Towards a systematic nucleus-nucleus potential with a single-folding model approach

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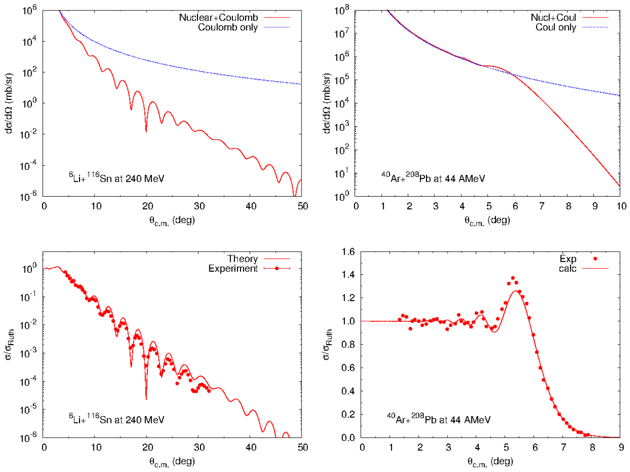
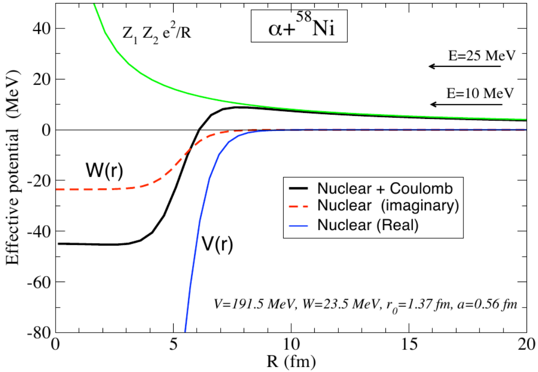
The optical model and optical potentials

Elastic scattering: two patterns of angular distributions



The oscillation patterns ⇔ **diffraction of light** with obstacles.

Elastic scattering: Optical model potential

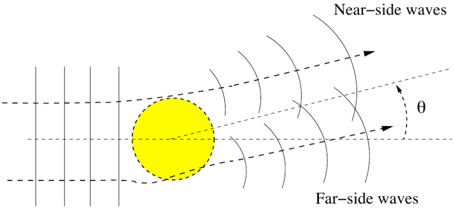


Coulomb potential: repulsive

Nuclear potential: attractive (real) and absorptive (imaginary)

Nuclear elastic scattering: Fraunhofer-type

FRAUNHOFER SCATTERING:



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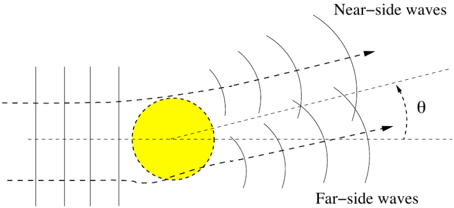

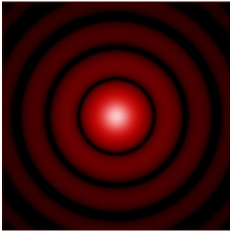

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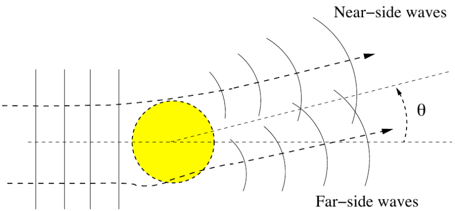

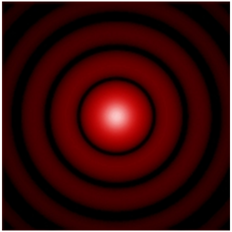

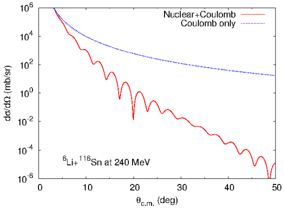

- Incident energy well above Coulomb barrier
- Coulomb force weak ($\eta \lesssim 1$)
- Nearside/farside interference (diffraction)

Nuclear elastic scattering: Fresnel-type

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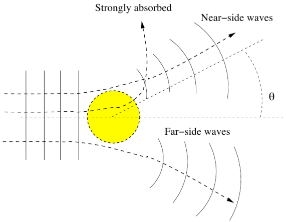

