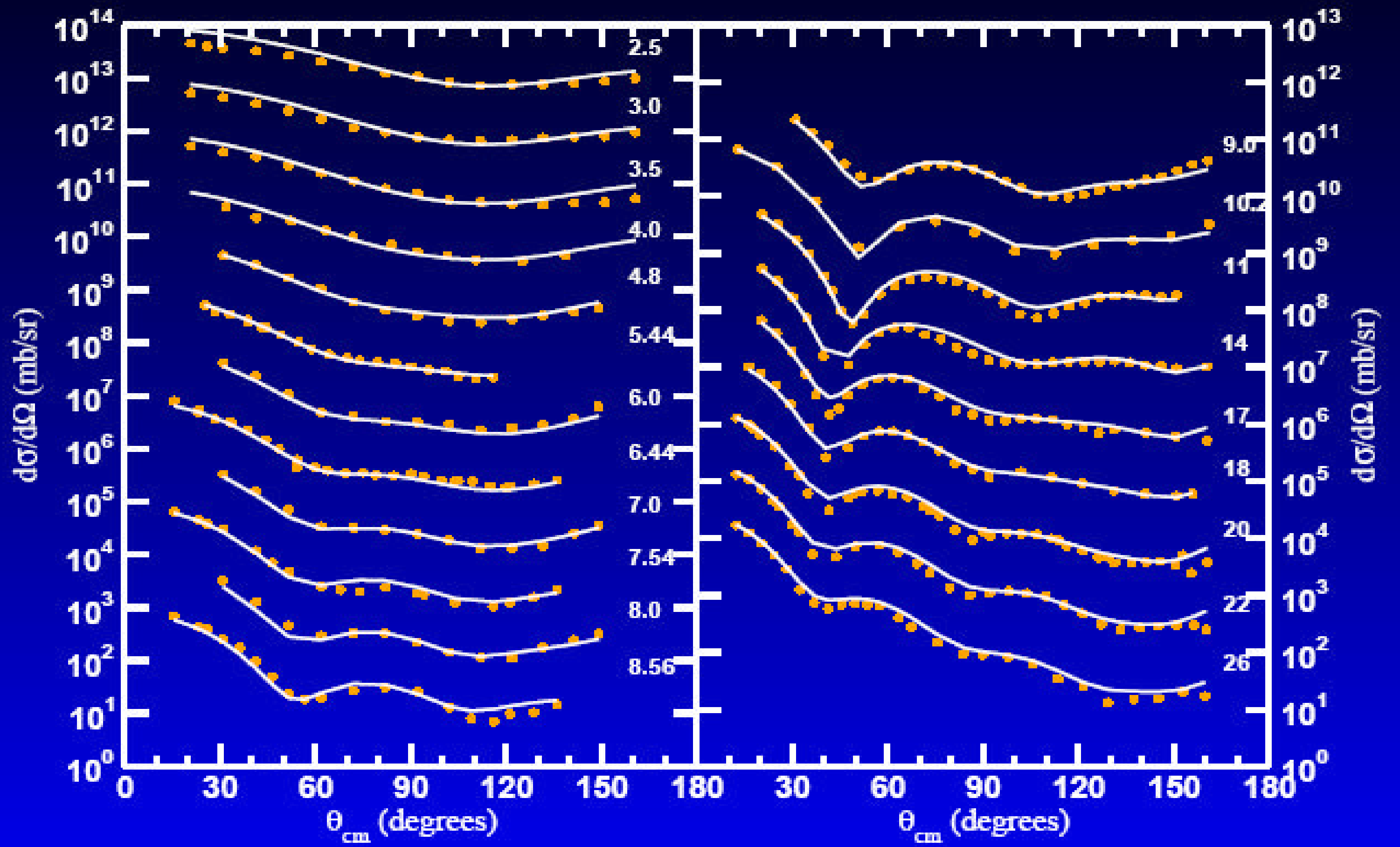
Energy dependence (III)

Functional form of the spin-orbit potentials:

$$V_{so} = A_{so} \cdot \exp(B_{so}(E - E_F))$$

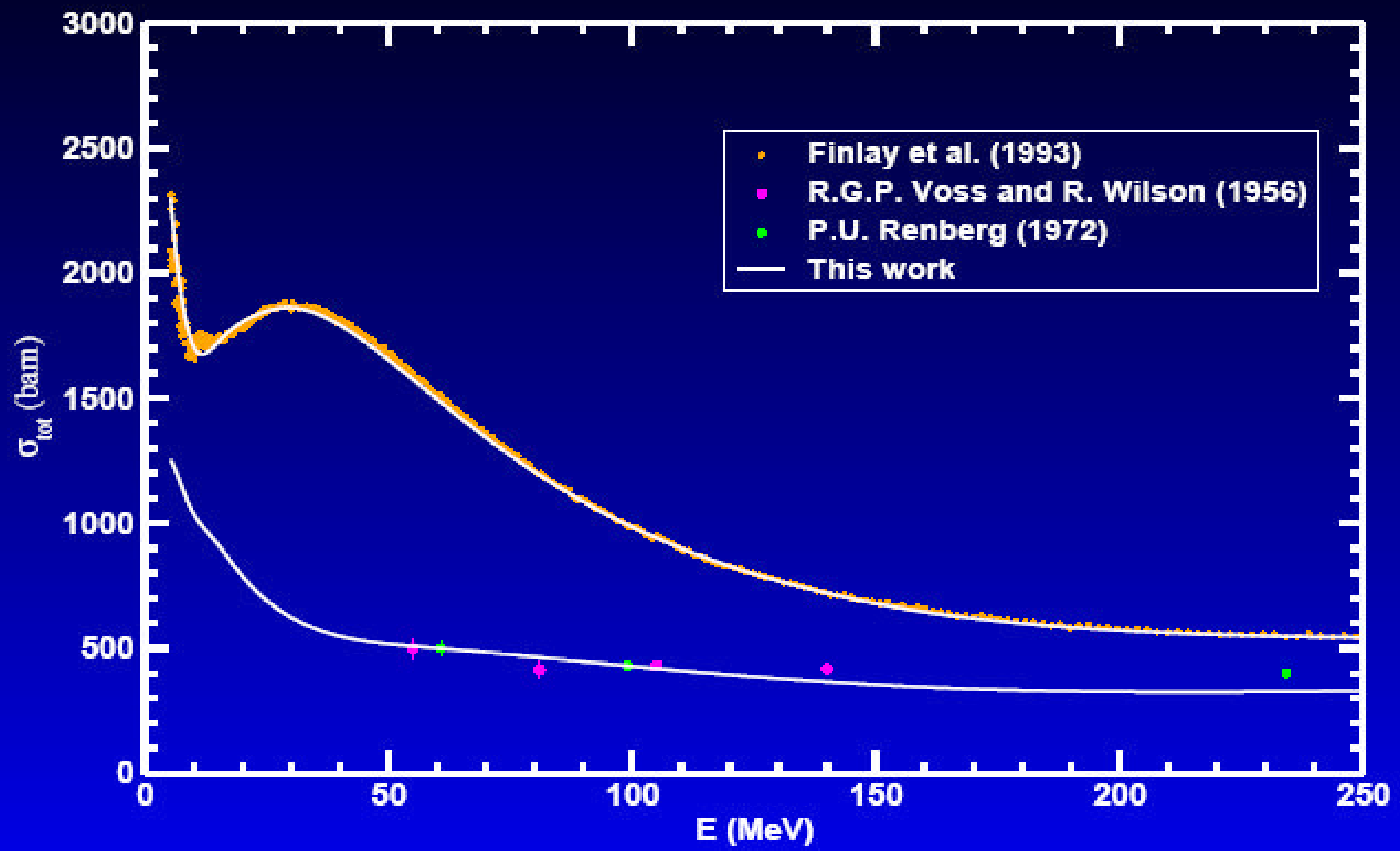
$$W_{so} = C_{so} \frac{(E - E_F)^2}{(E - E_F)^2 + D_{so}^2}$$

