Theory for low-energy nuclear reactions

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Outline

- Why are we interested in low-energy reactions?
  Why do we need theory to describe reaction processes?
- What types of reactions are relevant in this context?
- How do we describe compound-nuclear reactions?
- Which physics models and inputs are needed?
- Challenges and open questions

Why are we interested in low-energy reactions?

Why do we need theory to describe reaction processes?

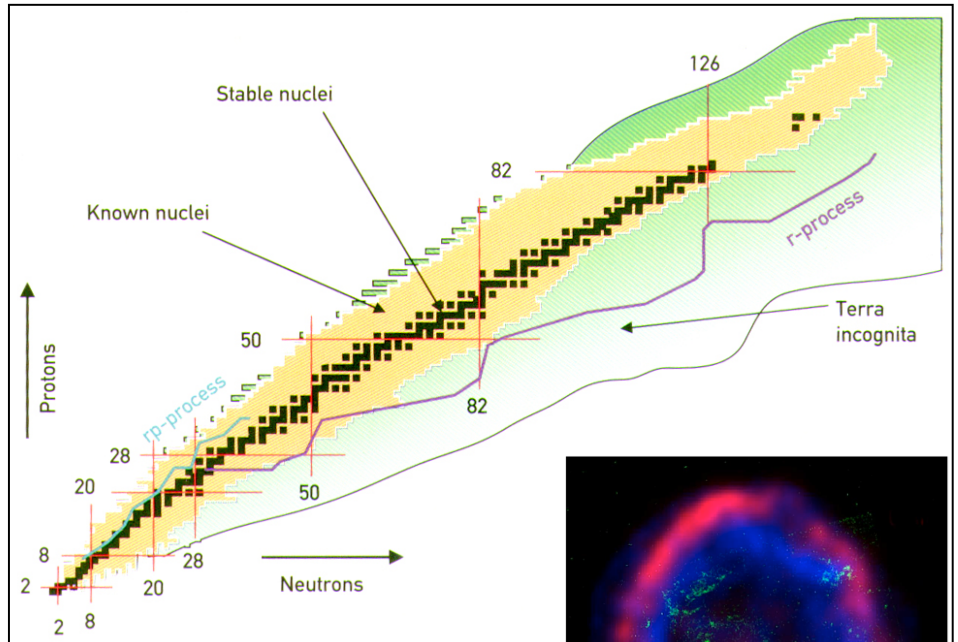
Goals of advanced reaction theory

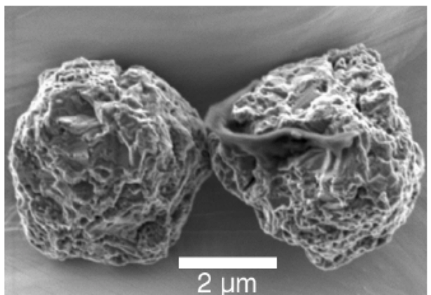
Achieve deeper understanding of underlying microscopic processes in reaction experiments

- *Determine of degrees of freedom relevant to the interaction between projectile and target*

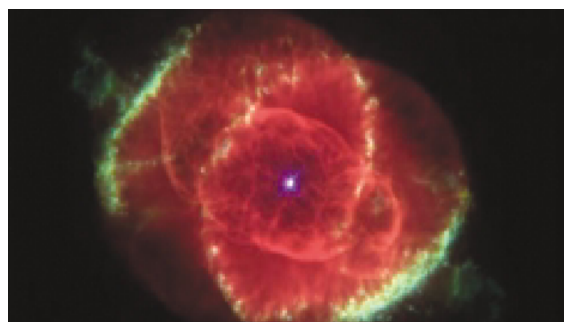
Determine cross sections needed for applications

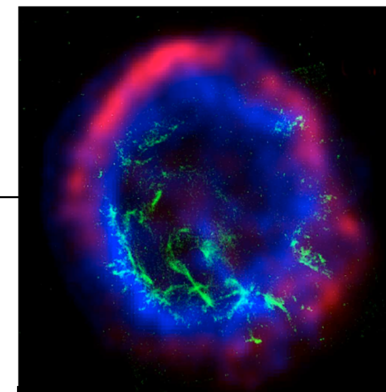
- *Astrophysics*
- *Nuclear energy*
- *National security*





Presolar grain


Cat' s eye nebula


Remnant of a supernova

Extract nuclear structure information from reaction experiments

- *Inform and test nuclear structure theories*
- *Determination of nuclear structure inputs for calculations*

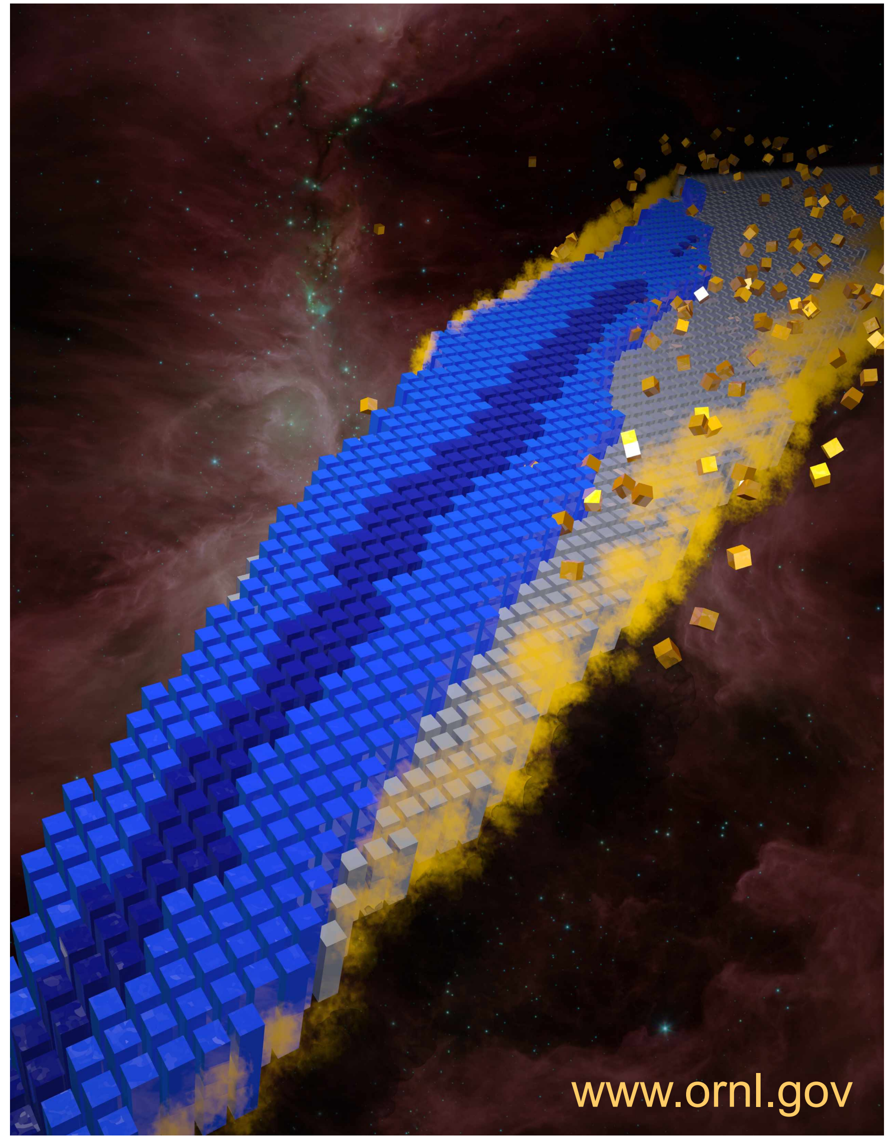
Low-energy reactions remain essential

Past

- *Stable beams & targets*
- *Probes of nuclear structure in/near valley of stability*
- *Nuclear radii, density distributions, levels, spins & parities, shell gaps, spin-orbit, tensor force, 2-nucleon correlations*
- *Direct measurements of cross sections*

- *Exotic beams on stable targets*
- *Study structure outside the valley (r-process, fission fragments, etc.)*
- *Pushing theory to new limits*
- *Indirect measurements of cross sections* using RIBs

Future



What types of reactions are relevant in this context?

Describing low-energy reactions

Basic notation

- Reaction: **a + A -> c + C + Q**
- Alternative: A(a,c)C
- a + A : projectile and target (entrance channel)
- c + C : electile and residual nucleus (exit channel)
- Q-value: $Q = E_f – E_i$

  Q>0 : exothermic (releases energy)

  Q<0 : endothermic (requires energy)
- Partition: combination of particles
- Channel: specified by partition plus state of excitation of nuclei

  Closed: not accessible for given E

  Open: energetically accessible

Observable: cross section

- Measured or calculated
- Definition:

$$\sigma = \frac{\text{\# particles c emitted}}{\text{(\#particles a incident/unit area) (\#target nuclei)}}$$

- Units: 1 barn = 10^{-28} m^2

Classification

- By observed entrance-exit channel combination
- By number of degrees of freedom excited (related to time scales)

‘Low energy’ reactions

- Involve collective, single-nucleon, few nucleon excitations
- Exit channel contains 2 (or three) fragments

Classification
by observed entrance-exit channel combination

Two particles in exit channel

- Elastic scattering: A(a,a)A

  Internal states unchanged

  $^{208}Pb(n,n)^{208}Pb$

- Inelastic scattering: A(a,a)A*

  Target and/or projectile excited

  $^{90}Zr(\alpha,\alpha')^{90}Zr^*$

- Transfer reaction: A(a,c)C

  Stripping: transfer part of projectile to target

  $^{90}Zr(d,p)^{91}Zr^*$

  Pickup: transfer part of target to projectile

  $^{157}Gd(^{3}He,\alpha)^{156}Gd^*$

- Charge exchange: A(a,c)C

  Mass numbers remain the same

  $^{14}C(p,n)^{14}N$

More classes….

- Capture: A(a,γ)C

  Projectile is captured, energy radiated

  $^{7}Be(p,\gamma)^{8}B$, $^{130}Sn(p,\gamma)^{131}Sn$

- Breakup:

  Projectile breaks apart in target field

  $d+^{90}Zr \rightarrow ^{90}Zr^*+p+n$

- Knockout:

  Nucleon/light nucleus emitted from target, projectile continues on

  Example: A(e,e'p)B

Combinations of these processes can occur in a reaction.

Classification by degrees of freedom excited

Direct reactions

- few collisions, fast: 10^{-21}-10^{-22}s
- target structure largely intact
- forward-peaked
- involve single-particle excitations

Compound reactions

- multiple collisions, slow: 10^{-15}-10^{-16}s
- target fuses with projectile
- symmetric wrt 90° axis
- involve many-particle excitations

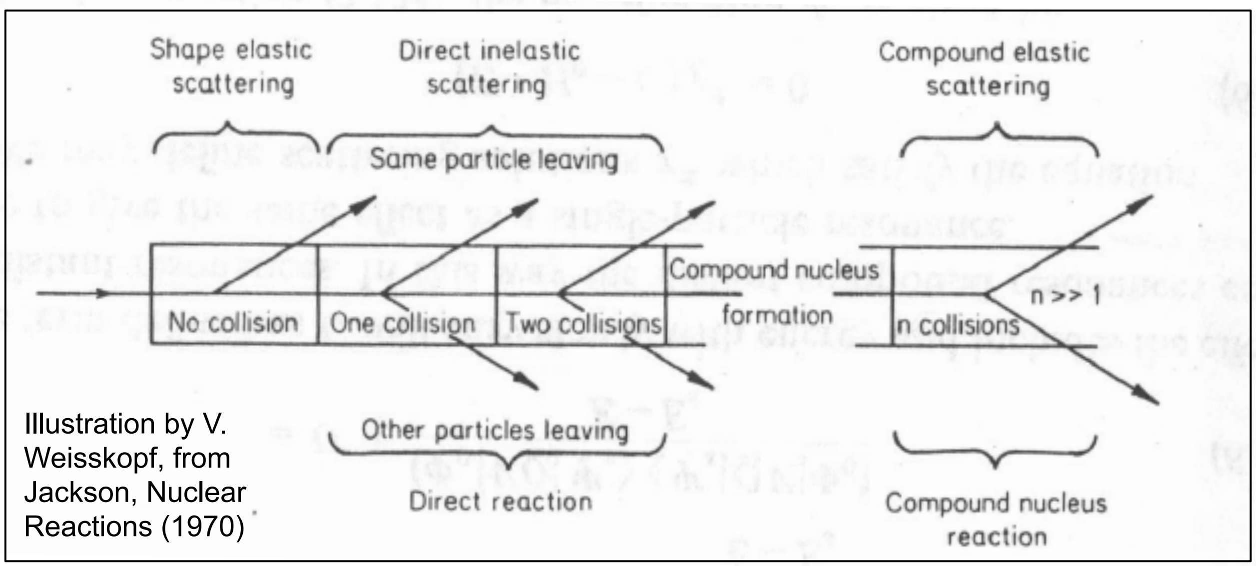


Illustration by V. Weisskopf, from Jackson, Nuclear Reactions (1970)