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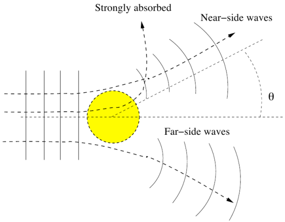

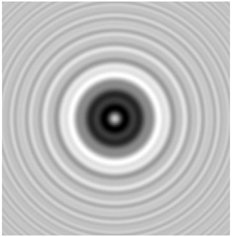

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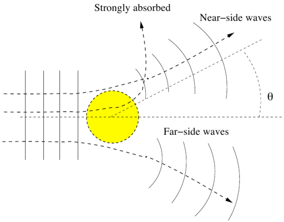

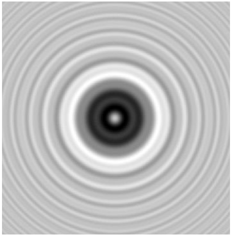

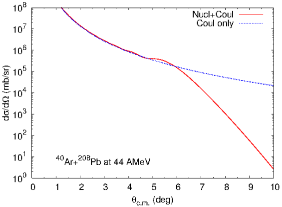

- $E_{inc} \sim V_C$, Coulomb strong
- "Illuminated" region: Nuclear&Coulomb interference
- "Shadow" region: strong absorption

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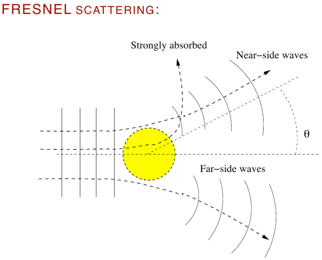

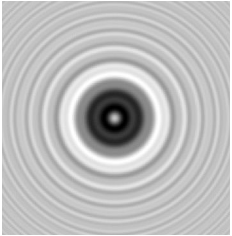

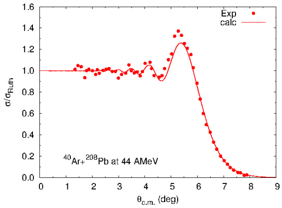

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Elastic scattering: optical model

The collision between projectile and target nuclei can be described with quantum mechanically.

- Hamiltonian: $H = T_R + U(R)$
  $U(R)$: optical model potential: effective projectile-target interaction.
- Schrödinger equation: $[H - E]\Psi(\boldsymbol{R}) = 0$
- Partial wave expansion of the model wave function:

$$\Psi(R,\theta) = \sum_L (2L+1) i^L P_L(\cos\theta) \frac{1}{kR} \chi_L(R)$$

- $\chi_L(R)$ obtained as solution of partial wave equation:

$$\left[-\frac{\hbar^2}{2\mu}\left(\frac{\mathrm{d}^2}{\mathrm{d}R^2} - \frac{L(L+1)}{R^2}\right) + U(R) - E\right]\chi_L(R) = 0$$

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Optical model: S-matrix and cross sections

- The asymptotic behavior of partial wave $\chi_L(R)$ defines the scattering S-matrix:

$$\chi_L(R) = \frac{i}{2}\left[H_L^-(\eta, kR) - S_L H_L^+(\eta, kR)\right]$$

where $H_L^\pm = G_L(\eta, kR) \pm iF_L(\eta, kR)$ are Coulomb Hankel functions. S_L relates with phase shift δ_L by $S_L = e^{2i\delta_L}$.

- Scattering amplitude: $A(\theta) = A_C(\theta) + A_n(\theta)$

$$\begin{aligned} A_C(\theta) &= \frac{i}{2K}\sum_L (2L+1)(1-S_L)P_L(\cos\theta) \\ A_n(\theta) &= \frac{i}{2K}\sum_L (2L+1)S_L(1-S_L)P_L(\cos\theta) \end{aligned}$$

- The differential cross section is:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = |A(\theta)|^2.$$

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Phenomenological and microscopic forms

Optical model potential is essential in study of nuclear reactions.