n+^{27}Al - Elastic scattering



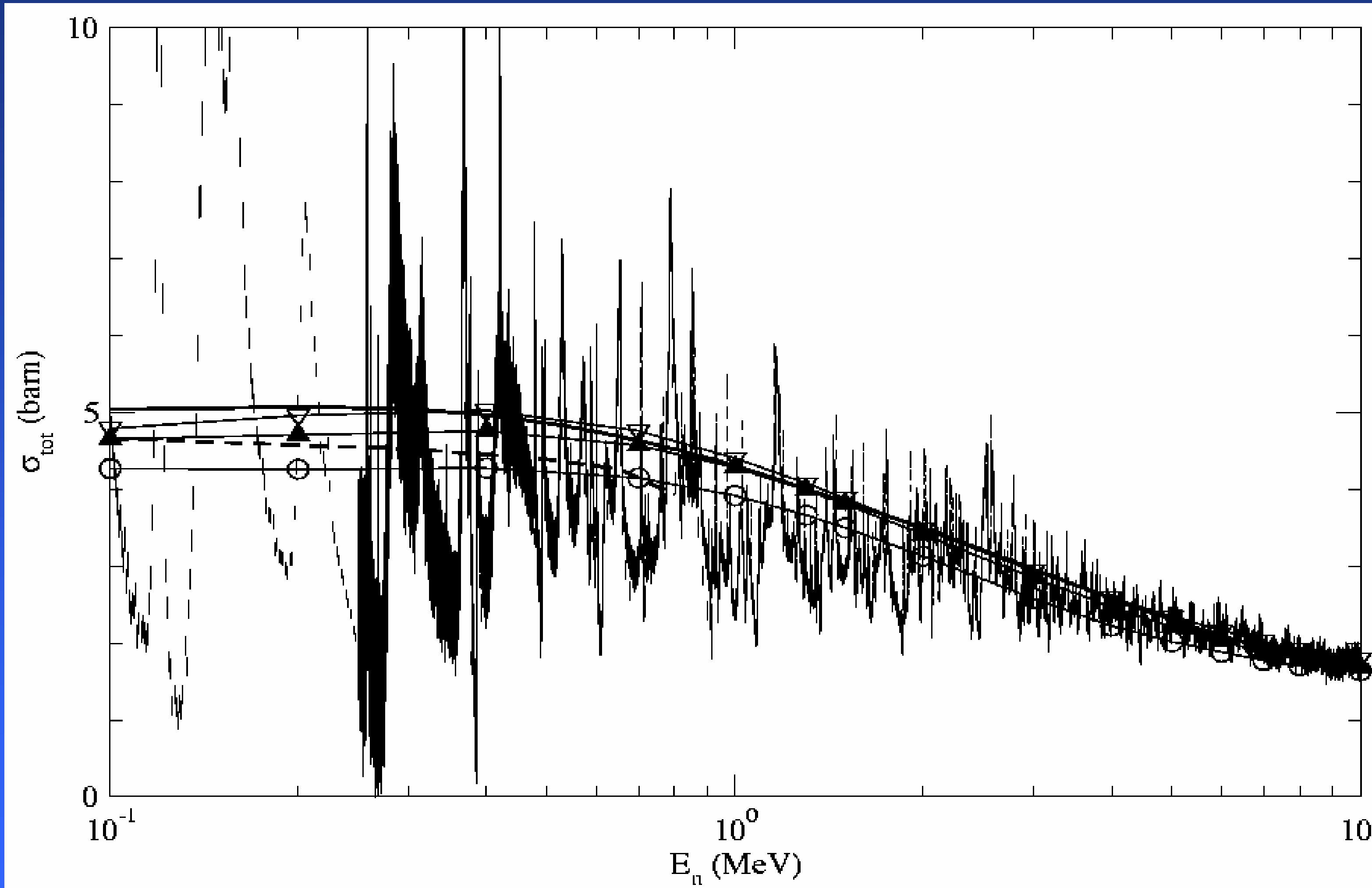
A.Molina Ph.D.Thesis, Univ.Sevilla 2003

n+^{27}Al - Total and Reaction xs

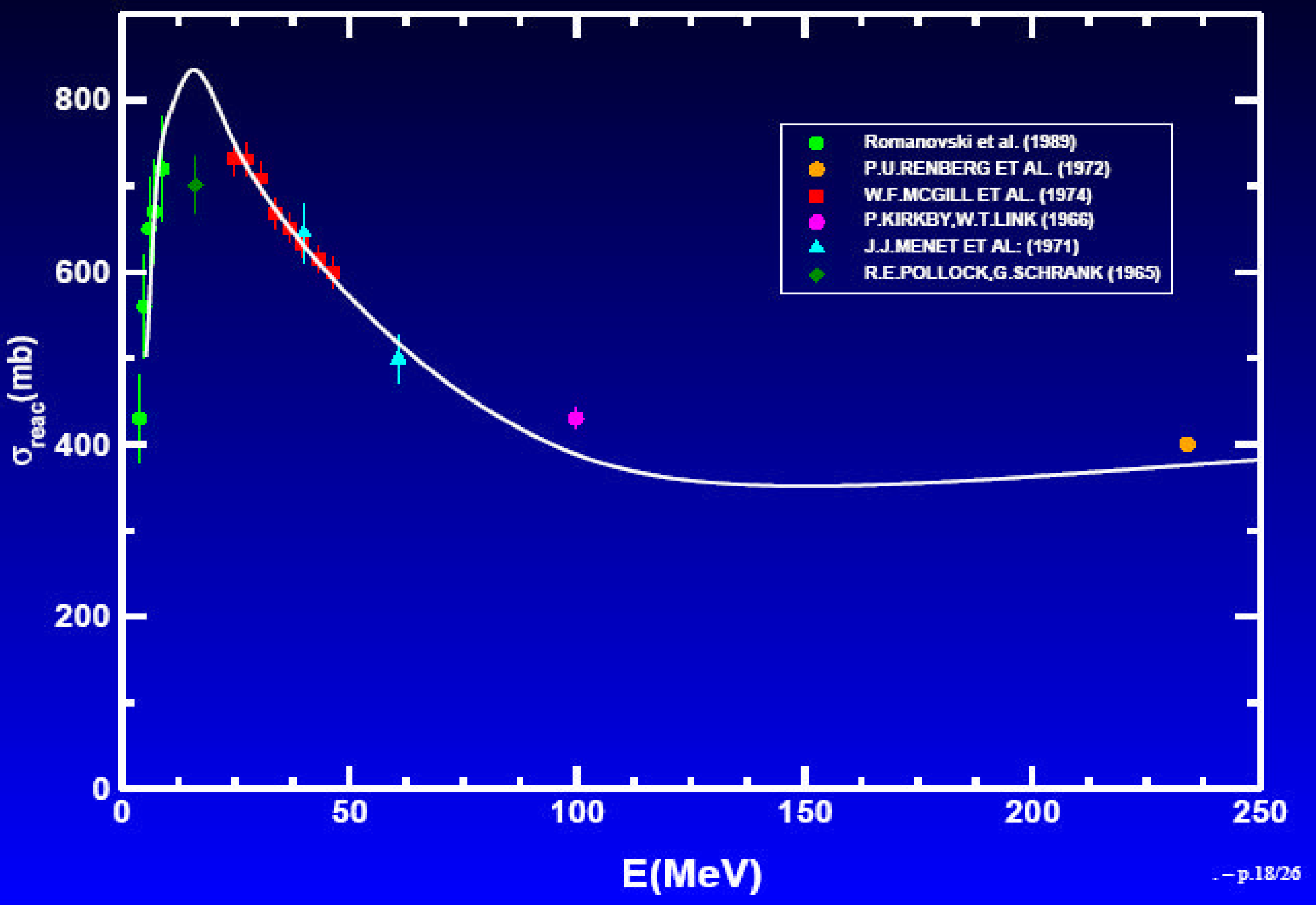


A.Molina Ph.D.Thesis, Univ.Sevilla 2003

OPTICAL MODEL AVERAGING

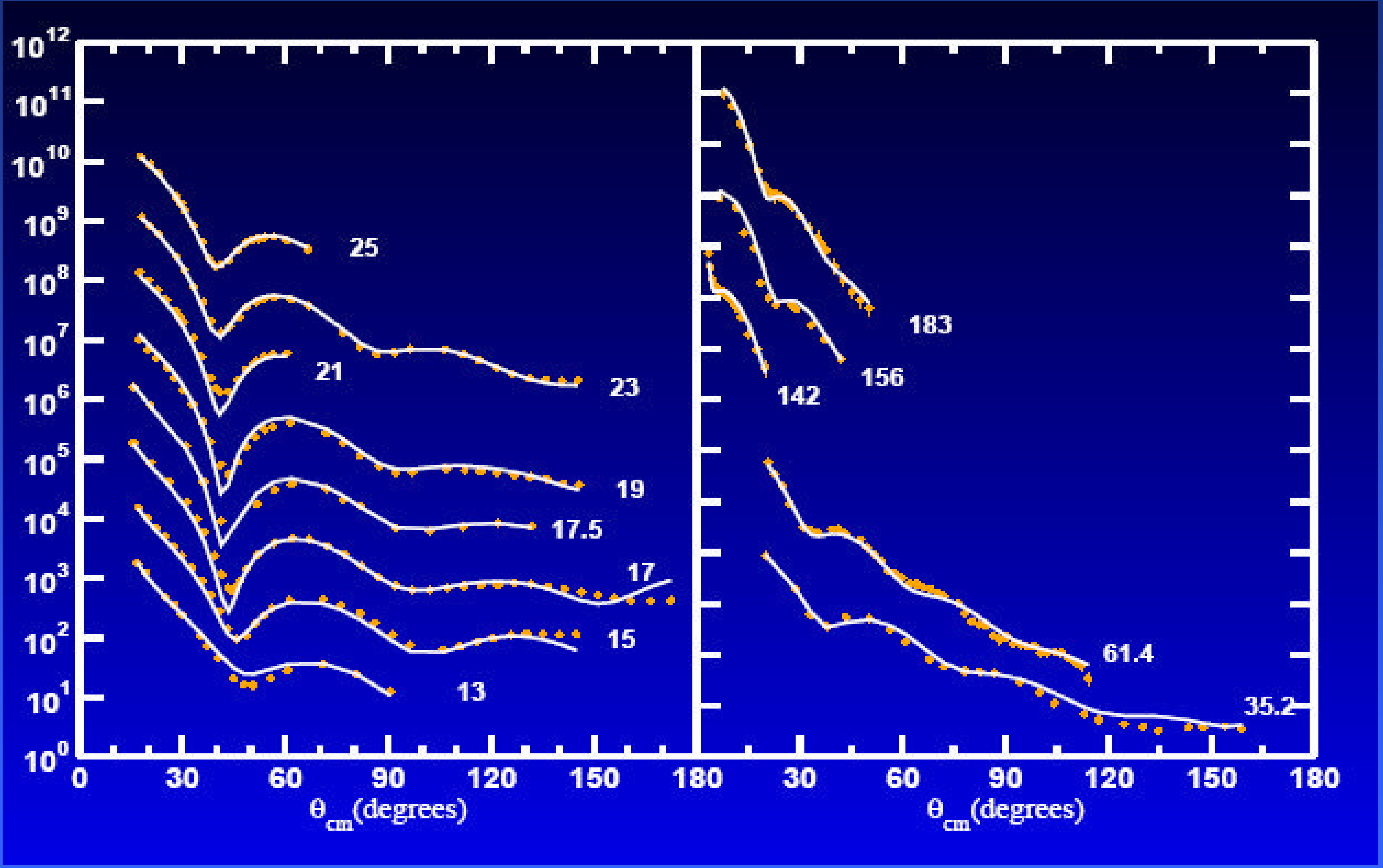


p+^{27}Al - Reaction xs



A.Molina Ph.D.Thesis, Univ.Sevilla 2003