Classification
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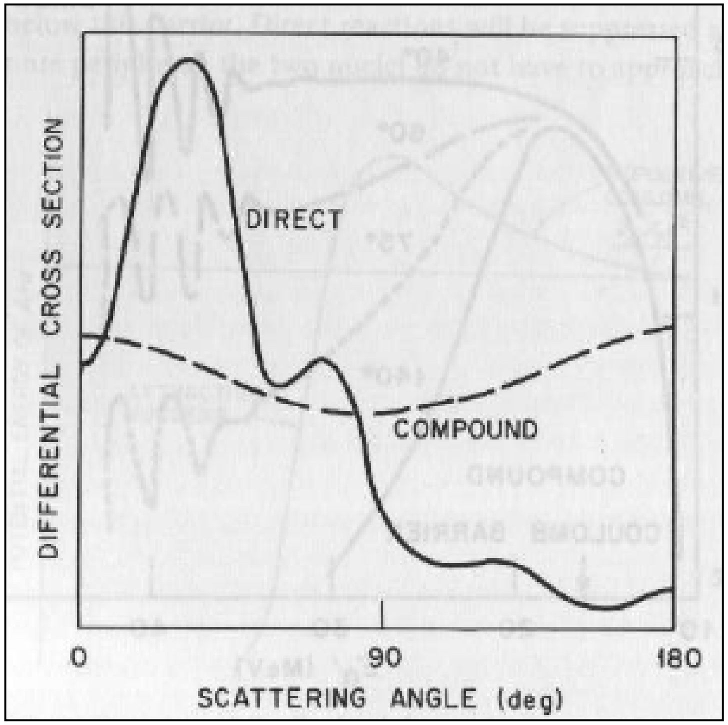
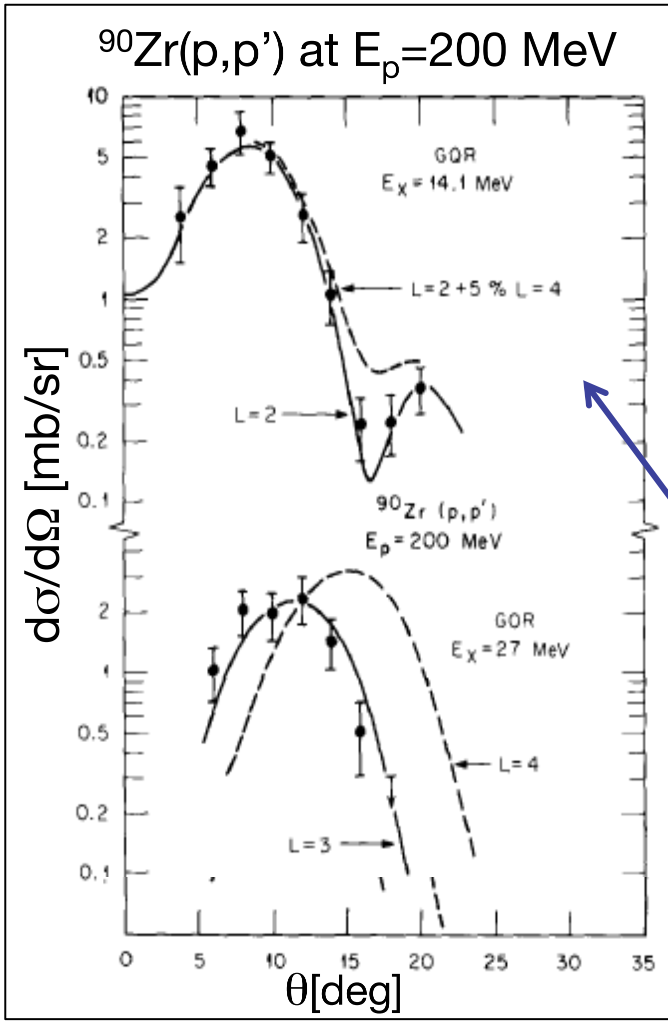
Typical angular distributions for direct and CN reactions.

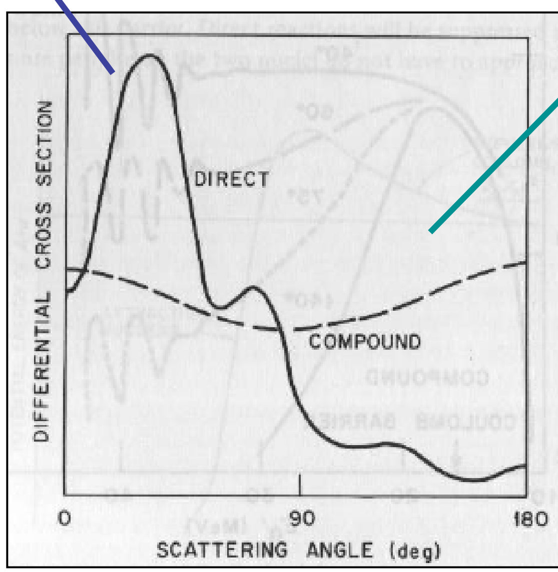


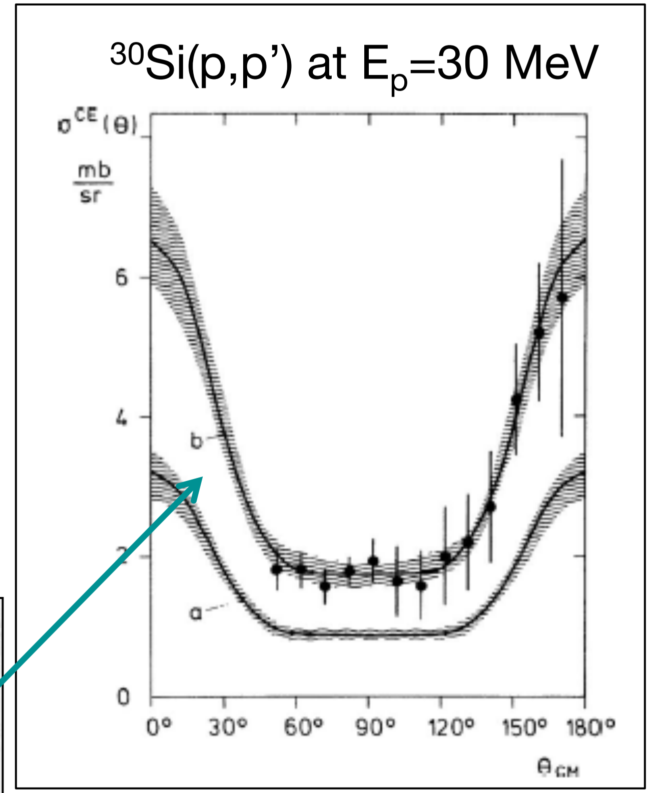
From: Satchler, Introduction to Nuclear Reactions (1990)

Angular distributions



From: Bertrand et al,
PLB 103, 326 (1980)





From: Mitchell, Richter,
Weidenmueller, RMP 82,
2845 (2010)

Classification
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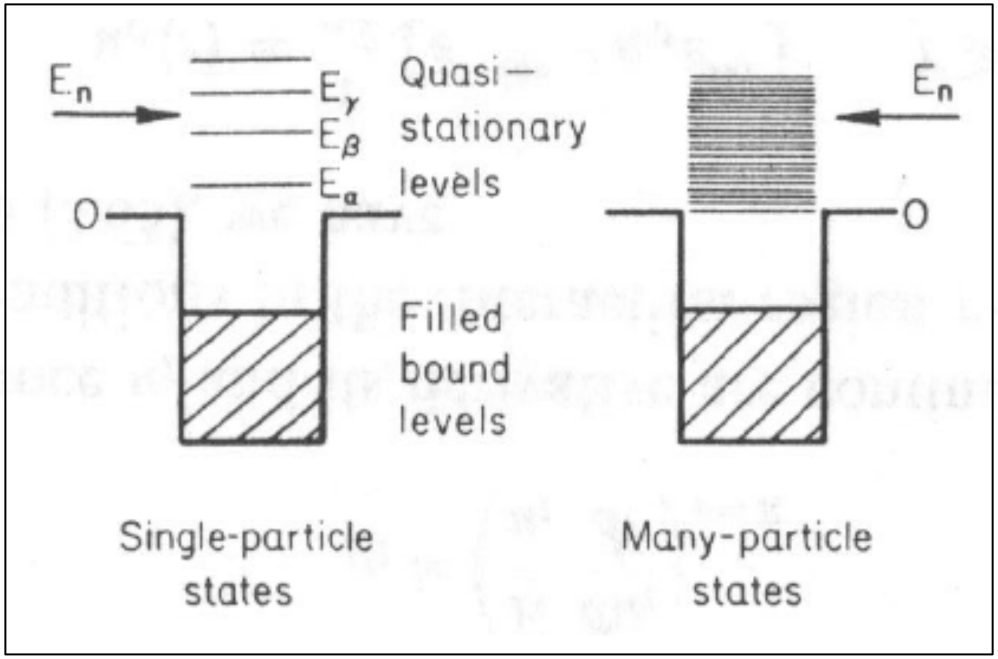
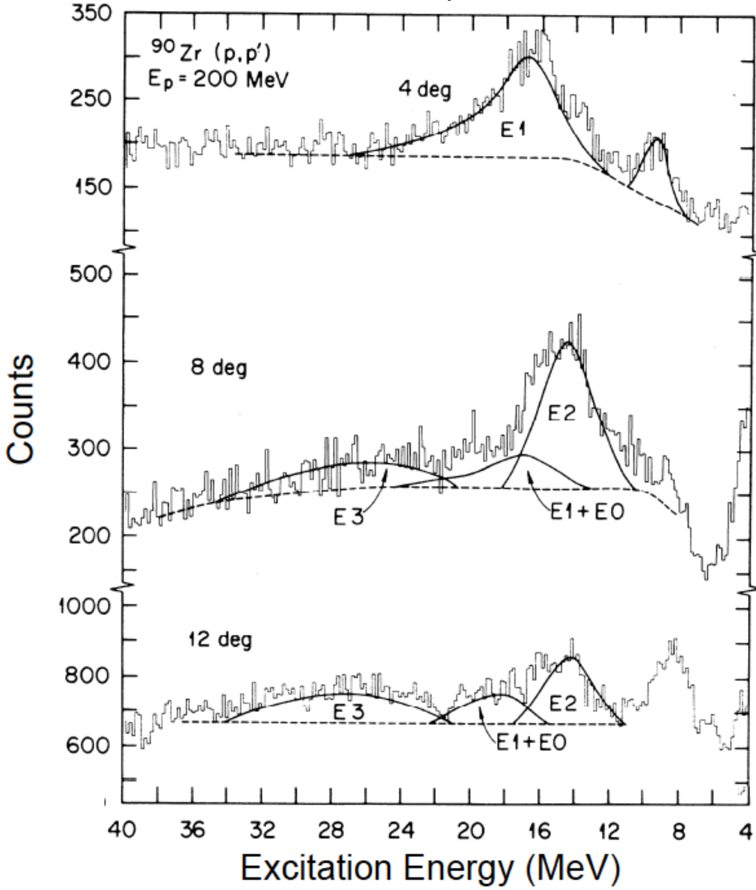


From Jackson, Nuclear Reactions (1970)

Single-particle vs. many-particle excitations

^{90}Zr(p,p') at E_p=200 MeV



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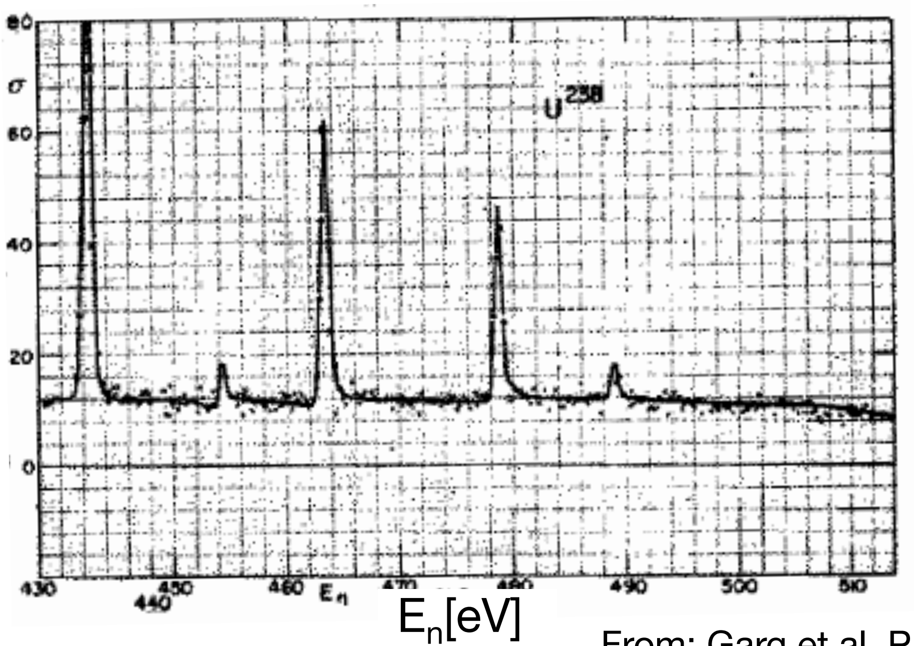
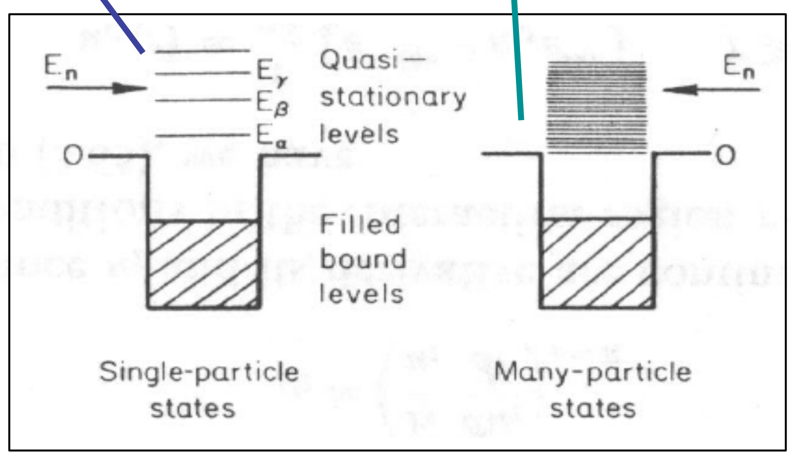


From: Garg et al, PR 134, B985 (1964)



From Jackson, Nuclear Reactions (1970)