Two ways to find the optical model potentials:

1. Phenomenological way (Woods-Saxon parameters):

$$
\begin{aligned}
U(R) &= V(R) + iW(R) \\
&= \frac{V_0}{1+e^{-(r-R_V)/a_V}} \\
&\quad + i\left\{\frac{W_0}{1+e^{-(r-R_W)/a_W}} - 4a_d\frac{d}{dR}\left[\frac{W_d}{1+e^{-(r-R_d)/a_d}}\right]\right\},
\end{aligned}
$$

2. Microscopic or semi-microscopic way (folding model):

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U_{DF}(\boldsymbol{R}) &= \iint \rho_1(\boldsymbol{r}_1)\rho_2(\boldsymbol{r}_2)v(|\boldsymbol{R}+\boldsymbol{r}_2-\boldsymbol{r}_1|)\mathrm{d}\boldsymbol{r}_1\mathrm{d}\boldsymbol{r}_2, \\
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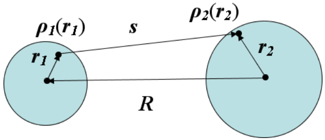
Semi-microscopic potential: the folding-model

- Double-folding: $U_{DF}(\boldsymbol{R}) = \iint \rho_1(\boldsymbol{r}_1)\rho_2(\boldsymbol{r}_2)V_{NN}(|\boldsymbol{s}|)\mathrm{d}\boldsymbol{r}_1\mathrm{d}\boldsymbol{r}_2$.



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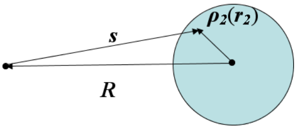

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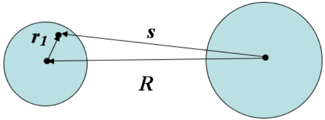

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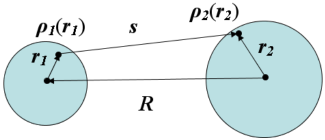

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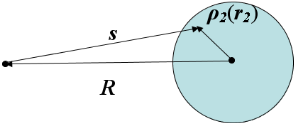

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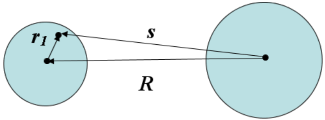

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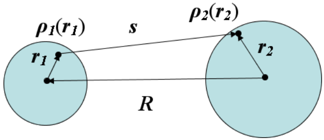

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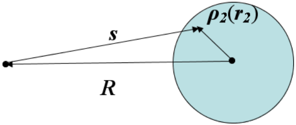

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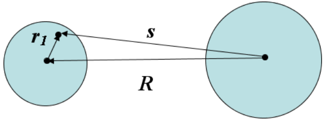

Parameterization with folding potentials

- To describe elastic scattering of charged particles, Coulomb potential has to be included:

$$U(R) = U_{folding}(R) + V_C(R), V_C(R) = \begin{cases} \frac{Z_1 Z_2 e^2}{r} & (r \geq R_C) \\ \frac{Z_1 Z_2 e^2}{2R_C}\left(3 - \frac{r^2}{R_C^2}\right) & (r \leq R_C). \end{cases}$$

- Double-folding (4 parameters or more):

$$U(E,R) = N_r(E) U_{DF}(E,R) + iW_{WS}(E,R) + V_C(R)$$

- Single-folding (2 parameters)

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Why do we need systematic optical potentials?

1. OMP from individual fitting has great uncertainty, global ones are more reliable.

   The best optical potentials are ones that attempt to describe the scattering over a broad region of nuclei and include the dependences on the number of nucleons, the neutron excess, etc. in a general way - without putting in specific information about the structure of the nucleus.