p+^{27}Al - Elastic scattering



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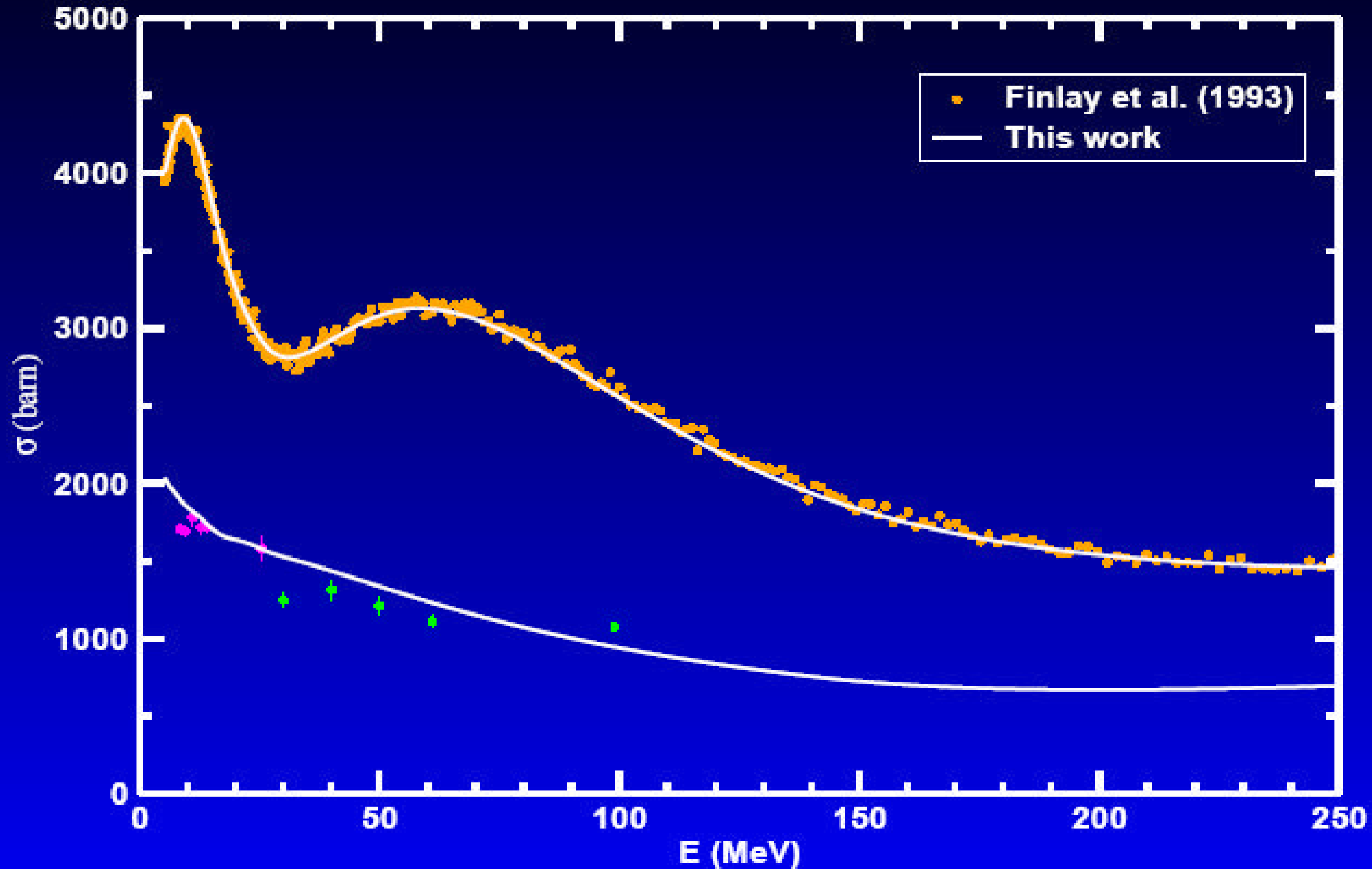
n+^{90}Zr - Total and Reaction xs



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SINGLE CHANNEL POTENTIAL

The single-channel or spherical optical model treates the target nucleus as if it was spherical.