Now: Focus on Compound Reactions

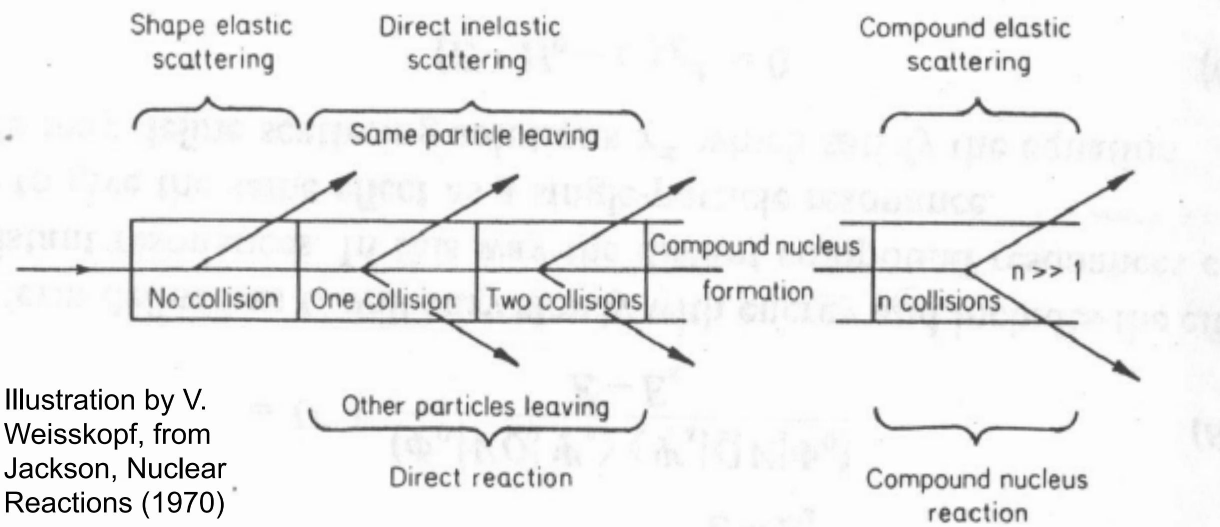
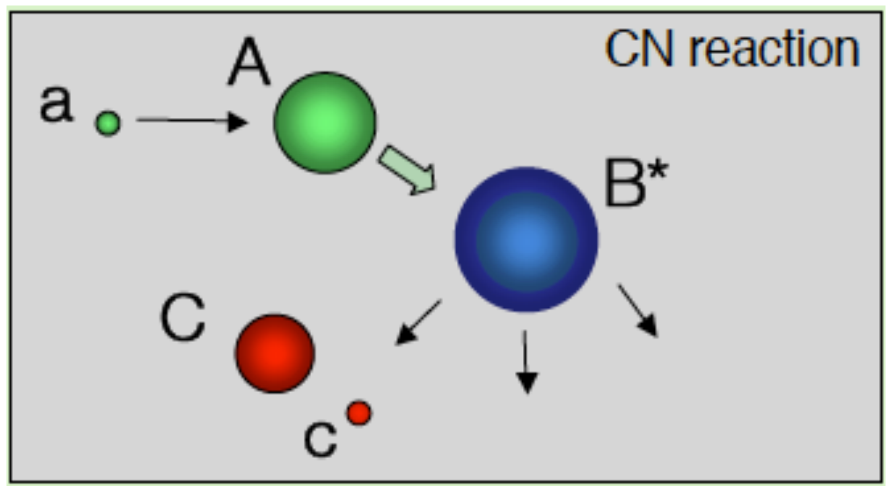


Illustration by V. Weisskopf, from Jackson, Nuclear Reactions (1970)



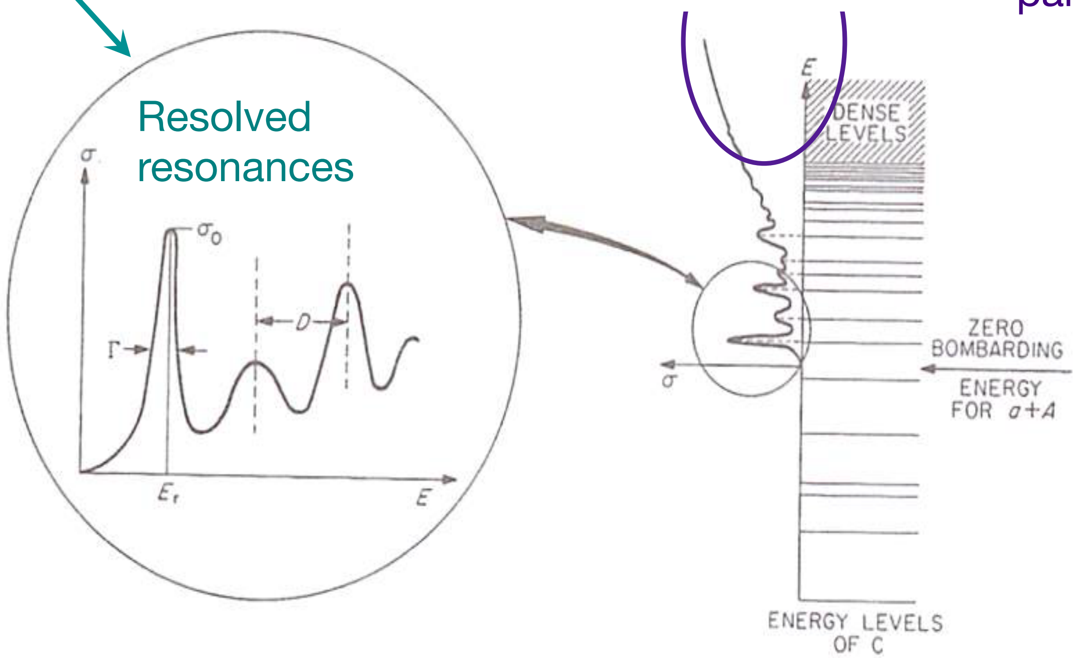
How do we describe compound-nuclear reactions?

Resonances, from isolated to strongly overlapping

R-matrix approach
- Resolved resonances
- In principle an exact description
- In practice, fits to known resonance data (E,J,π)

Hauser-Feshbach approach
- Assumes strongly overlapping resonances
- Averages…
- Calculations require structure models and parameters

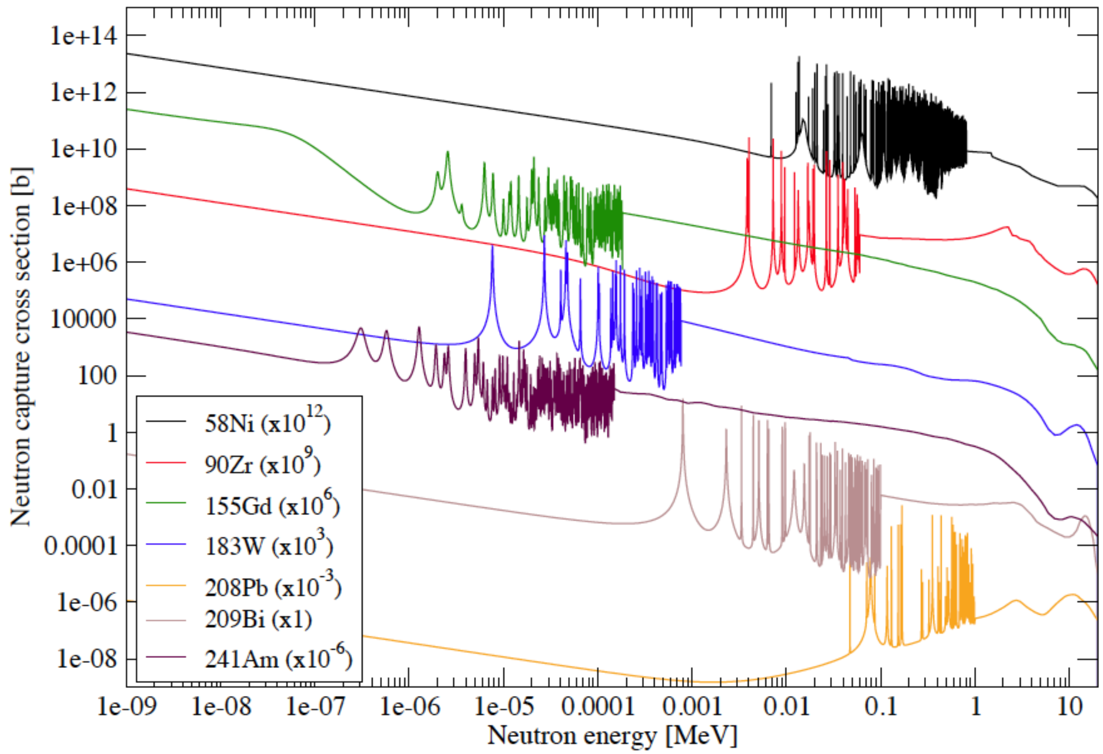
Strongly overlapping resonances



From Satchler, Introduction to Nuclear Reactions (1980)

Resonances, from isolated to strongly overlapping

Evaluated (n,γ) cross sections from thermal to 20 MeV (ENDF/B-VII)



The demarcation between the resolved and unresolved resonance regions, and the Hauser-Feshbach regime, depends on mass region and proximity to closed shells.

Hauser-Feshbach formalism:
A hint of a derivation

Ingredients

- Bohr's hypothesis: formation and decay of CN are independent

$$\sigma_{\alpha\chi}(E,J,\pi) = \sigma_\alpha^{CN}(E,J,\pi) \, . \, G^{CN}_\chi(E^{CN},J,\pi)$$

- Principle of detailed balance: time-reverals invariance of reaction

$$k_\alpha^2 \sigma_{\alpha\chi} = k_\chi^2 \sigma_{\chi\alpha}$$

- Combining this, one obtains the partial CN cross section

$$\sigma_{\alpha\chi}(E,J,\pi) = k_\alpha^2 \sigma_\alpha^{CN}(E_\alpha,J,\pi) \;\; \sigma_\chi^{CN}(E_\chi,J,\pi) \, / \, \Sigma_{\chi'} \; k_{\chi'}^2 \, \sigma_{\chi'}^{CN}(E_{\chi'},J,\pi)$$

- Introducing transmission coefficients

$$\sigma_\alpha^{CN}(E_\alpha,J,\pi) = \pi \, k^{-2}_\alpha \; (2J+1) \, T_\alpha^J$$

- We obtain the CN cross section (for fixed J,π)

$$\sigma_{\alpha\chi}(E,J,\pi) = (2J+1) \frac{\pi \;\; T_\alpha^J \, T_\chi^J}{k^2_\alpha \;\; \Sigma_{\chi'} \;\; T_{\chi'}^J}$$

Hauser-Feshbach calculations: physics input

Cross section for formation of CN

$$\sigma_\alpha^{CN}(E,J,\pi) = \pi\lambda_\alpha\omega_\alpha{}^J \Sigma_{ls} T^J{}_{\alpha ls}$$

Probability for decay of CN

$$G^{CN}{}_\chi(E^{CN},J,\pi) = \frac{\Sigma_{l's'} T^J{}_{\chi l's'} \rho_{I'}(U')}{\Sigma_{\chi''l''s''} T^J{}_{\chi''l''s} + \Sigma_{\chi''l''s''} \int T^J{}_{\chi''l''s''} \rho_{I''}(U'')dE_{\chi''}}$$

Quantities required

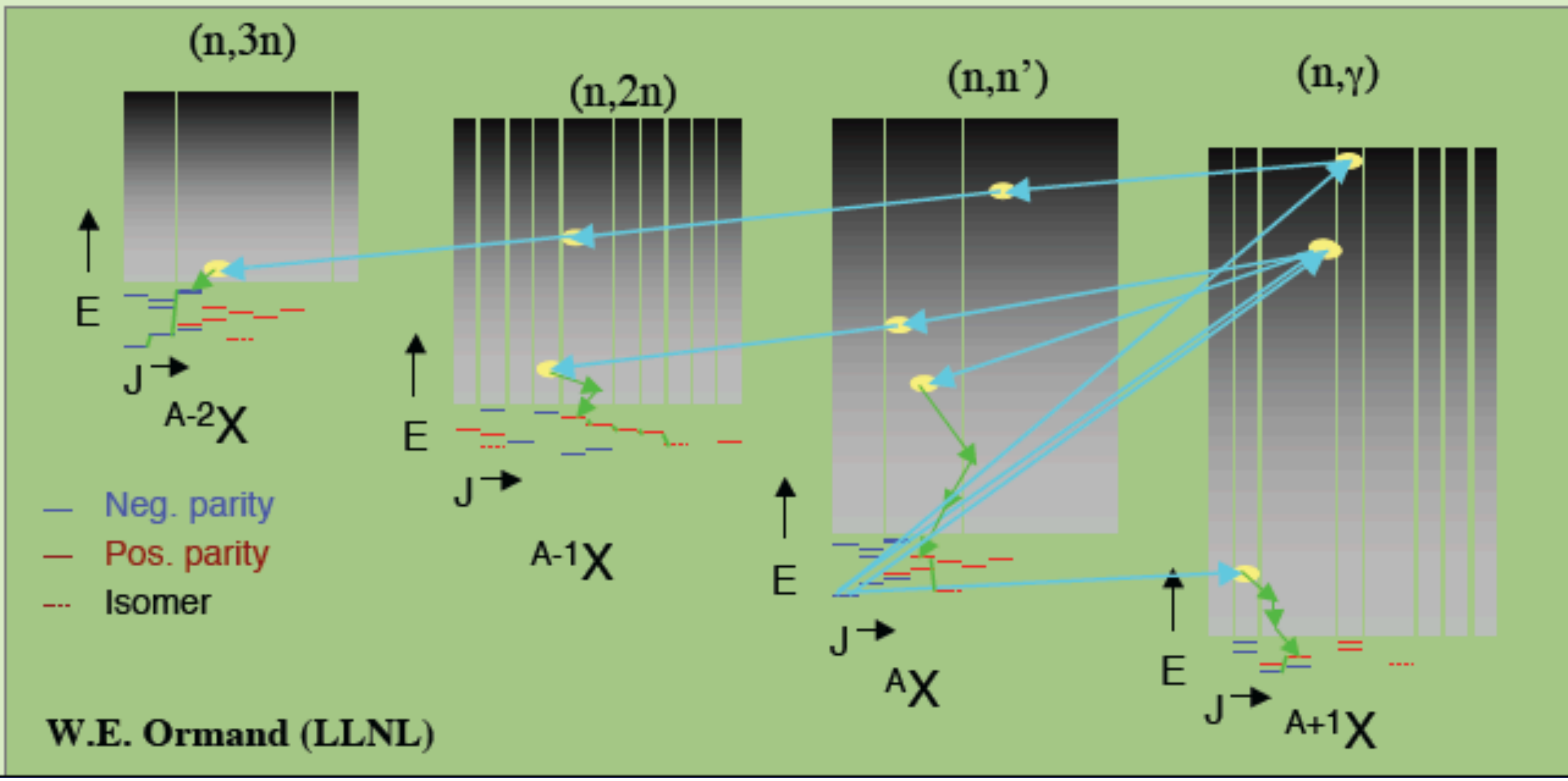
- Transmission coefficients T_χ for all channels χ: neutron, proton, charged particles, γ, fission
- Level densities for nuclei involved
- Discrete levels with J,π