   -- by Prof. J. P. Schiffer (ANL), 2009

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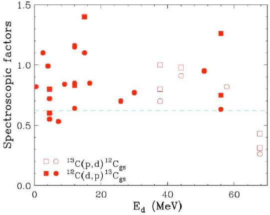

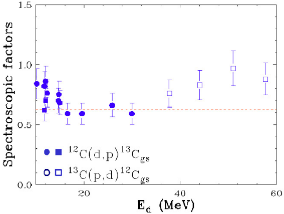

Current status of systematic potentials

p/n	CH89	$A > 40$, $E > 10$	R.L. Varner, Phys.Rep. 201, 57 (1991)
	KD02	$A > 24$, $E < 200$	Koning&Delaroche, NPA 713, 231 (2003).
	Bechetti-Greenlees	$A > 40$, $20 < E < 50$	Perey&Perey, ADNDT 17, I (1976).
	Watson&Singh	1p-shell, $E = 10 \sim 50$	B.A. Watson, Phys.Rev. 182, 977 (1969)
	JLMB	$A > 40$, $E < 200$	E.Bauge et al., PRC 63, 024607 (2001)
d	Daehnick	$A > 27$, $12 < E < 90$	W.W. Daehnick, PRC, 21, 2253 (1980)
	Lohr-Haeberli	$A > 40$, $8 < E < 13$	Lohr&Haeberli, NPA 232, 381 (1974)
	Perey-Perey	$12 < E < 25$	Perey&Perey, ADNDT, 17, I (1976).
	An-potential	$A > 12$, $E < 183$	An&Cai, PRC 73, 054605 (2006)
	Pang-potential	$A > 40$, $20 < E < 200$	**D.Y. Pang, PRC 83, 064619 (2011)**
3He/3H	Bechetti-Greenlees	$A > 40$, $20 < E < 50$	Perey&Perey, ADNDT, 17, I (1976).
	Li-potential	$A > 20$, $E < 40$	Li Xiaohua, NPA789, 103, (2007)
	GDP08	$A > 40$, $30 < E < 217$	**D.Y. Pang,PRC, 79 024615 (2009)**
4He	Nolte-potential	$A > 12$, $E > 80$	M. Nolte, PRC 36(1987)1312
	Avrigeanu	$50 < A < 120$, $13 < E < 50$	M. Avrigeanu, ADNDT 95, 501 (2009)
	Pang-potential	$A > 40$, $40 < E < 386$	**D.Y. Pang, PRC 83, 064619 (2011)**
	Pang-potential	$A = 12$, $40 < E < 386$ MeV	**D.Y. Pang, JPG 39, 095101 (2012).**
6Li/7Li	Cook-potential	$A > 24$, $13 < E < 156$	J. Cook, NPA 388, 153 (1982)
AA	SPP	global	L.C. Chant, PRC 66, 014610 (2002)
	Xu-potential	$A \gtrsim 30$, $E \gtrsim V_C$	**Xu&Pang, in preparation, (2012)**

Towards a systematic nucleus-nucleus potential
with a single-folding model

A systematic nucleus-nucleus potential with folding model

- With single-folding model we have only two free parameters N_r and N_i.
- Systematics (energy dependence) of N_r and N_i will provide systematics of nucleus-nucleus potential.
- It has been successfully applied to deuteron and α-particles.

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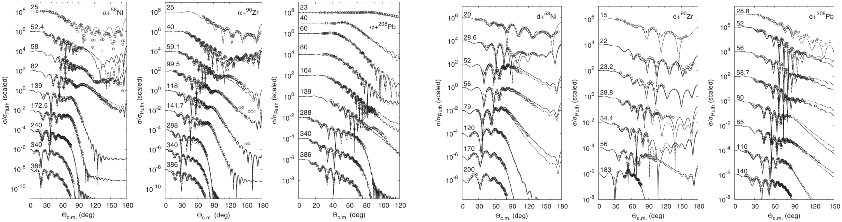
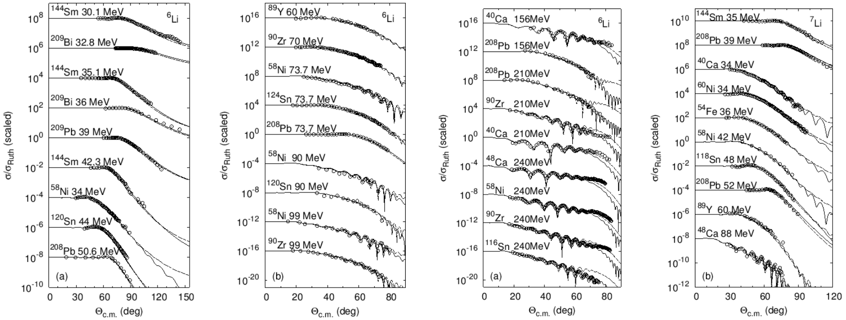


D.Y. Pang, Y.L. Ye, and F.R. Xu, Phys. Rev. C 83, 064619 (2011), ibid. J. Phys. G: Nucl. Part. Phys. 39, 095101 (2012).