Even those that are spherical are often susceptible to shape oscillations → *g lized optical model*

COUPLED-CHANNEL POTENTIAL

*T Tamura,"***Coupled-Channel Approach to Nuclear Reactions"**
Annual Review of Nuclear Science, Vol. 19 (1969) 99-138
(doi:10.1146/annurev.ns.19.120169.000531)

The expected deviation from spherical symmetry is considered by modifying the radii R_i of the OMP

VIBRATIONAL MODEL – SPHERICAL NUCLEI

$$
\begin{aligned}
R_i &= R_{0i}\left(1+\sum_{\lambda\mu} a_{\lambda\mu}\, Y_{\lambda\mu}(\hat{r})\right) \\
&= R_{0i}\left(1+\sum_{\lambda} \frac{\beta_\lambda}{\sqrt{2\lambda+1}} \sum_{\mu} (b^\dagger_{\lambda\mu} + (-)^\mu\, b_{\lambda-\mu})\, Y_{\lambda\mu}(\hat{r})\right)
\end{aligned}
$$

RIGID ROTATOR – AXIAL SIMMETRY

$$
R_i(\theta') = R_{0i}\left(1+\sum_{\lambda} \beta_\lambda\, Y_{\lambda 0}(\theta')\right)
$$

SOFT ROTATOR – TRIAXIAL SHAPE

$$R(\theta', \varphi') = R_0 \left\{ 1 + \sum_{\lambda\mu} \beta_{\lambda\mu} Y_{\lambda\mu}(\theta', \varphi') \right\}$$

$$= R_0 \left\{ 1 + \beta_2 \left[\cos\gamma\, Y_{20}(\theta', \varphi') + \frac{1}{\sqrt{2}} \sin\gamma \left(Y_{22}(\theta', \varphi') + Y_{2-2}(\theta', \varphi') \right) \right] \right.$$

$$+ \beta_3 \left[\cos\eta\, Y_{30}(\theta', \varphi') + \frac{1}{\sqrt{2}} \sin\eta \left(Y_{32}(\theta', \varphi') + Y_{3-2}(\theta', \varphi') \right) \right]$$

$$\left. + b_{40} Y_{40}(\theta', \varphi') + \sum_{\mu=2,4} b_{4\mu} \left(Y_{4\mu}(\theta', \varphi') + Y_{4-\mu}(\theta', \varphi') \right) \right\},$$

where $0 \le \beta_2 < \infty$, $-\infty < \beta_3 < \infty$, and $\frac{n\pi}{3} \le \gamma \le \frac{(n+1)\pi}{3}$.

$$b_{40} = \beta_4 \left(\sqrt{7/12} \cos\delta_4 + \sqrt{5/12} \sin\delta_4 \cos\gamma_4 \right),$$

$$b_{42} = \beta_4 \left(\sqrt{12} \sin\delta_4 \sin\gamma_4 \right),$$

$$b_{44} = \beta_4 \sqrt{1/2} \left(\sqrt{5/12} \cos\delta_4 + \sqrt{7/12} \sin\delta_4 \cos\gamma_4 \right)$$

SINGLE CHANNEL EQUATION

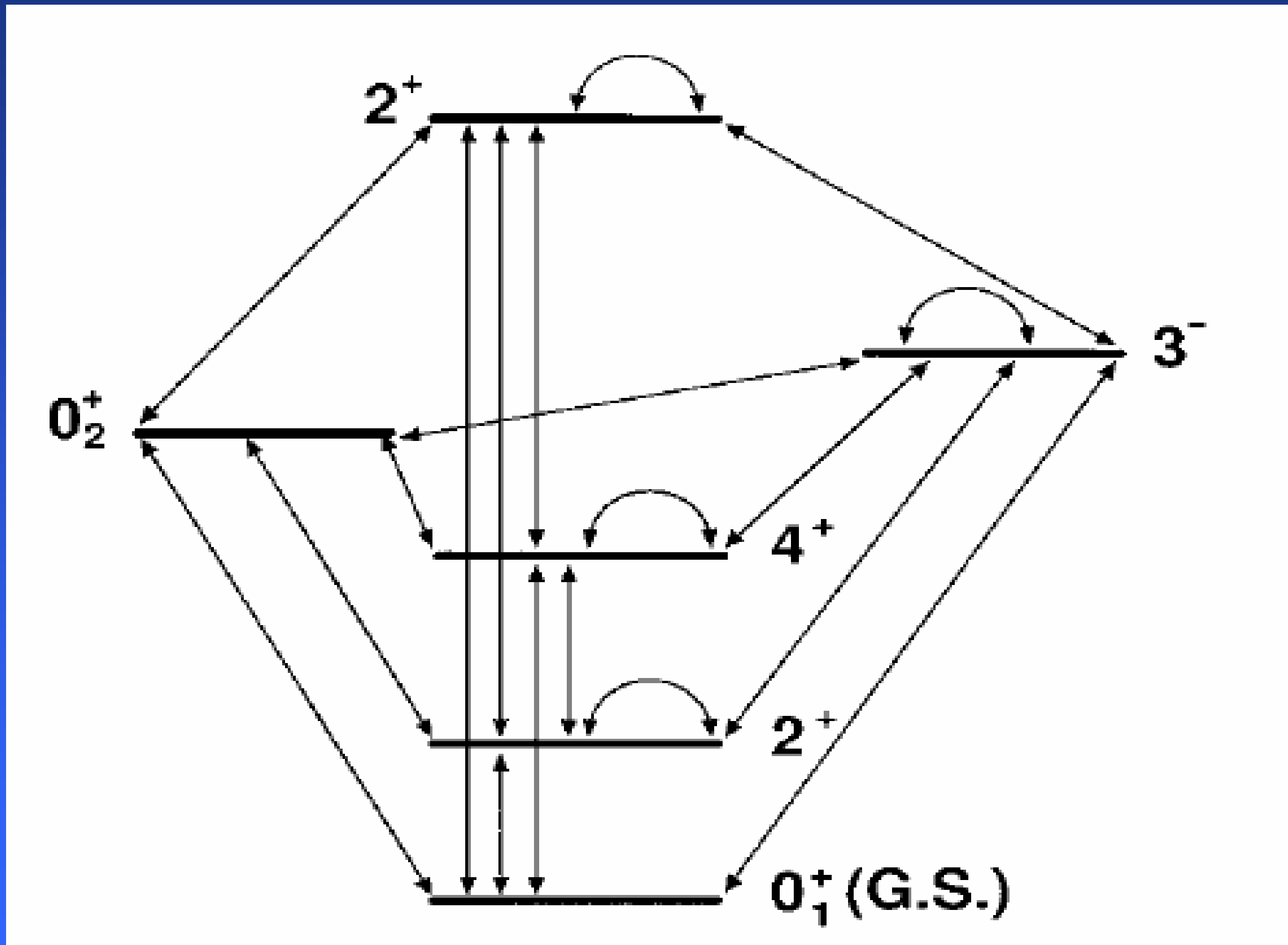
$$\left\{ \frac{d^2}{dr^2} - \frac{l(l+1)}{r^2} + k^2 - \frac{2\mu}{\hbar^2} \Big(U(r) + d_l^j \, U_{so}(r) \Big) \right\} \psi_l^j(r) = 0$$