HF calculations for compound-nucleus cross sections

Average cross section per unit energy in the outgoing channel:

$$\frac{d\sigma_{\alpha\chi}^{HF}}{dE_{\chi}} = \pi\lambda_{\alpha}^{2}\sum_{J\pi}\omega_{\alpha}^{J}\sum_{lsl's'I'}\frac{T_{\alpha ls}^{J}T_{\chi l's'}^{J}\rho_{I'}(U)}{\sum'_{\chi''l''s''}T_{\chi''l''s''}^{J}+\sum_{\chi''l''s''}\int T_{\chi''l''s''}^{J}(E_{\chi''})\rho_{I''}(U'')dE_{\chi''}}$$

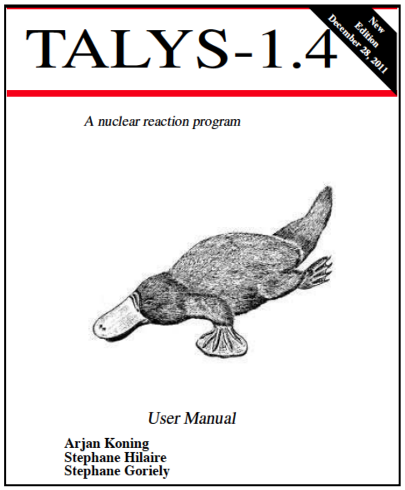
Evaluating this expression requires knowledge of optical potentials and the structure of the nuclei that can be reached in the decay of the CN:



Finding a code…

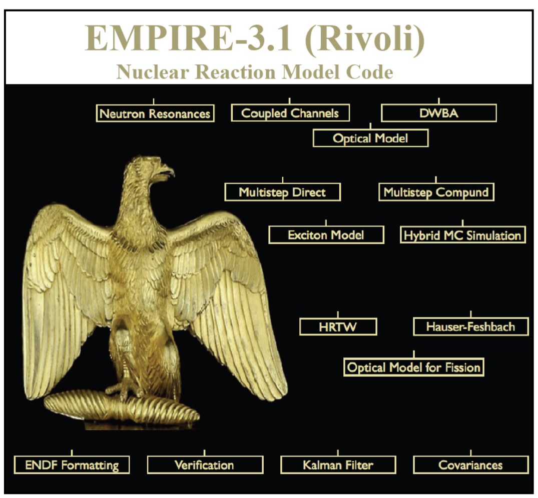
Hauser-Feshbach codes:

- Many Hauser-Feshbach codes have been written: STAPRE, TALYS, EMPIRE, MCNASH, COH, SMOKER, NON-SMOKER, YAHFC,….
- Publicly available, widely used, documented, and supported: TALYS and EMPIRE



Talys:

- Developers: A. Koning, S. Hilaire, M. Duijwestijn (NRG Petten, Netherlands, and CEA Bruyere-le-Chatel, France)
- Website: www.talys.eu/home/
- Reference: Koning & Rochman, NDS 113 (2012) 2841-2934
- Interesting feature: minimal input file requires only 4 pieces of information: Proj, Z_T, A_T, E



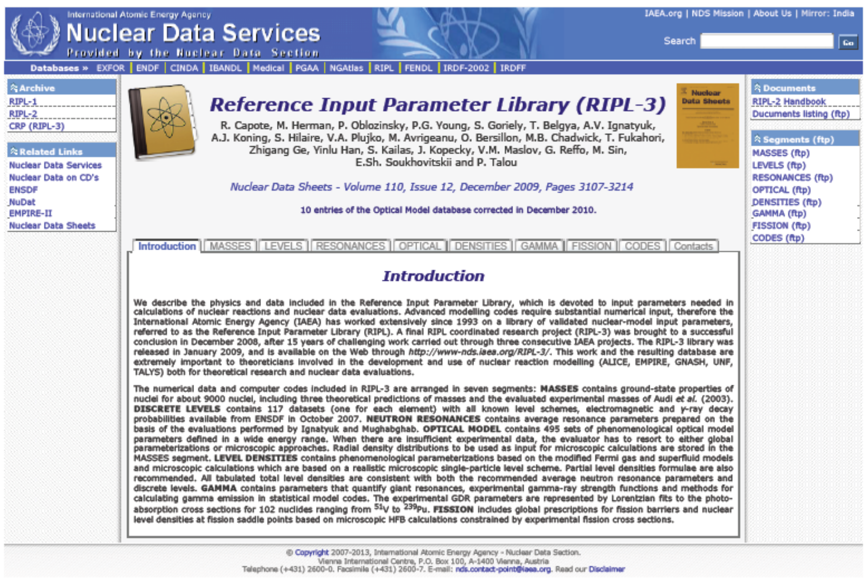
Empire:

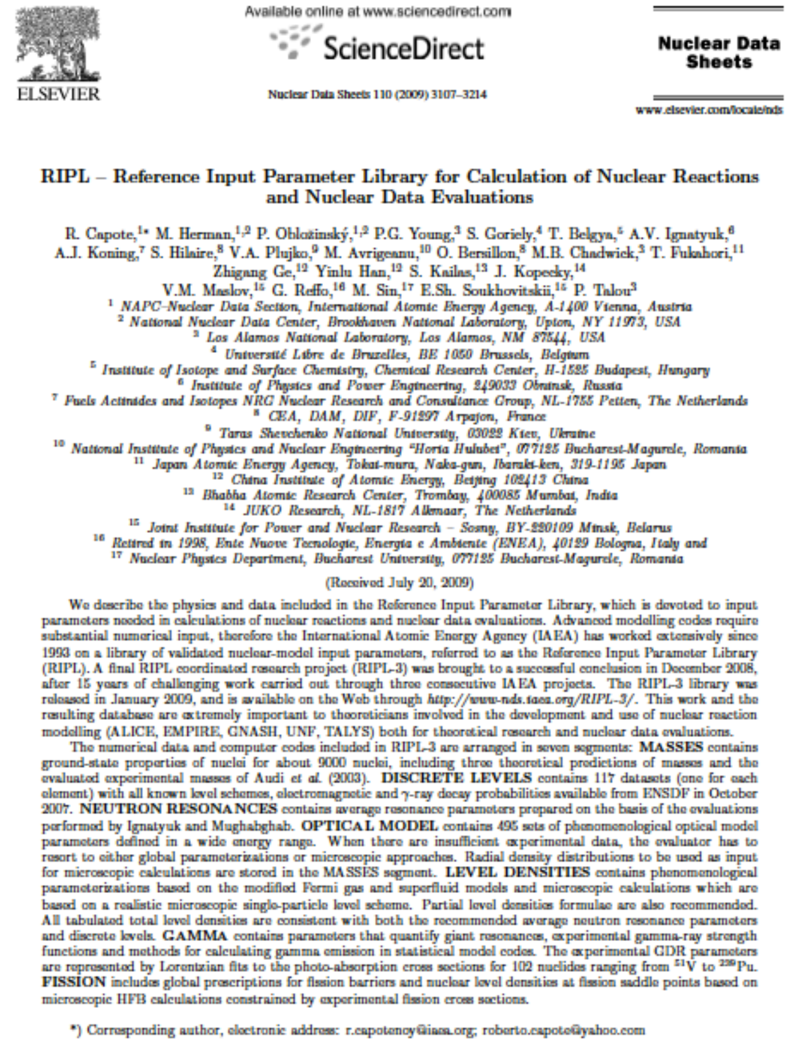
- Developers: M. Herman et al. (BNL, IAEA, Bucharest, Lubljana, LLNL, Brazil, Bratislava, KAERI, Kiev)
- Website: www.nndc.bnl.gov/empire/index.html
- Reference: Herman et al, NDS 108 (2007) 2655-2715
- Interesting feature: code versions named after battles fought by Napoleon Bonaparte

Getting the physics inputs…

Good starting points:

- Use default models and parametriziations, read the manuals for instructions on improvements
- Consult RIPL - "Reference Input Parameter Library": web site and review paper **www-nds.iaea.org/RIPL-3**





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Nuclear Data Sheets 110 (2009) 3107–3214

Nuclear Data Sheets

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RIPL – Reference Input Parameter Library for Calculation of Nuclear Reactions and Nuclear Data Evaluations

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We describe the physics and data included in the Reference Input Parameter Library, which is devoted to input parameters needed in calculations of nuclear reactions and nuclear data evaluations. Advanced modelling codes require substantial numerical input, therefore the International Atomic Energy Agency (IAEA) has worked extensively since 1993 on a library of validated nuclear-model input parameters, referred to as the Reference Input Parameter Library (RIPL). A final RIPL coordinated research project (RIPL-3) was brought to a successful conclusion in December 2008, after 15 years of challenging work carried out through three consecutive IAEA projects. The RIPL-3 library was released in January 2009, and is available on the Web through *http://www-nds.iaea.org/RIPL-3/*. This work and the resulting database are extremely important to theoreticians involved in the development and use of nuclear reaction modelling (ALICE, EMPIRE, GNASH, UNF, TALYS) both for theoretical research and nuclear data evaluations.

The numerical data and computer codes included in RIPL-3 are arranged in seven segments: **MASSES** contains ground-state properties of nuclei for about 9000 nuclei, including three theoretical predictions of masses and the evaluated experimental masses of Audi *et al.* (2003). **DISCRETE LEVELS** contains 117 datasets (one for each element) with all known level schemes, electromagnetic and γ-ray decay probabilities available from ENSDF in October 2007. **NEUTRON RESONANCES** contains average resonance parameters prepared on the basis of the evaluations performed by Ignatyuk and Mughabghab. **OPTICAL MODEL** contains 495 sets of phenomenological optical model parameters defined in a wide energy range. When there are insufficient experimental data, the evaluator has to resort to either global parameterizations or microscopic approaches. Radial density distributions to be used as input for microscopic calculations are stored in the MASSES segment. **LEVEL DENSITIES** contains phenomenological parameterizations based on the modified Fermi gas and superfluid models and microscopic calculations which are based on a realistic microscopic single-particle level scheme. Partial level densities formulae are also recommended. All tabulated total level densities are consistent with both the recommended average neutron resonance parameters and discrete levels. **GAMMA** contains parameters that quantify giant resonances, experimental gamma-ray strength functions and methods for calculating gamma emission in statistical model codes. The experimental GDR parameters are represented by Lorentzian fits to the photo-absorption cross sections for 102 nuclides ranging from ^{51}V to ^{239}Pu. **FISSION** includes global prescriptions for fission barriers and nuclear level densities at fission saddle points based on microscopic HFB calculations constrained by experimental fission cross sections.

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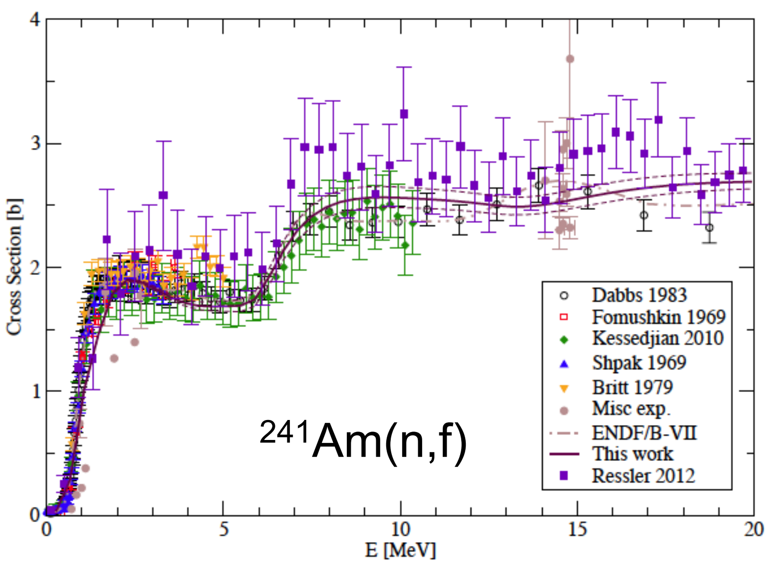
Capote *et al*, Nuclear Data Sheets 110 (2009) 3107
23 authors, 108 pages, many years…

Checking the calculations…

Experimental data and evaluations:

- National Nuclear Data Center:
  www.nndc.bnl.gov
- CSISRS (EXFOR):
  Nuclear reaction experimental data
- ENDF (and other evaluations):
  Evaluated Nuclear (reaction) Data File
- NuDat:
  Nuclear structure and decay Data
- And many more resources:
  Codes, publications, meeting info, …



Points to remember:

- Nuclear physics input is provided through data bases or by the user
- Models and input parameters are not unique, calculating a good cross section is both art *and* science
- The old principle holds: garbage in ➔ garbage out
- Make use of cross-checks, whenever possible

Which physics models and inputs are needed?