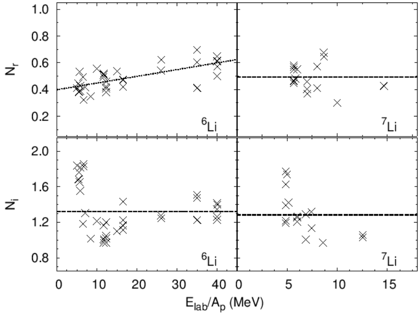
A systematic nucleus-nucleus potential with folding model

We start with ^{6}Li and ^{7}Li for study of nucleus-nucleus potentials.



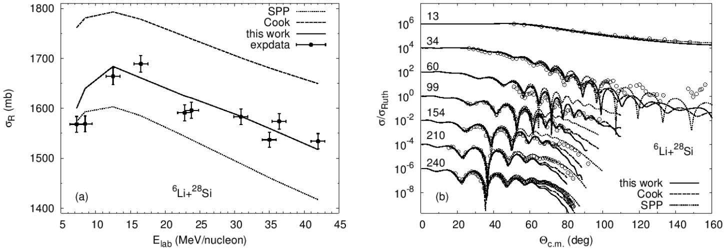
We fit the elastic scattering data for N_r and N_i and found their energy dependence.
Targets: $A \geq 40$, incident energy: $5 \leq E_{lab} \leq 40$ MeV/nucleon.

$$
\begin{aligned}
N_r(E_{lab}) &= 0.005025 E_{lab}/A_p \\
&\quad +0.3983 \\
N_i(E_{lab}) &= 1.323
\end{aligned}
$$



Test of the new systematics: extrapolation to light targets

Elastic scattering and total reaction cross sections for ^{6}Li+^{28}Si at various energies.

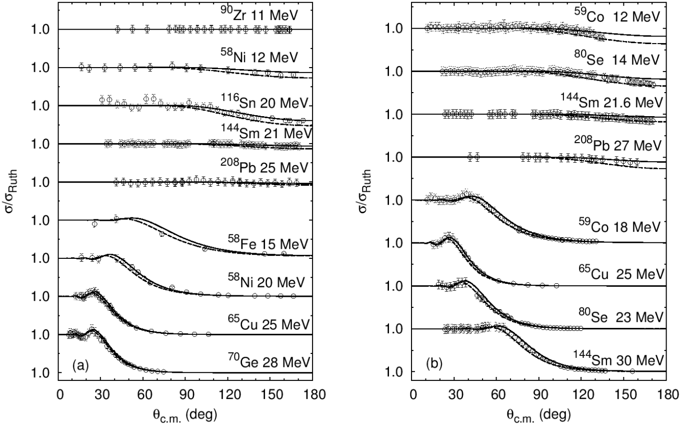


J. Cook, Nucl. Phys. **A388**, 153 (1982);

(SPP) L.C. Chamon et al., Phys. Rev. C 66, 014610 (2002).

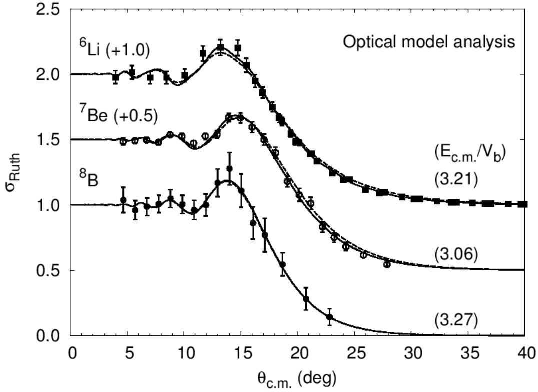
Test of the new systematics: extrapolation to low energies

Application of the systematics for ^{6}Li and ^{7}Li elastic scattering below 5 MeV/nucleon.