COUPLED CHANNEL EQUATIONS

$$\frac{\hbar^2}{2\mu} \left\{ \frac{d^2}{dr^2} - \frac{l'(l'+1)}{r^2} + k_{c'}^2 \right\} \psi^J_{l'j'c',ljc}(r) - \sum_{l''j''c''} \mathcal{U}^J_{l'j'c',l''j''c''}(r) \psi^J_{l''j''c'',ljc}(r) = 0 \,,$$

$$\mathcal{U}^J_{l'j'c',ljc}(r) = \int d^3 r_{int} \, d\Omega \mathcal{Y}^{JM\dagger}_{l'sj'c'}(\hat{r}) U_{opt}(\vec{r}, \vec{r}_{int}) \mathcal{Y}^{JM}_{lsjc}(\hat{r}) \,.$$

Coupling scheme for matrix element calculations



Journal of NUCLEAR SCIENCE and TECHNOLOGY, Vol. 40, No. 9, p. 635–643 (September 2003)

ORIGINAL PAPER

Coupled-Channels Analysis of Nucleon Interaction Data of $^{28,30}Si$ up to 200 MeV Based on the Soft Rotator Model

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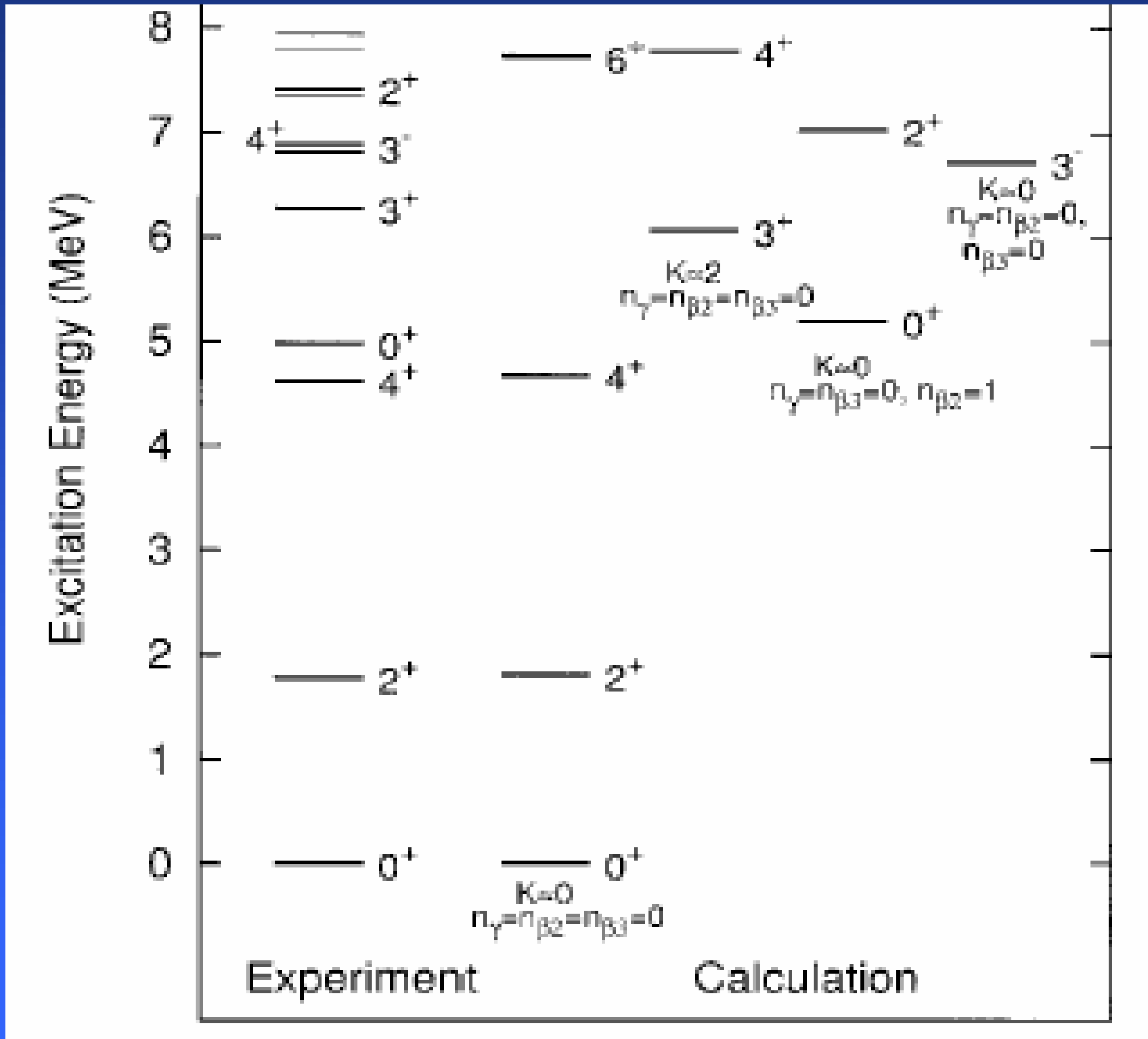
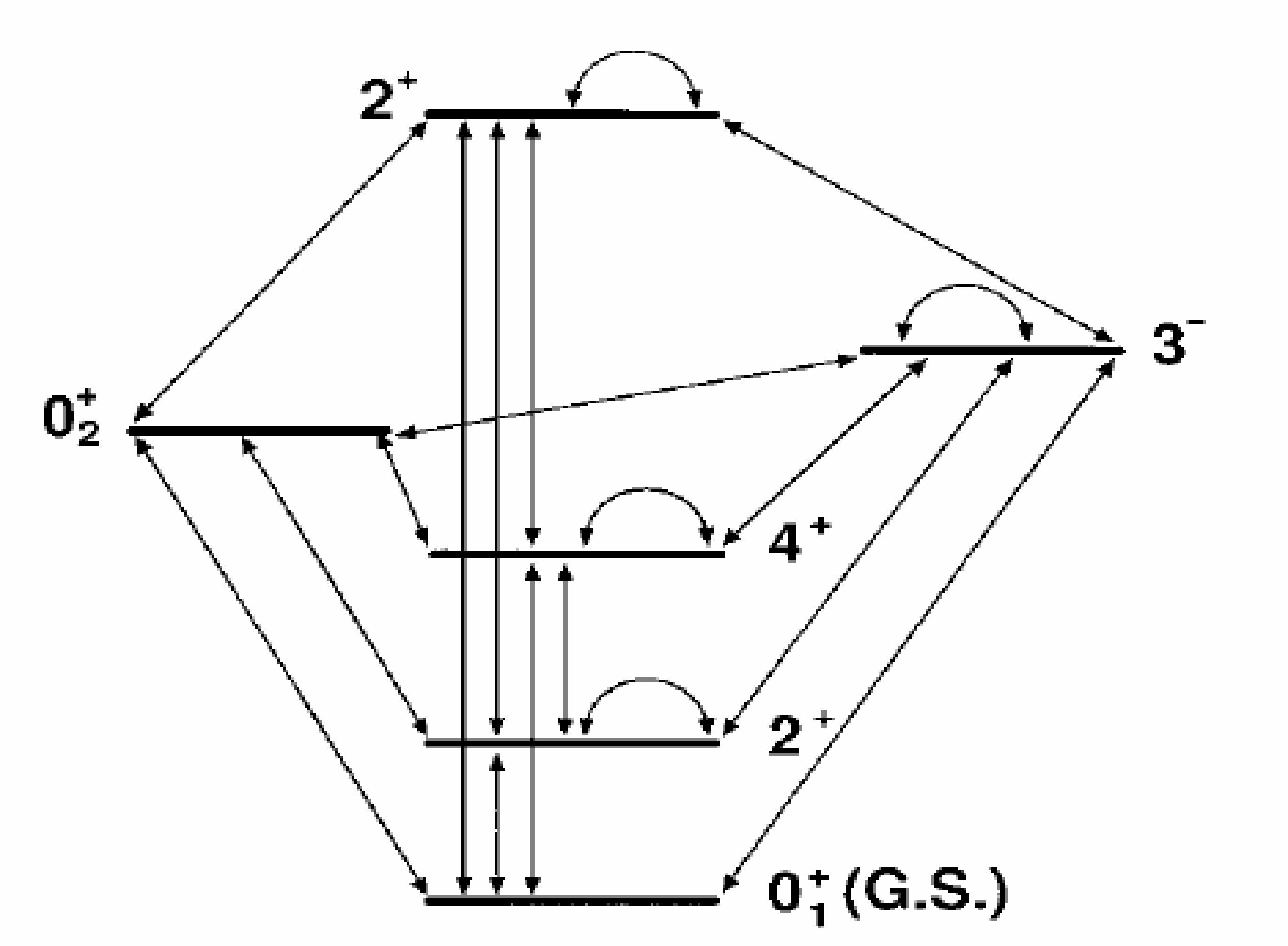
[1] *Institute of Applied Physics and Computational Mathematics, No. 6, Huayuan Road, Hai-Dian District, Beijing 100088, China*
[2] *Department of Advanced Energy Engineering Science, Kyushu University, Kasuga-koen, Kasuga-shi, Fukuoka 816-8580*
[3] *Joint Institute of Energy and Nuclear Research-Sosny, 220109, Minsk-Sosny, Belarus*
[4] *Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki 319-1195*