Optical model potentials

Optical model potential

- Reduces complicated interaction of projectile with target to effective one-body problem
- Imaginary components account for channels not explicitly treated (loss of flux)
- Formally, a complicated function (non-local, energy dependent)
- Practical applications use phenomenological forms
- Popular: Woods-Saxon shape

$$\mathcal{U}(r,E) = -\mathcal{V}_V(r,E) - i\mathcal{W}_V(r,E) - i\mathcal{W}_D(r,E) + \mathcal{V}_{SO}(r,E).\mathbf{l}.\sigma + i\mathcal{W}_{SO}(r,E).\mathbf{l}.\sigma + \mathcal{V}_C(r),$$

$$\mathcal{V}_V(r,E) = V_V(E) f(r, R_V, a_V),$$

$$\mathcal{W}_V(r,E) = W_V(E) f(r, R_V, a_V),$$

$$\mathcal{W}_D(r,E) = -4a_D W_D(E) \frac{d}{dr} f(r, R_D, a_D),$$

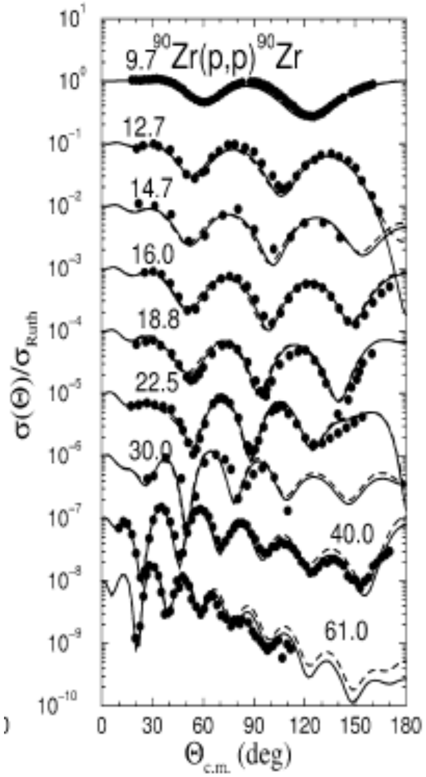
$$\mathcal{V}_{SO}(r,E) = V_{SO}(E) \left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r}\frac{d}{dr} f(r, R_{SO}, a_{SO}),$$

$$\mathcal{W}_{SO}(r,E) = W_{SO}(E) \left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r}\frac{d}{dr} f(r, R_{SO}, a_{SO}).$$

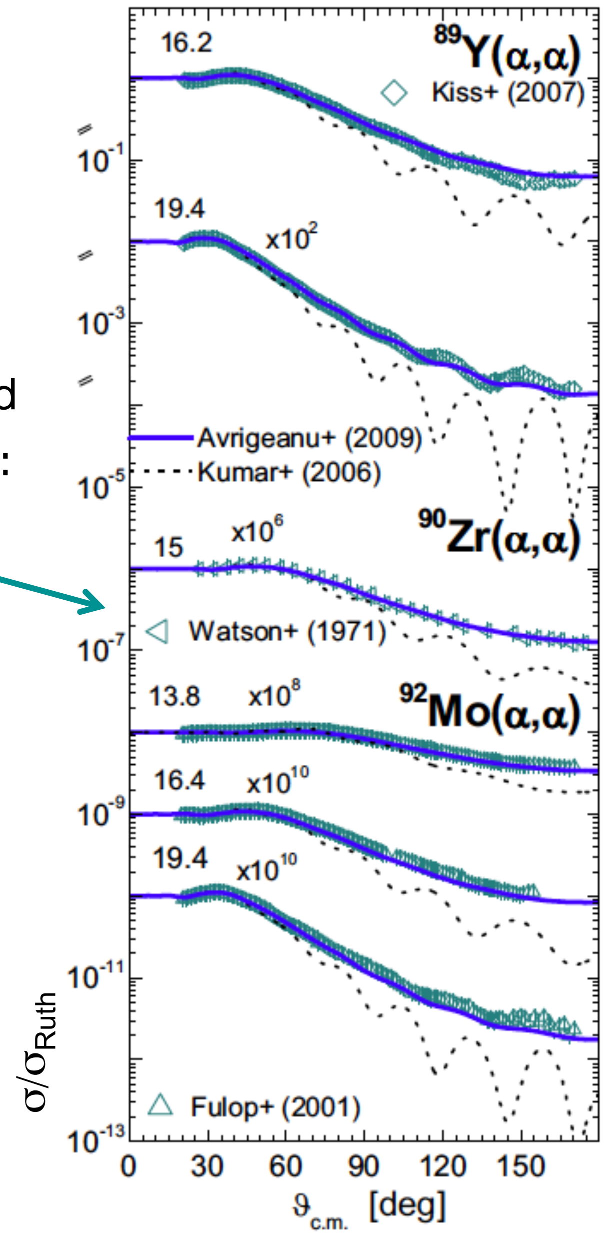
$$f(r, R_i, a_i) = \left(1 + \exp[(r - R_i)/a_i]\right)^{-1},$$

Nucleon-nucleus OMP
Koning & Delaroche, NPA 713 (2003) 231

Optical model potentials

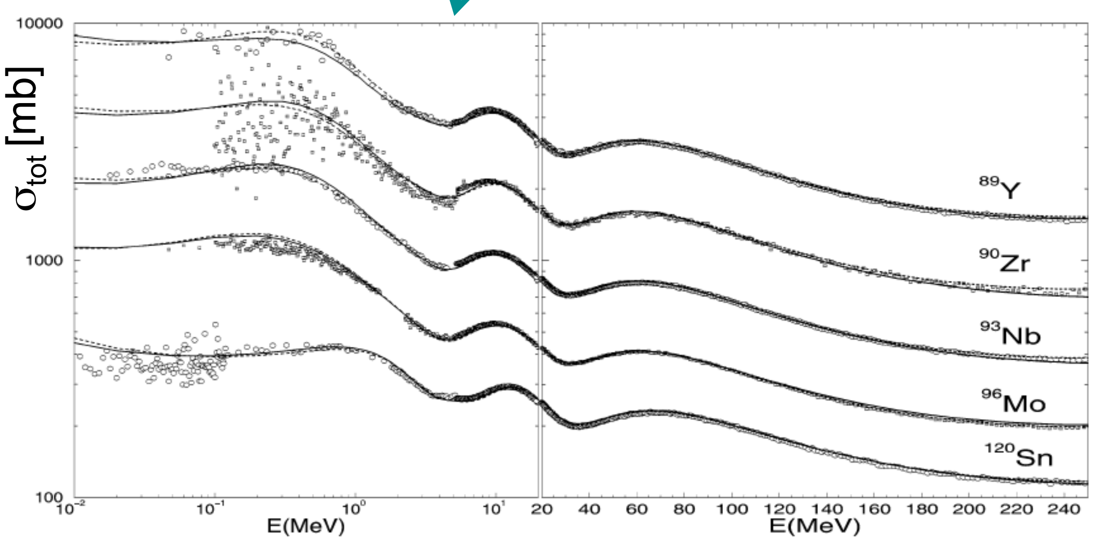


Capote et al, NDS 110 (2009) 3107



OMPs for HF calculations

- Required to calculate transmission coefficients for particle emission
- Parameters from systematic (global or regional) studies
- Nucleon-nucleus OMPs well-studied
- Nucleus-nucleus OMPs challenging: d-A, t-A, ^{3}He-A, α-A



Koning & Delaroche, NPA 713 (2003) 231

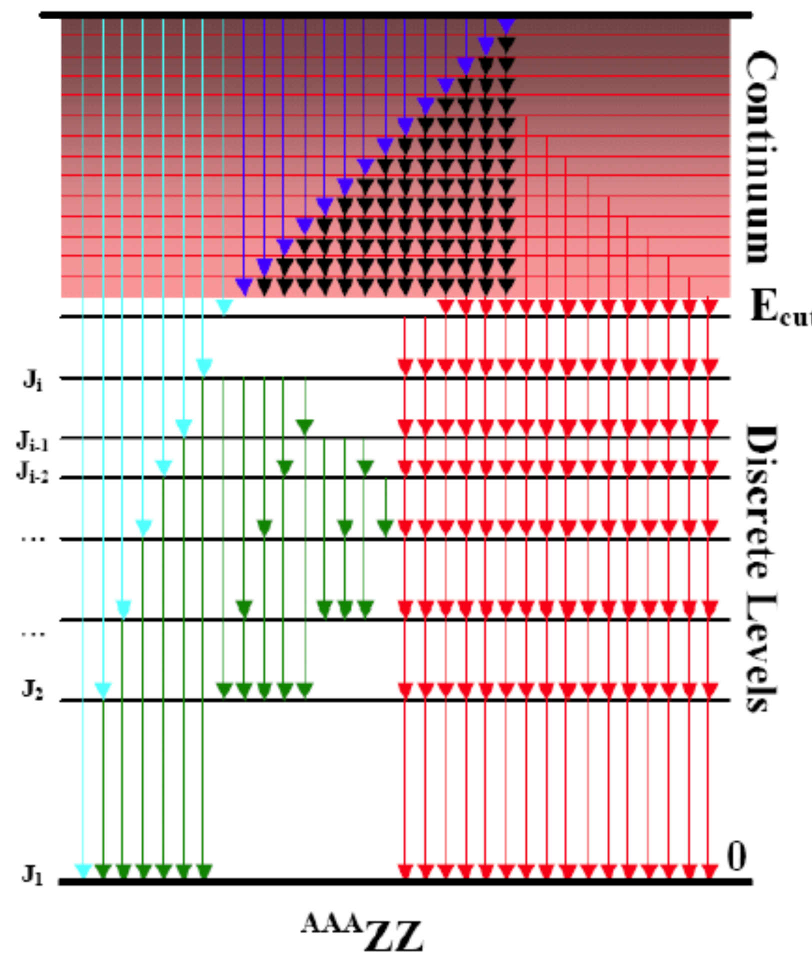
Hauser-Feshbach calculations:
Discrete states and level densities

Level densities above E_{cut}

- Cover energy regime above highest included discrete level
- Microscopic and phenomenological models available
- Reproduce related measurements, e.g. resonance spacing at S_n
- Parametrizations of popular models, and tables of microscopic LDs available at RIPL-3 web site

Discrete states below E_{cut}

- Complete E,J,π information
- Branching ratios for γ-decay
- ENSDF & NuDat databases at NNDC
- Reproduced at RIPL-3 website



From: R.B. Firestone

Hauser-Feshbach calculations: γ-ray transmission coefficients

γ-ray strength function

- Gives TC: $T^{\gamma}_{XL}(\epsilon) = 2\pi\epsilon^{2L+1} f^{\gamma}_{XL}(\epsilon)$
- E1 dominates
- Various phenomenological forms exist, mostly variants of Lorentzian
- RIPL-3 gives GDR parameters E_{GDR},Γ,σ
- Constraint radiative width:

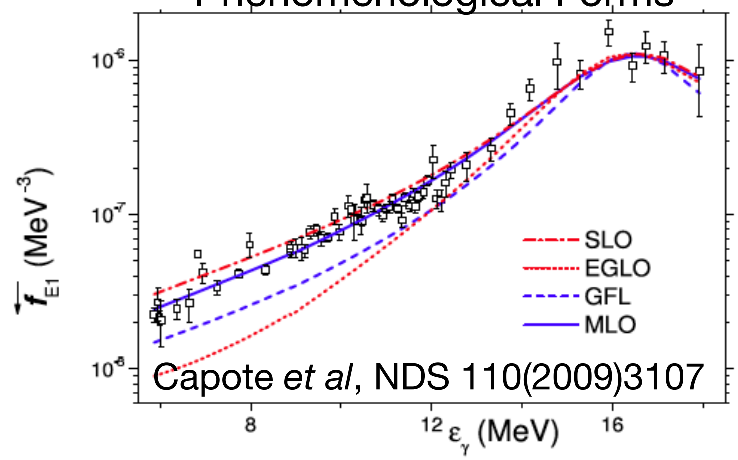
$$\overleftarrow{f}_{\mathrm{XL}}(\epsilon_\gamma) = \epsilon_\gamma^{-(2L+1)} \frac{\langle \Gamma_{\mathrm{XL}}(\epsilon_\gamma)\rangle}{D_l}$$

- Related to photo-absorption xsec:

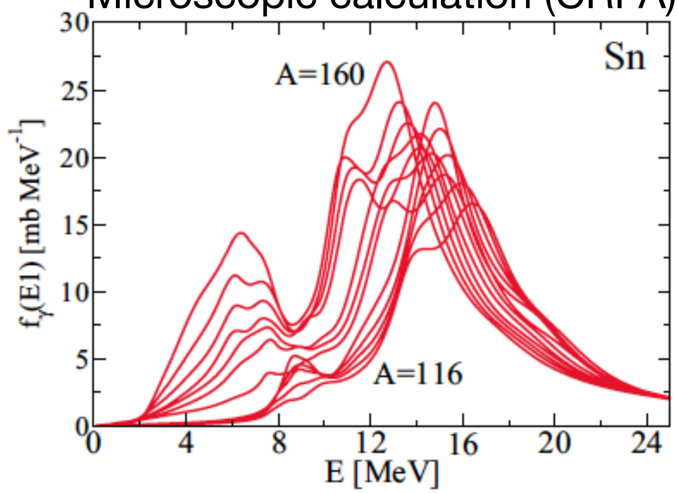
$$\overrightarrow{f}_{\mathrm{EL}}(\epsilon_\gamma) = \frac{\epsilon_\gamma^{-2L+1}}{(\pi\hbar c)^2} \frac{\langle \sigma_{\mathrm{XL}}(\epsilon_\gamma)\rangle}{2L+1}$$

- Microscopic theories predict γSF

E1 γ-ray strength function
Phenomenological Forms



E1 γ-ray strength function
Microscopic calculation (CRPA)



Daoutidis & Goriely, PRC 86 (2012) 034328

Hauser-Feshbach calculations:
Level density prescriptions

Gilbert-Cameron

- Product form:

$$\rho(E_x,J,\pi) = P(E_x,J,\pi)R(E_x,J)\rho^{tot}(E_x)$$

$$R(E_x,J) \;=\; \frac{2J+1}{2\sigma^2}\exp\left[-\frac{(J+1/2)^2}{2\sigma^2}\right]$$

- Back-shifted Fermi-Gas at high E:

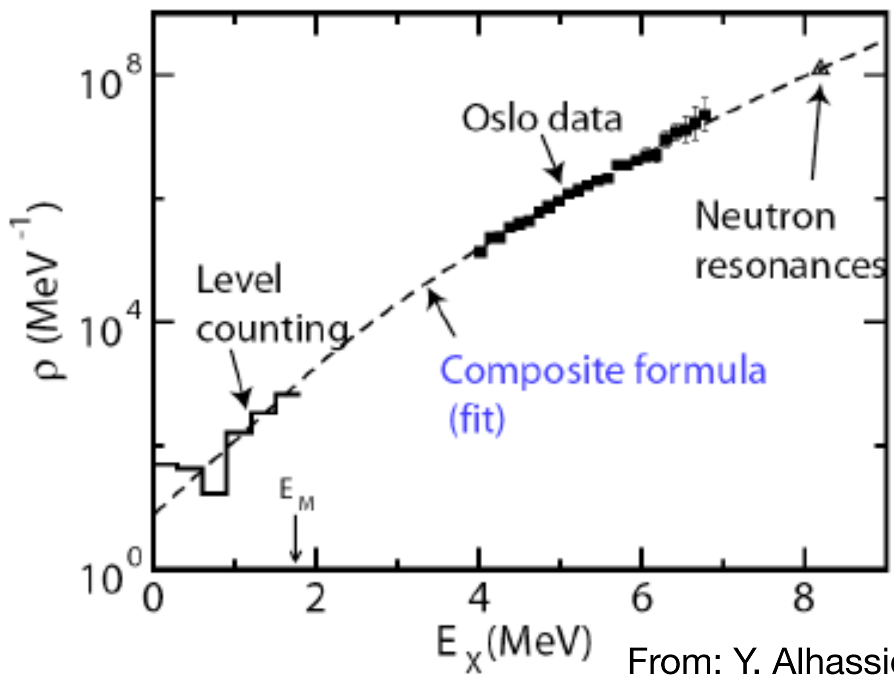
$$\rho_F^{\rm tot}(E) = \frac{1}{\sqrt{2\pi}\sigma}\frac{\sqrt{\pi}}{12}\frac{\exp\left[2\sqrt{aU}\right]}{a^{1/4}U^{5/4}}$$

- Constant-T at low E:

$$\rho_{CT}^{tot}(E_x) = \frac{dN(E_x)}{dE_x} = \frac{1}{T}\exp\left[\frac{E_x - E_0}{T}\right]$$

- Constraints: cumulative number of levels at low E, resonance spacing at S_n

Experimental constraints



From: Y. Alhassid CNR*2007 talk

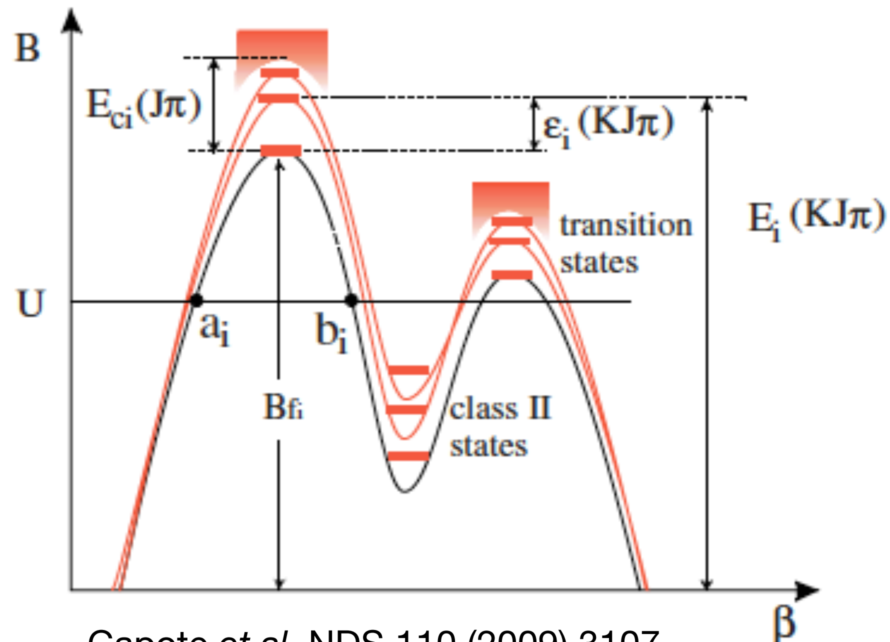
Alternatives

- Other phenomenological forms
- Theoretical predictions (SMMC, etc.)

Hauser-Feshbach calculations: fission model

Phenomenological Model

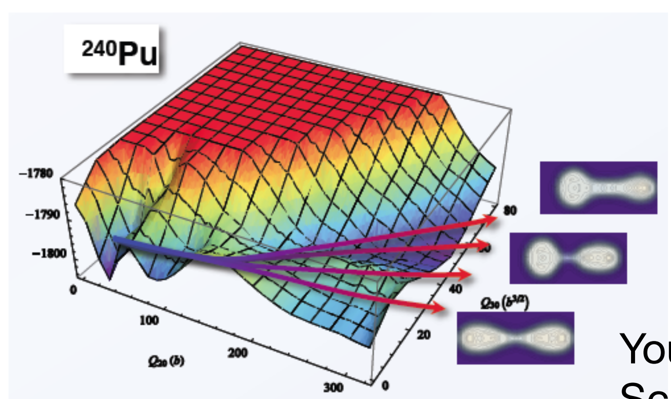
- Static, one-dimensional fission barriers along the deformation path, to be traversed
- Allows for calculation of T_{fiss}
- Single, double, or triple-humped fission barrier models
- Parameters: Heights, curvature hω, quasistationary states, transition states, level densities
- Parameters found in RIPL-3



Capote *et al*, NDS 110 (2009) 3107

Alternatives

- Microscopic calculations of fission barriers and level densities exist
- Truly dynamic descriptions of fission process is challenging



Younes, Gogny, Schunck (LLNL)

Beyond Hauser-Feshbach: Pre-equilibrium processes

Pre-equilibrium reactions

- Important contributions
- Models: Exciton, FKK, NWY, TUL
- Models incorporated in most codes (Talys, Empire)

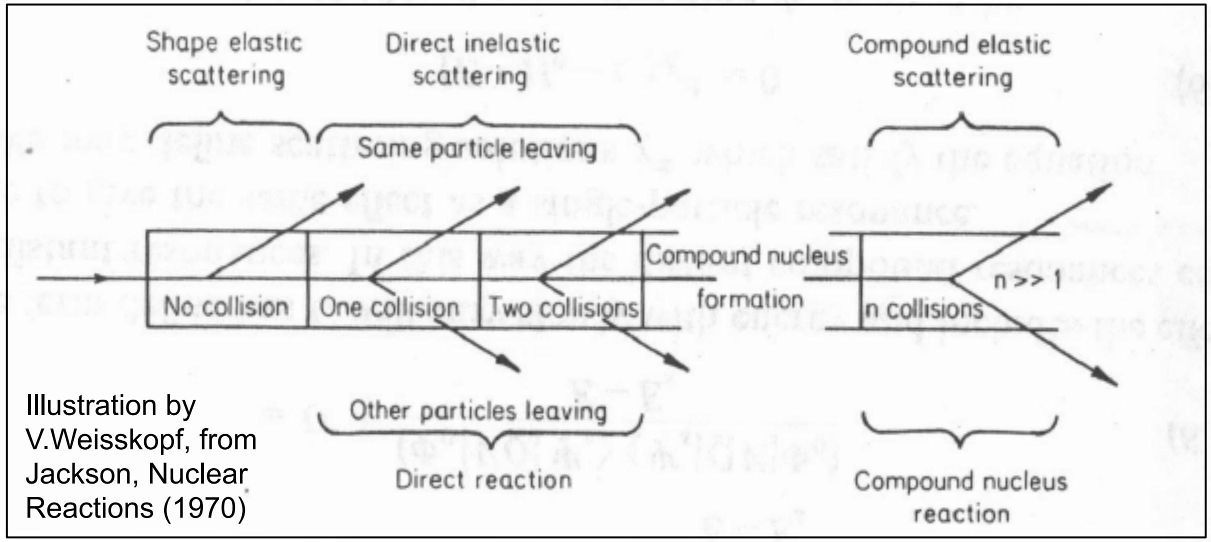
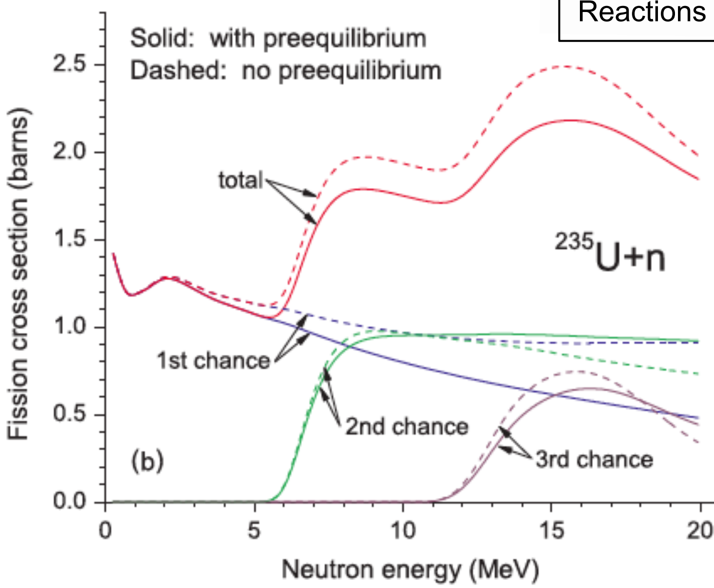
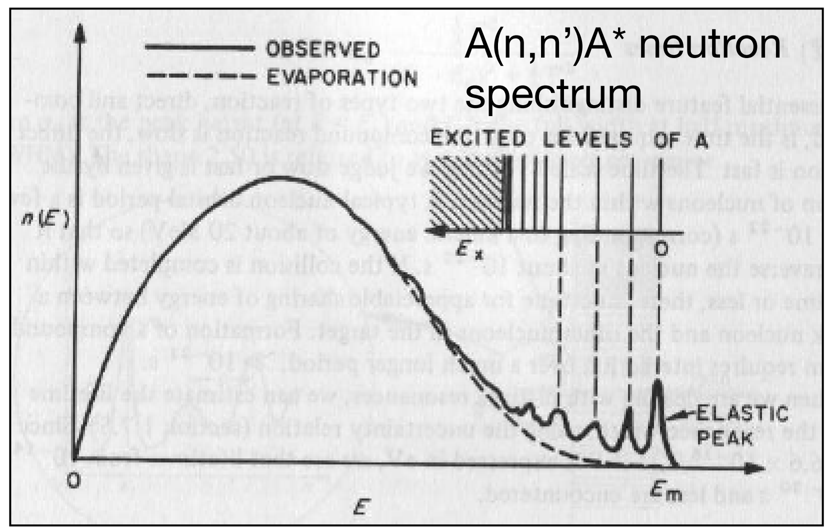


Illustration by V.Weisskopf, from Jackson, Nuclear Reactions (1970)



Escher & Dietrich, PRC 74 (2006) 054601



Satchler (1990)

Concluding remarks

Questions addressed today

- Why are we interested in low-energy reactions?
  Why do we need theory to describe reaction processes?
- What types of reactions are relevant in this context?
- How do we describe compound-nuclear reactions?
- Which physics models and inputs are needed?
- Challenges and open questions
- Many thanks to my collaborators….

Challenges and Open Questions

Improvements to physics inputs

- Optical models
- Level densities
- γ-ray strength functions
- Fission model

Reaction mechanisms

- Interplay of direct and compound reactions (preequilibrium)
- Modification of formalism for low level densities

Experiments

- Measurements of inputs (level densities, strength functions)
- Constraints for cross sections

Thanks to my Collaborators

Surrogate Reactions

Theory

Frank Dietrich, Daniel Gogny, Ian Thompson, Walid Younes (LLNL)

Experiment

J. Burke, R. Casperson, R. Hughes, J.J. Ressler, N.D. Scielzo (LLNL)
C. Beausang, T. Ross (U Richmond)

J. Cizewski et al (Rutgers)

Capture-γ Project

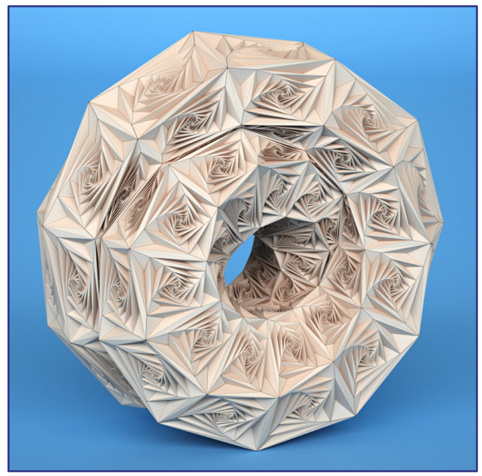
B. Sleaford and N. Summers (LLNL)

R.B. Firestone, A. Hurst, S. Basunia (LBNL)

ReactionTheory.org

TORUS: Theory of Reactions for Unstable iSotopes
A Topical Collaboration for Nuclear Theory

www.reactiontheory.org



TORUS members

Ian Thompson, LLNL
Jutta Escher, LLNL
Filomena Nunes, MSU
Neelam Upadhyay MSU
A. Mukhamedzhanov, TAMU
L. Hlophe, OU
V. Eremenko, OU
Charlotte Elster, OU
Goran Arbanas, ORNL