Test of the new systematics: applications to unstable nuclei

Application of the systematics for to ^{7}Be and ^{8}B – for angular distributions.



Exp data: Yang Yanyun (IMP, Lanzhou), unpulibshed, (2012).

Test of the new systematics: applications to unstable nuclei

Application the systematics to carbon isotopes from A=11 to A=19: total reaction cross sections at various energies with ^{nat}Cu target.

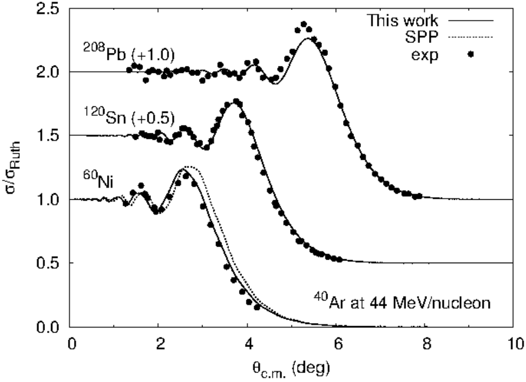
isotope	E_{lab}	σ_R^{Exp}	σ_R^{GA}	$\frac{\lvert\sigma_R^{Exp}-\sigma_R^{GA}\rvert}{\Delta\sigma_R^{Exp}}$	σ_R^{HF}	$\frac{\lvert\sigma_R^{Exp}-\sigma_R^{HF}\rvert}{\Delta\sigma_R^{Exp}}$
^{11}C	36.77	2.28 ± 0.44	2.39	0.243	2.35	0.163
^{12}C	29.78	2.404 ± 0.099	2.47	0.669	2.41	0.054
^{13}C	24.23	2.09 ± 0.13	2.50	3.174	2.48	2.978
	46.52	2.22 ± 0.35	2.43	0.593	2.41	0.540
^{14}C	19.78	1.88 ± 0.28	2.64	2.711	2.53	2.339
	39.52	2.521 ± 0.051	2.60	1.524	2.51	0.261
	45.00	2.62 ± 0.22	2.57	0.237	2.48	0.639
^{15}C	33.82	2.847 ± 0.59	2.76	0.152	2.61	0.398
	38.68	2.666 ± 0.081	2.73	0.805	2.59	0.938
^{16}C	29.10	2.69 ± 0.11	2.81	1.060	2.70	0.096
	33.44	2.743 ± 0.059	2.79	0.768	2.69	0.976
	44.64	2.19 ± 0.77	2.72	0.691	2.63	0.567
^{17}C	24.55	2.24 ± 0.51	3.03	1.541	2.78	1.062
	29.07	2.31 ± 0.20	3.01	3.518	2.77	2.318
	39.15	2.96 ± 0.12	2.96	0.034	2.73	1.938
^{18}C	34.51	2.89 ± 0.20	2.94	0.263	2.82	0.368
^{19}C	45.12	2.7 ± 1.5	2.82	0.078	2.81	0.076
average				1.062		0.924

Exp: M.G. Saint-Laurent, et al., Z.Phys.A 332, 457 (1989), similar result for $^{15-21}$O.

Test of the new systematics: heavy nuclei

^{40}Ar elastic scattering form ^{60}Ni, ^{120}Sn and ^{208}Pb at 1760 MeV.

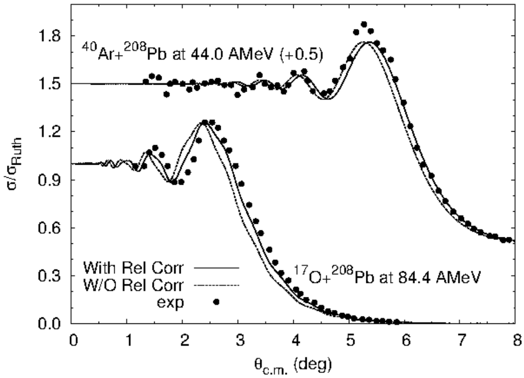
How amazing that systematics established from ^{6}Li elastic scattering being applicable to heavy ions like ^{40}Ar!