First step: Nuclear structure calculation



Second step: Define the coupling scheme

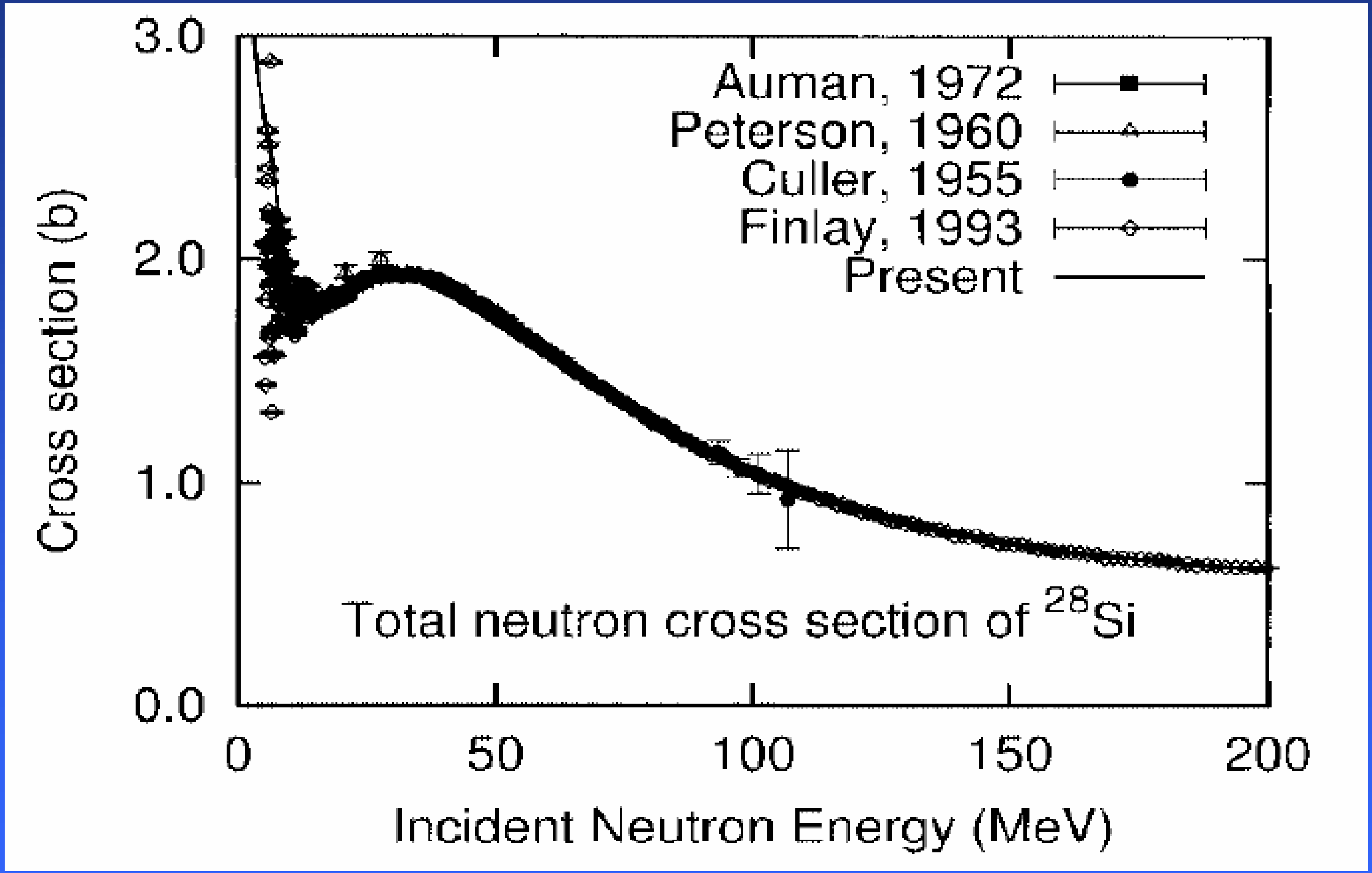


3^{rd} step: Solve the CC equations

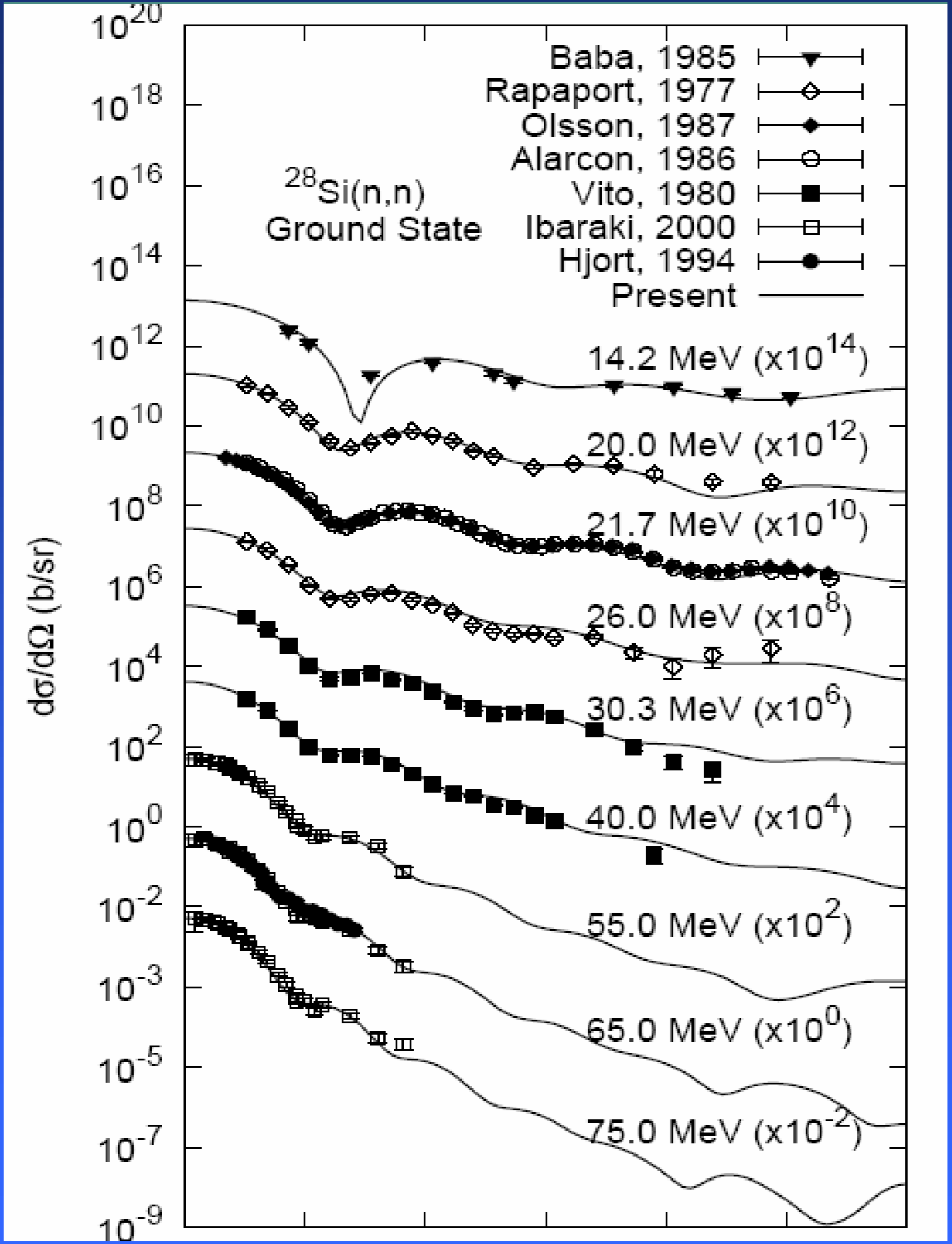
Calculate cross section, angular distribution and polarization observables for both, elastic and inelastic scattering on coupled levels.