Appendix

Hauser-Feshbach calculations: γ-ray transmission coefficients

γ-ray strength function

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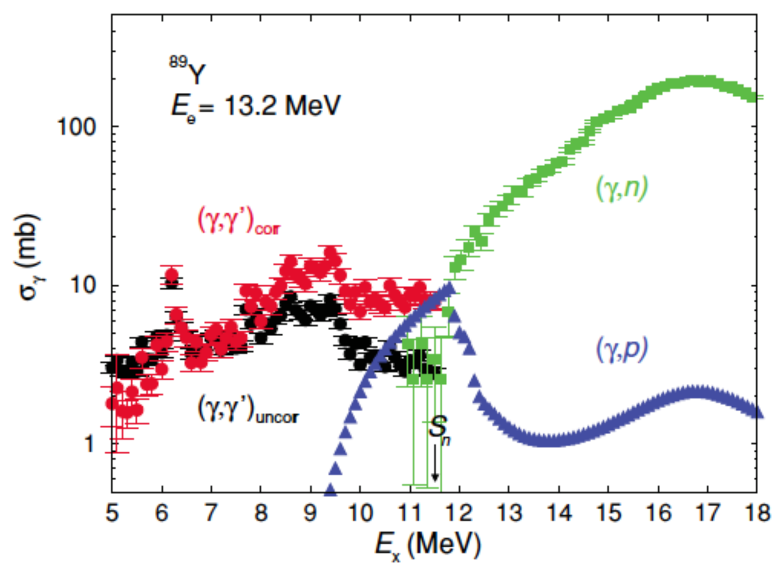
- Microscopic theories predict γSF

$$\frac{f_{E1}(S_n)}{f_{M1}(S_n)} = 0.0588 \cdot A^{0.878}$$

$$\begin{aligned}
f^{\gamma}_{E2}(\epsilon) &= 7.2\times 10^{-7} A_C^{2/3} f^{\gamma}_{E1}(S_n) \\
f^{\gamma}_{M2}(\epsilon) &= 2.2\times 10^{-7} f^{\gamma}_{E1}(S_n) \\
f^{\gamma}_{E3}(\epsilon) &= 3.4\times 10^{-13} A_C^{4/3} f^{\gamma}_{E1}(S_n) \\
f^{\gamma}_{M3}(\epsilon) &= 1.1\times 10^{-13} A_C^{2/3} f^{\gamma}_{E1}(S_n)
\end{aligned}$$



Benouaret, PRC 79 (2009) 014303

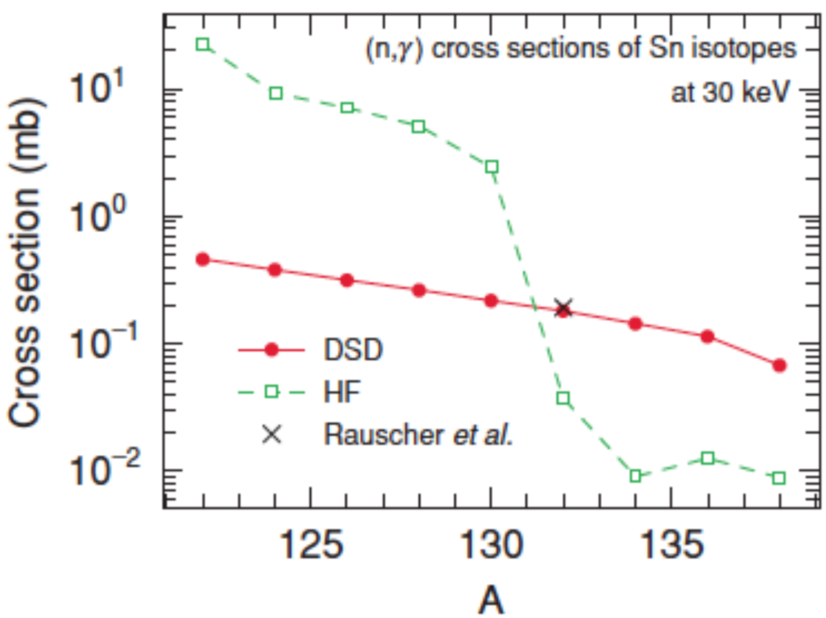
Reaction mechanisms in neutron capture

Capture contributions

Direct: single-step EM transition
Semidirect: via GDR excitation
Compound: via equilibrated CN

Relevance

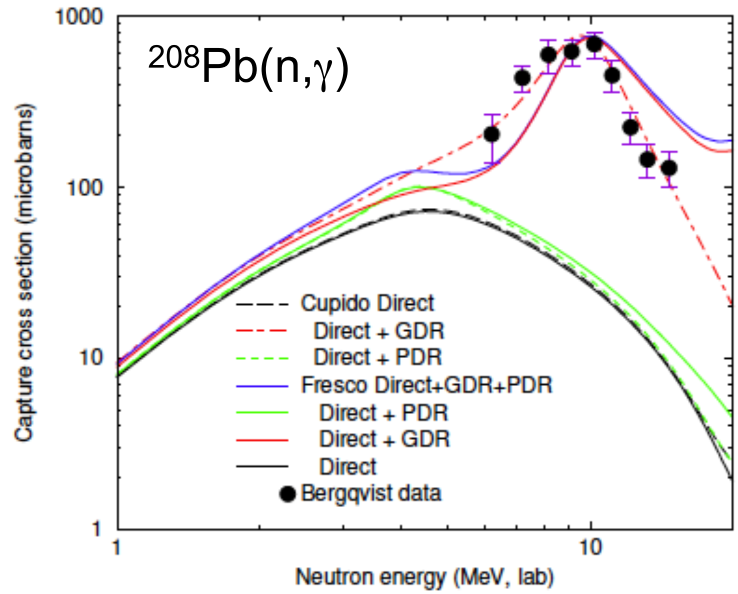
What happens away from stability, where level densities are low?



Chiba et al, PRC 77 (2008) 015809

Our work

- Implementation of DSD calculations
- Study of relative contributions
- Extension to include CN contributions



Thompson, Escher, Arbanas, ND2013 proceedings, submitted.

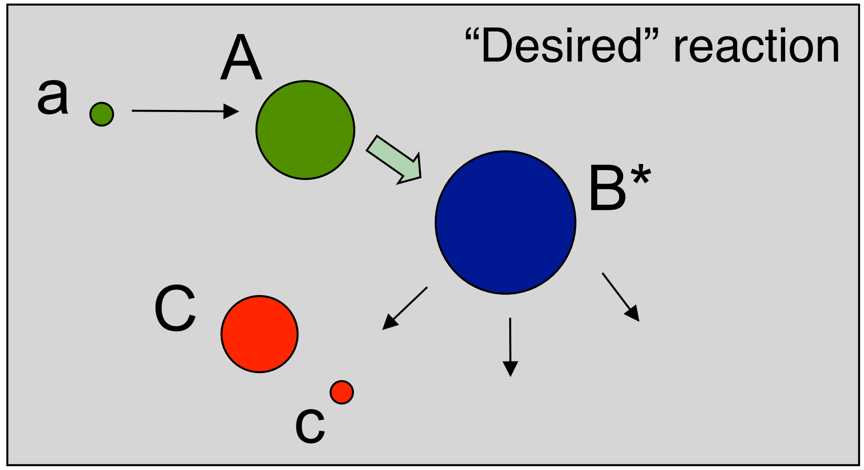
Challenge: cross sections for compound reactions

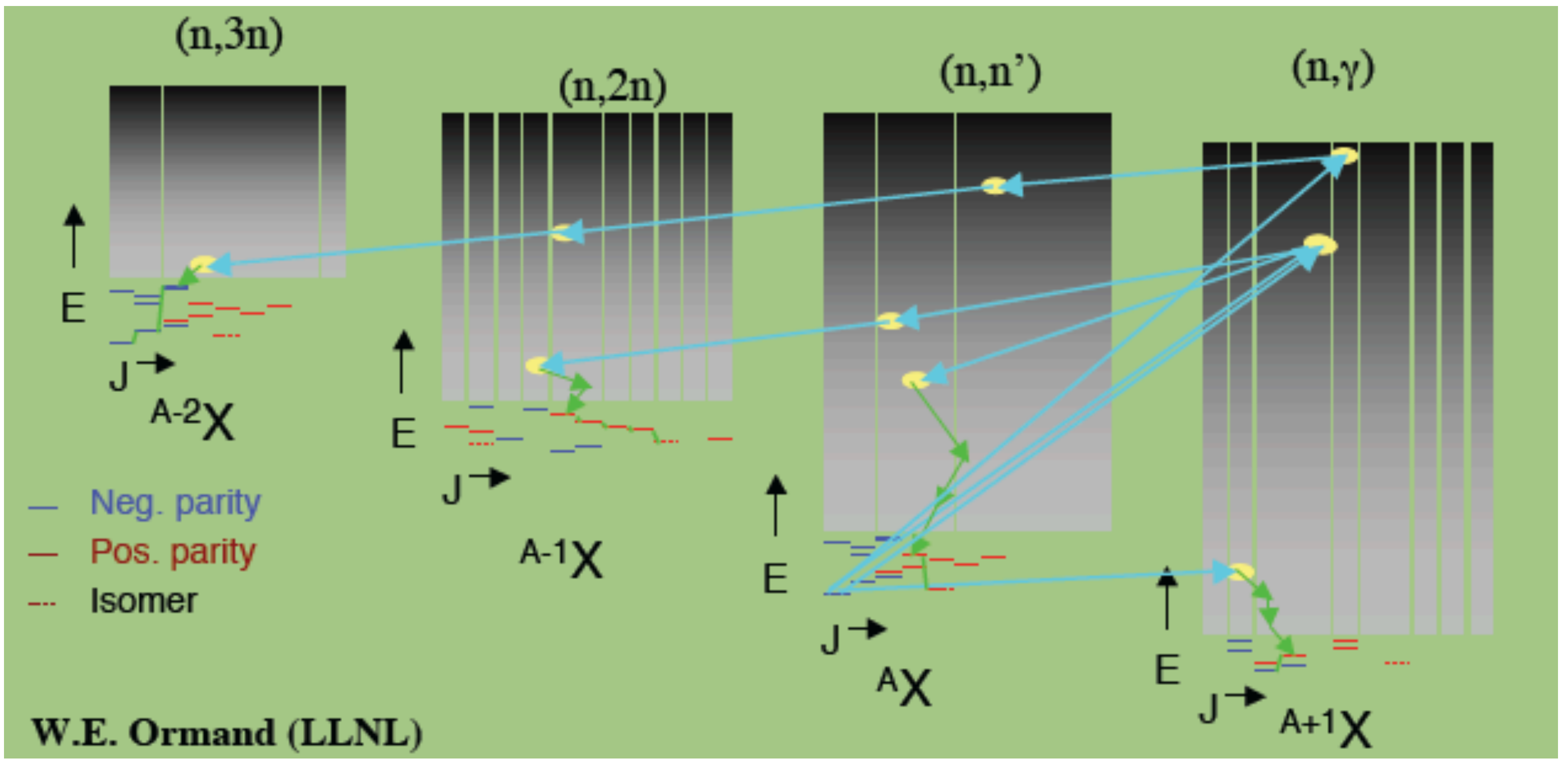
Hauser-Feshbach (HF) theory describes the "desired" CN reaction

$\sigma_{\alpha\chi} = \Sigma_{J,\pi}\, \sigma_{\alpha}^{CN}(E,J,\pi) \cdot G^{CN}_{\chi}(E,J,\pi)$

The issue:

- σ_{α}^{CN} can be calculated
- G^{CN}_{χ} are difficult to predict





Surrogate Idea

Hauser-Feshbach (HF) theory describes the "desired" CN reaction

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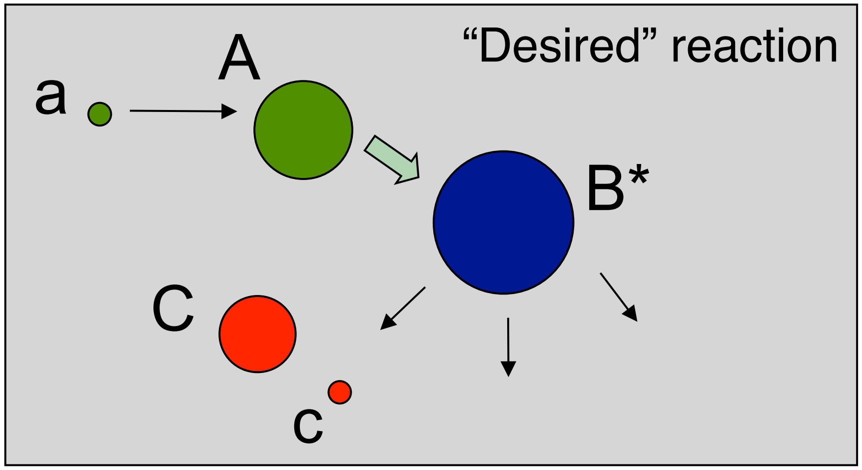
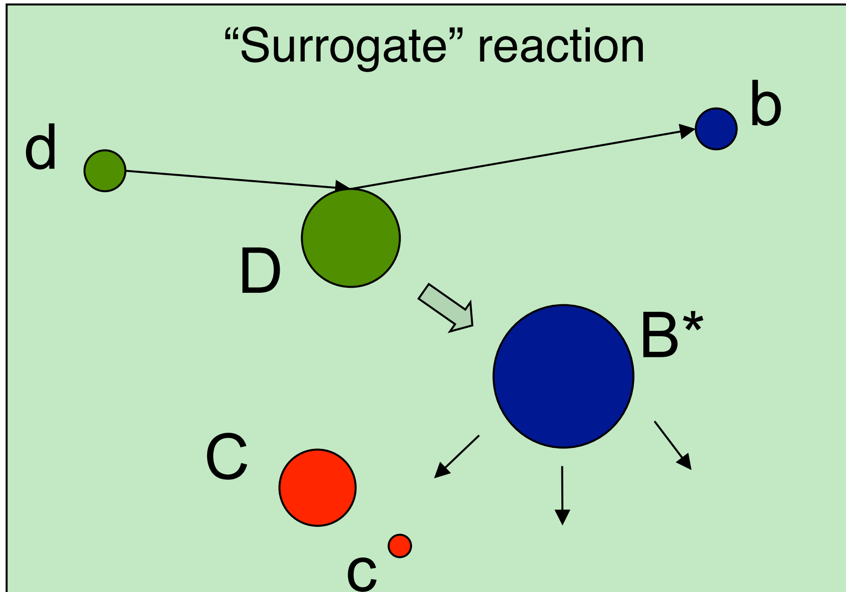