Necessity for relativistic corrections

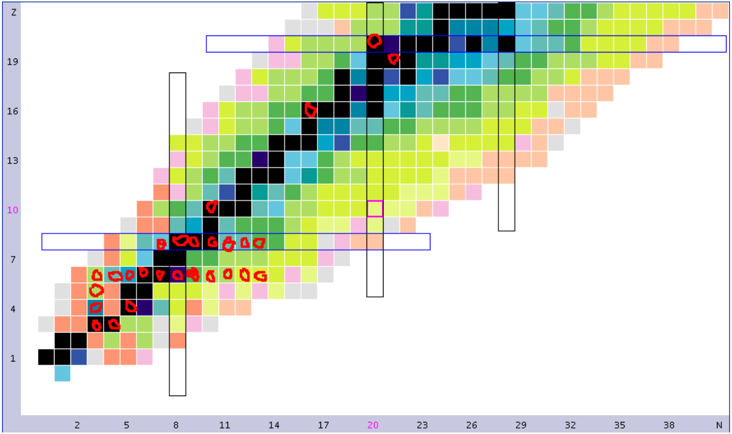
^{40}Ar+^{208}Pb at 44 MeV/nucleon and ^{17}O+^{208}Pb at 84.4 MeV/nucleon.

Corrections to reaction kinematics are necessary for energy as low as around 40 MeV/nucleon for heavy-ions!



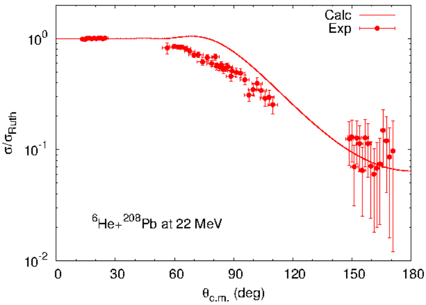
Applicability of new systematics in nuclear chart

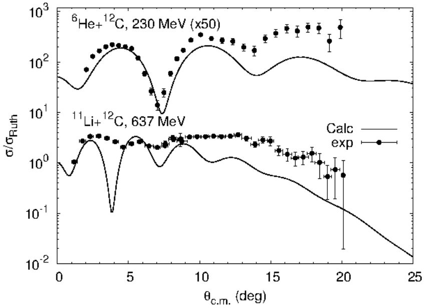
Remember: we got the systematics from analysis of ^{6}Li scattering and it is found applicable for almost all heavy nuclei including radioactive isotopes!



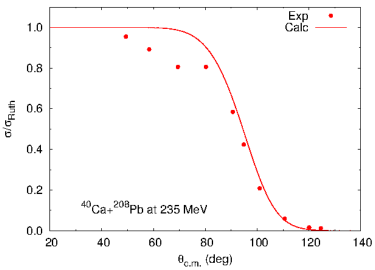
“Failed” cases: exotic nuclei

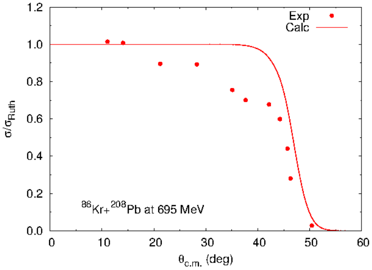
This systematics fails for (i) weakly-bound nuclei below Coulomb barrier and for (ii) light targets – limitation of the model.

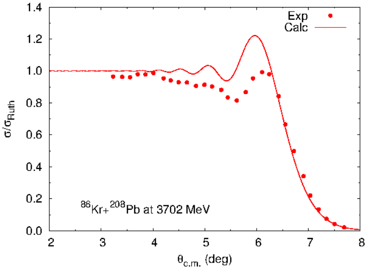




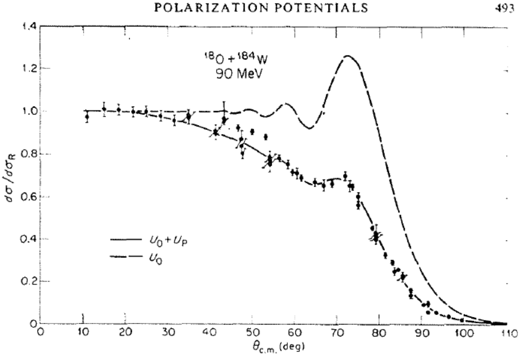
"Failed" cases: very heavy nuclei







Very heavy cases: Strong Coulomb excitation?