(EMPIRE/ECIS …)

TOTAL xs (similar to spherical OMP)



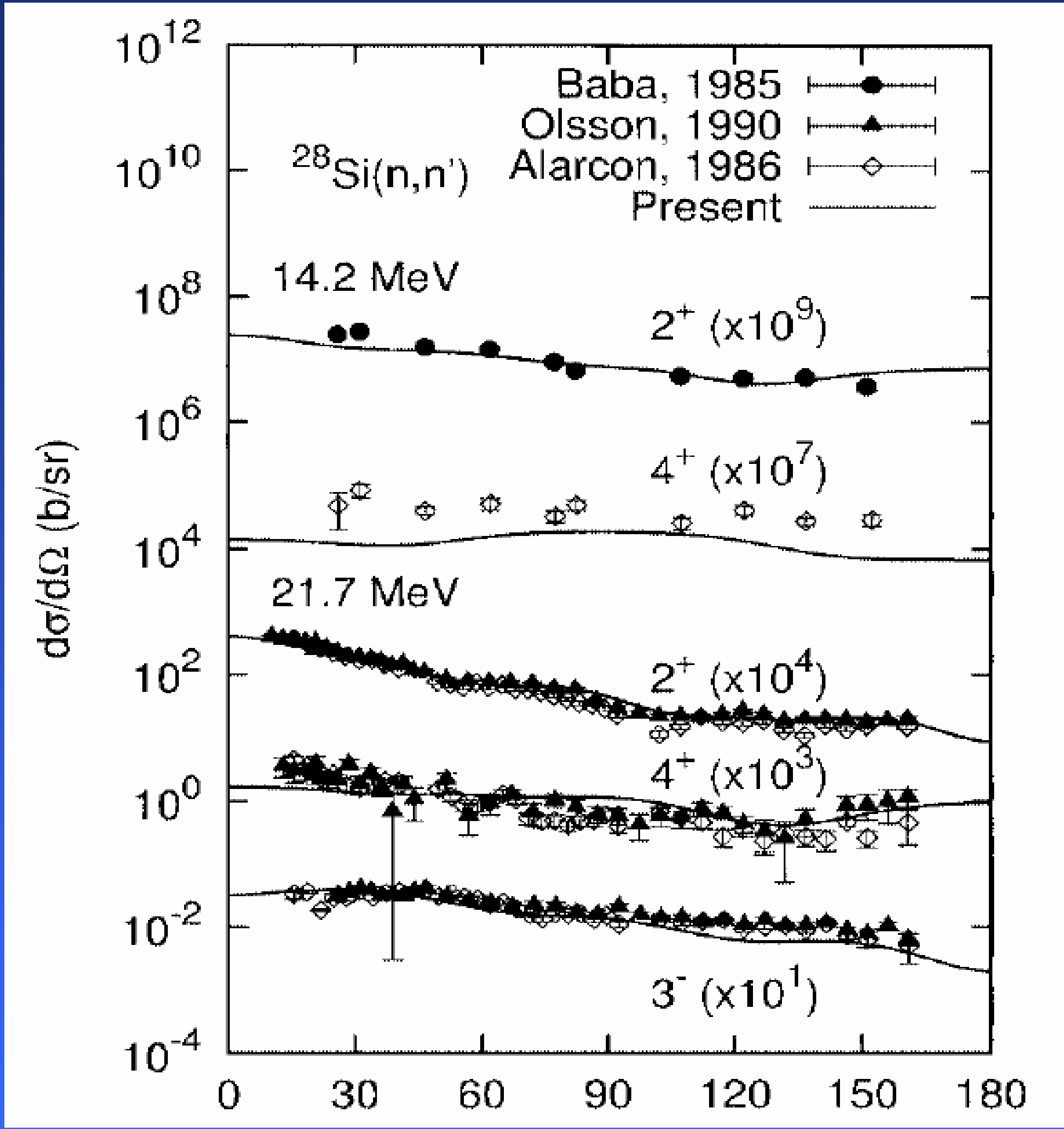
ELASTIC xs (~ spher.OMP)