A Surrogate experiment gives

$$P_\chi(E) = \Sigma_{J,\pi}\, F_\delta^{CN}(E,J,\pi) \cdot G^{CN}_\chi(E,J,\pi)$$

Preferred approach: calculate $F_\delta^{CN}(E,J,\pi)$, model CN decay, adjust HF parameters to reproduce measured $P_\chi(E)$, obtain G^{CN}_χ

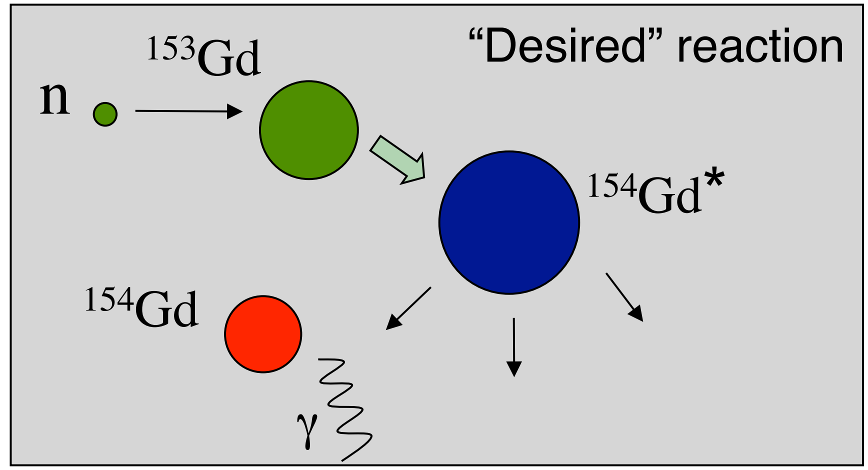
Typical approach so far - *approximations:* assume (J,π)-independent G^{CN} and employ simplified formulae ("Weisskopf-Ewing" and "Surrogate Ratio" approaches)

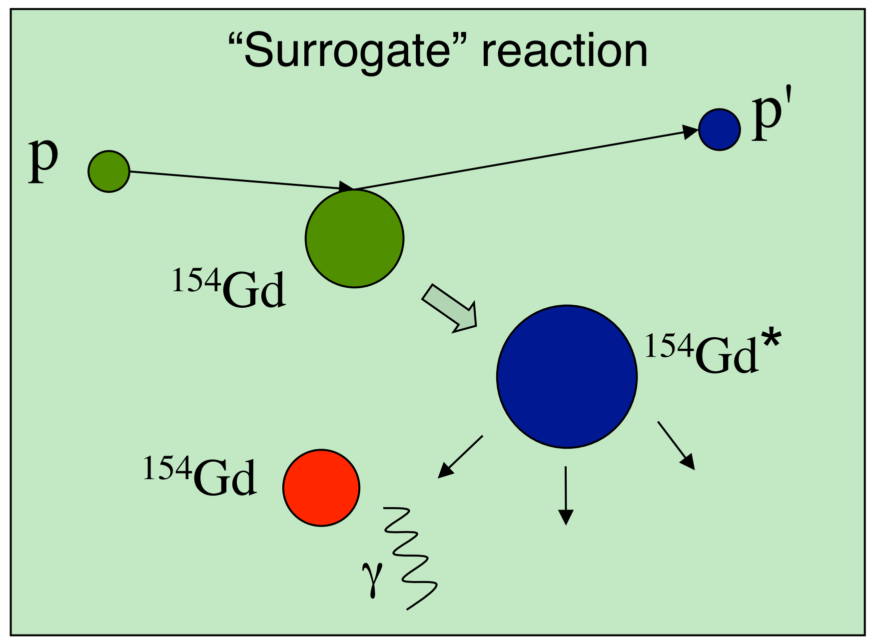


$$P_\chi = N_{\delta\chi}/N_\delta$$

J. Escher *et al*, Review of Modern Physics (2012)

Example: radiative capture

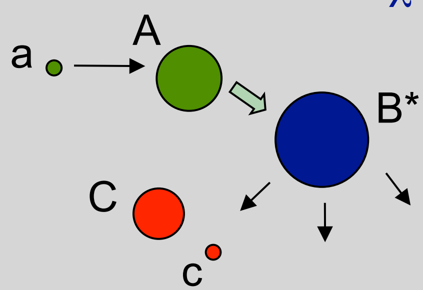




The Weisskopf-Ewing (WE) limit

HF theory of the "desired" reaction:

$$\sigma_{\alpha\chi} = \Sigma_{J,\pi}\, \sigma_{\alpha}^{CN}(E,J,\pi) \cdot G^{CN}_{\chi}(E,J,\pi)$$



Weisskopf-Ewing description of the "desired" reaction:

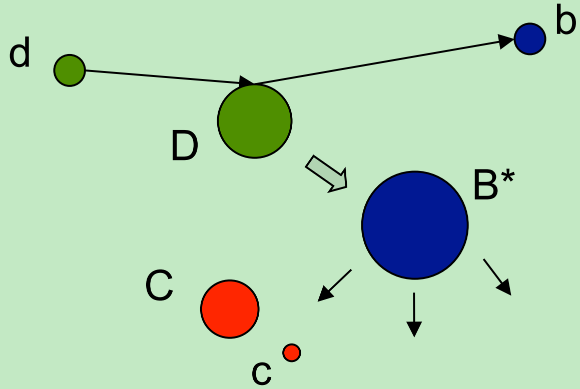
$$G^{CN}_{\chi}(E,J,\pi) \;\text{------>}\; \mathcal{G}^{CN}_{\chi}(E)$$

Thus:

$$\sigma_{\alpha\chi}^{WE}(E) = \sigma_{\alpha}^{CN}(E) \cdot \mathcal{G}^{CN}_{\chi}(E)$$

HF expression for the "Surrogate" measurement :

$$P_{\chi}(E) = \Sigma_{J,\pi}\, F_{\delta}^{CN}(E,J,\pi) \cdot G^{CN}_{\chi}(E,J,\pi)$$



Weisskopf-Ewing expression for the "Surrogate" measurement:

$$\text{------>}\; P_{\chi}(E) = \mathcal{G}^{CN}_{\chi}(E)$$

Cross section for the desired reaction:

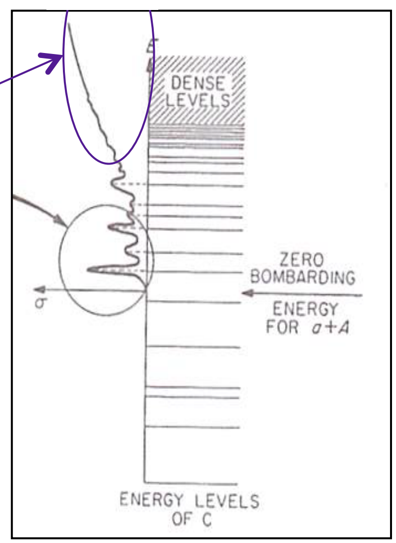
$$\sigma_{\alpha\chi}^{WE}(E) = \underbrace{\sigma_{\alpha}^{CN}(E)}_{\text{calculated}} \cdot \underbrace{P_{\chi}(E)}_{\substack{=N_{coinc}/N_{single} \\ \text{measured}}}$$

Predicting compound-nuclear spin-parity distributions

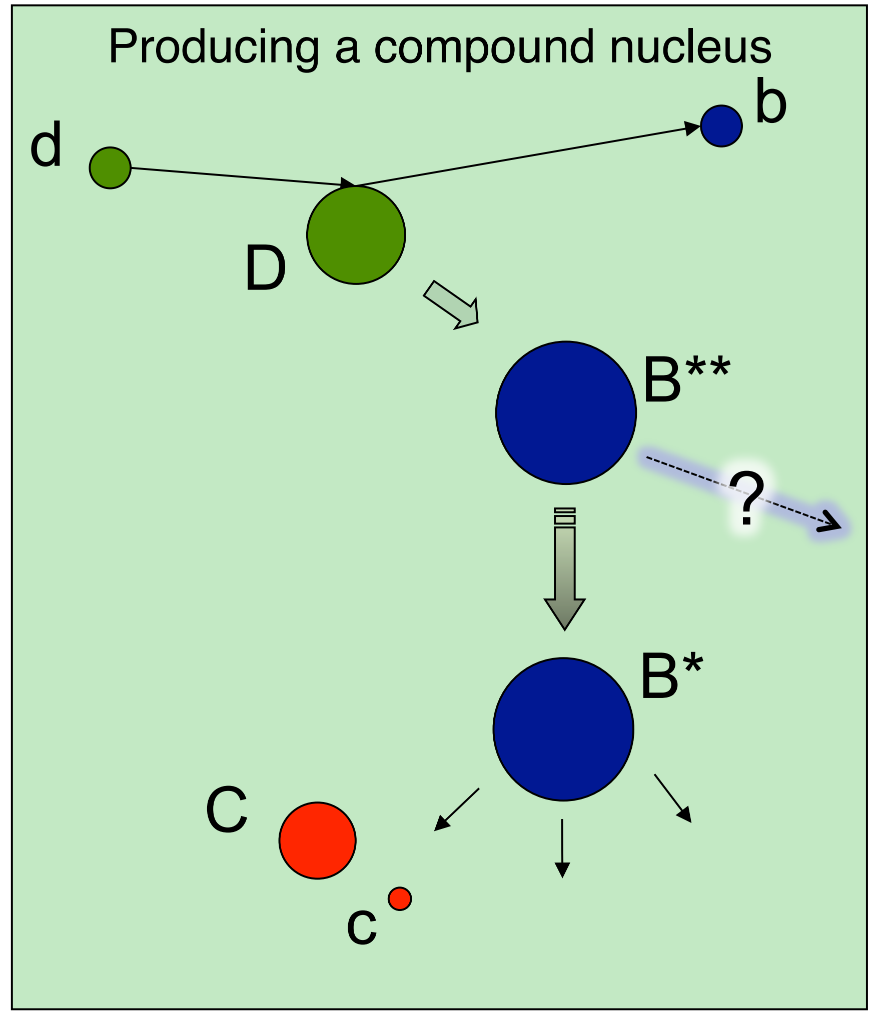
Formation of a highly excited nucleus in a direct reaction
- inelastic scattering, pickup, stripping reactions
- various projectile-target combinations

Damping of the excited states into a compound nucleus
- competition between CN formation and non-equilibrium decay (particle escape)
- dependence on J^{π}

Hauser-Feshbach regime



Satchler, Introduction to Nuclear Reactions (1980)



The Surrogate Ratio approach

Goal: Determine experimentally

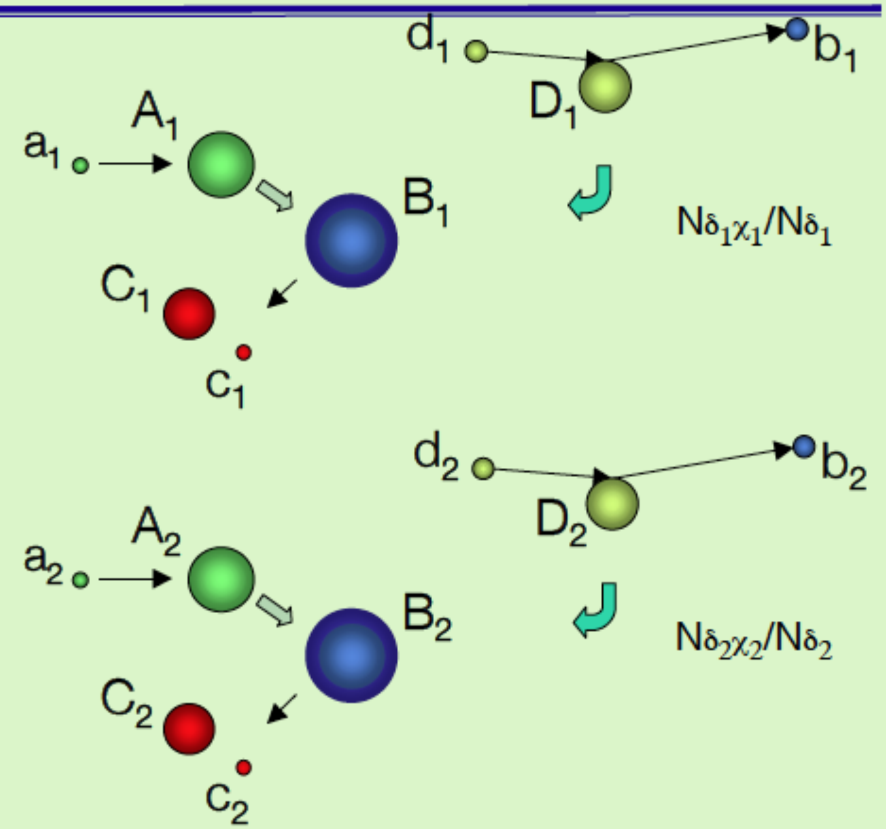
$$R(E) = \frac{\sigma_{\alpha_1 x_1}(E)}{\sigma_{\alpha_2 x_2}(E)}$$

$$\xrightarrow{\text{WE}} \underbrace{\frac{\sigma^{CN}_{\alpha_1}(E)}{\sigma^{CN}_{\alpha_2}(E)}}_{\text{calculated}} \cdot \underbrace{\frac{\mathcal{G}^{CN}_{\chi_1}(E)}{\mathcal{G}^{CN}_{\chi_2}(E)}}_{\text{measured}}$$

measured $= N_{\delta_1 \chi_1}/N_{\delta_1} \times N_{\delta_2}/N_{\chi_2 \delta_2}$

Advantages of the Ratio approach:

- Eliminates need to measure direct-reaction "singles" events in *Ncoinc/Nsingle*
- Small systematic errors or violations of assumptions underlying a Surrogate WE analysis might cancel



$N_{\delta_2}/N_{\delta_1}$ = const