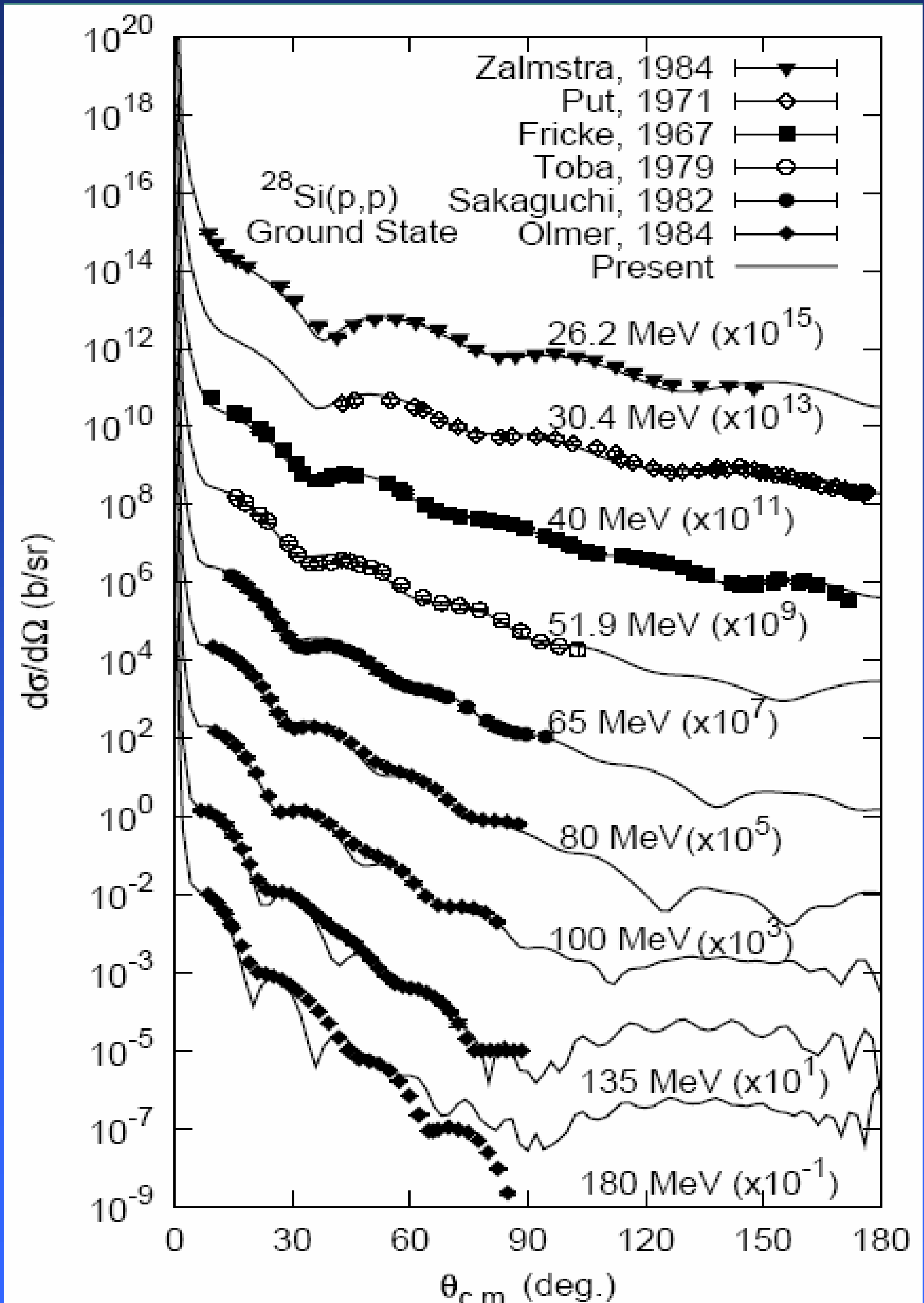
PLUS

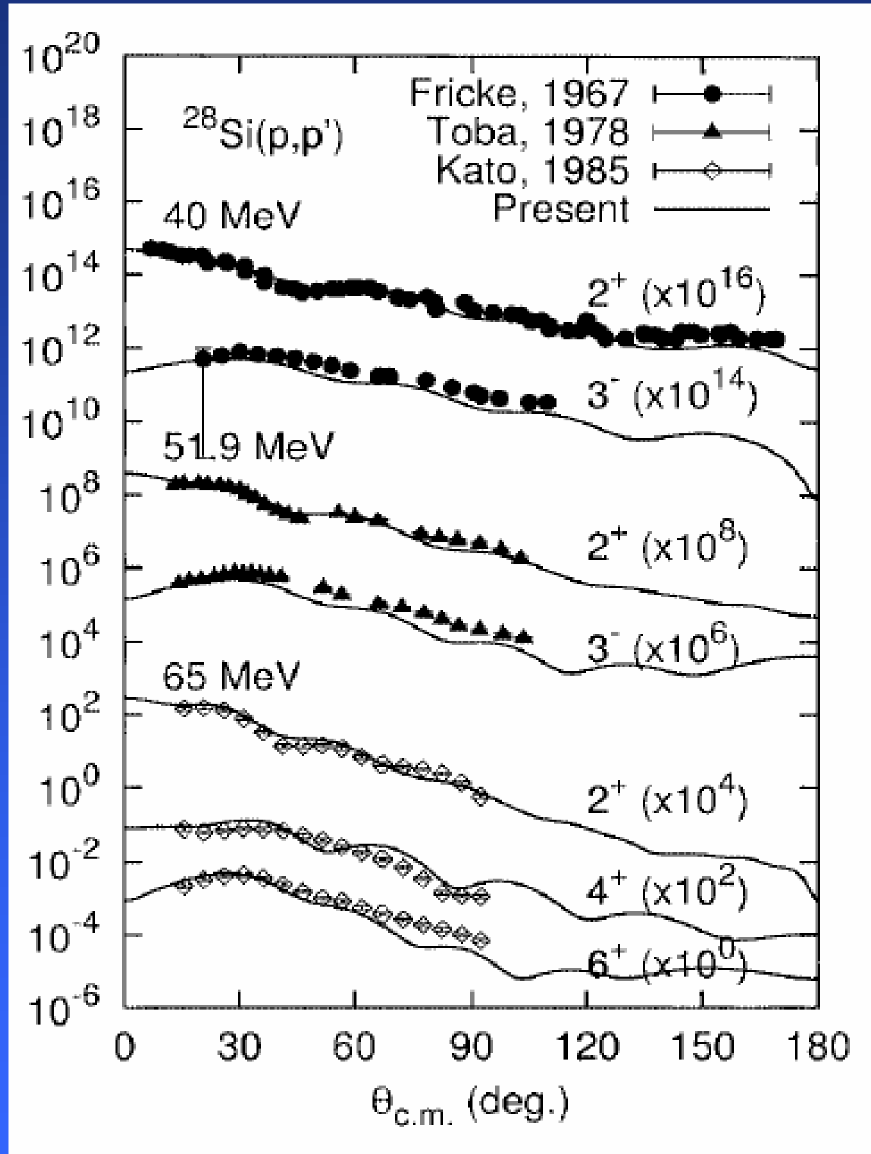
INELASTIC xs

for coupled levels !!



PROTON CHANNEL





Solve the CC equations (EMPIRE)

EMPIRE/ECIS highlights

- Spherical optical model (DIRECT = 0 *default*)
- Coupled-channel method (DIRECT = 1,2)
  (vibrational, rotational, vibrational-rotational)
- DWBA calculations (DIRECT = 3)

RIPL-II optical model database

Lib. No.	Inc. Part.	Model Type	Disp Pot	Rel Pot	Z-Range	A-Range	E-Range (MeV)	Ref. No.	First Author
neutrons									

200	n	spher.	no	no	0-69	0-146	0.0- 20.0	1	S.Igarasi
240	n	spher.	no	no	0-69	0-146	0.0- 20.0	2	S.Igarasi
2001	n	spher.	no	yes	6-82	12-208	50.0-400.0	4	D.G.Madland
101	n	spher.	no	no	12-83	24-209	11.0- 11.0	5	J.C.Ferrer
116	n	spher.	no	no	20-83	40-209	0.0- 5.0	12	P.A.Moldauer
401	n	spher.	no	no	20-92	40-238	0.0- 25.0	13	D.Wilmore
2100	n	spher.	no	no	20-83	40-209	10.0- 26.0	14	R.L.Varner
100	n	spher.	no	no	20-92	40-238	10.0- 50.0	15	F.D.Becchetti
800	n	spher.	no	no	20-83	40-210	0.0-155.0	16	C.A.Engelbrecht
404	n	spher.	no	no	23-41	50- 95	0.0- 30.0	17	B.Strohmaier
600	n	CC rot.	no	no	90-103	227-260	0.0- 20.0	56	G.Vladuca

Part of the EMPIRE input file for CC calculation

```
DIRECT    1.
DIRPOT  -600.
OMPOT  -2002.    1
OMPOT  -5405.    2
....
```

First run produces "collective level file"

```
Collective levels selected automatically from ...
Dyn.deformations are not used in symm.rot.model
 94 240      nucleus is treated as deformed

   Ncoll   Lmax IDef   Kgs   (Def(1,j),j=2,IDef,2)
      6     4     4     .0    .223E+00    .000E+00

 N    E[MeV]   J    pi  Nph  L   K   Dyn.Def.
 1    .0000    .0   1.   0   0   0    .100E-01
 2    .0428   2.0   1.   0   0   0    .100E-01
 3    .1417   4.0   1.   0   0   0    .100E-01
 4    .2943   6.0   1.   0   0   0    .100E-01
 5    .8600   0.0   1.   1   0   0    .08
 6    .900    2.0   1.   1   2   0    .095
```

The "collective level file" should be edited to modify the parameters of the nuclear structure model

```
Collective levels selected automatically from ...
Dyn.deformations are not used in symm.rot.model
 94 240      nucleus is treated as deformed

   Ncoll   Lmax IDef   Kgs   (Def(1,j),j=2,IDef,2)
      6      4     4     .0   .223E+00    .000E+00

 N    E[MeV]   J    pi  Nph  L   K   Dyn.Def.
 1    .0000    .0   1.   0   0   0    .100E-01
 2    .0428   2.0   1.   0   0   0    .100E-01
 3    .1417   4.0   1.   0   0   0    .100E-01
 4    .2943   6.0   1.   0   0   0    .100E-01
 5    .8600   0.0   1.   1   0   0    .08
 6    .900    2.0   1.   1   2   0    .095
```

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Trieste, Febr.2004

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