G.R. Satchler, «Direct Nuclear Reactions», P.493

Anyway, it is better than expected!

Happy to have something better our expectation!

填写概括课题内容的六个关键词（主题词），关键词个数可少于六个，关键词之间用逗号隔开
光学势，弹性散射，微观光学势，单折叠模型
课题摘要（300 字以内）
光学模型势是研究原子核反应的基本输入量，对于核物理特别是当前的放射性核物理的研究具有重要的作用。本项目拟从唯象和微观两个角度研究原子核的单折叠模型势。从唯象的角度：利用单折叠模型研究 Z≤10 的稳定核的光学势的系统学行为，结合兰州近代物理研究所已有的质子滴线核的弹性散射实验数据，考察它们在对 Z≤10 的质子滴线核的弹性散射研究上的应用；从微观的角度：考察核内核子光学势的能量依赖、三体效应以及泡利原理等因素对单折叠模型势重归一化因子的理论解释，期望最终建立没有自由参数的基于单折叠模型的核-核微观光学势。

D.Y.Pang, proposal to "New Teachers' Fund for Doctor Stations, Ministry of Education", 2012.

The next step

Next step: to explain N_r and N_i and their energy dependence theoretically. The PKR model or some other possibilities (non-locality)

2.E:2.N

Nuclear Physics **A245** (1975) 343—364; © *North-Holland Publishing Co., Amsterdam*

REAL PART OF THE OPTICAL POTENTIAL FOR COMPOSITE PARTICLES

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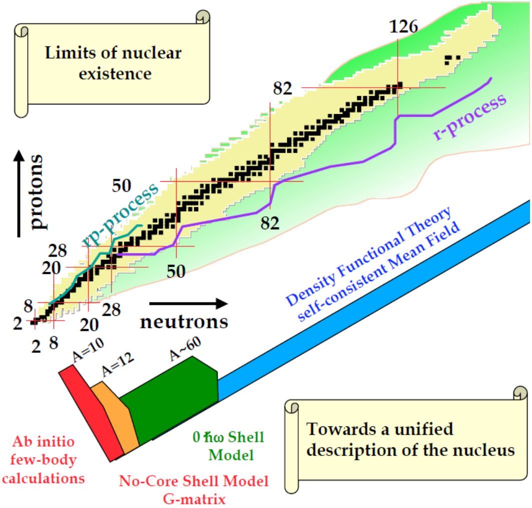
Nuclear Physics Laboratory, Oxford

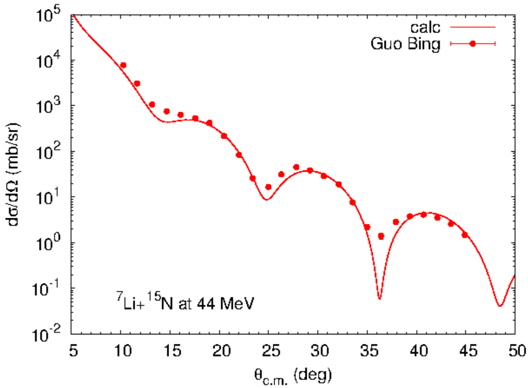
Received 10 January 1975
(Revised 6 February 1975)

Abstract: The optical potential for a composite particle is most simply approximated by the sum of the optical potentials of the constituent nucleons. Restricting ourselves to the real parts of the potentials we use this model as a first approximation in a calculation of the potentials for d, ^{3}He, α and ^{12}C. We add corrections for (i) the energy dependence of the nucleon potentials, (ii) three-body terms, (iii) the Pauli principle. All corrections can be important and that for the Pauli principle can be very large. We obtain a good explanation of the following phenomena: (a) the deuteron potential is nearly the sum of the neutron and proton potentials, (b) the potential for ^{3}He is about 20 % less than the sum of the potentials of the nucleons in the ^{3}He projectile, (c) the volume integral of the potential for ^{3}He falls at both high and low energies in the energy range 20–100 MeV, (d) shallow potentials with large radii are found for low energy (30 MeV) scattering of α-particles, (e) deeper potentials are found for higher energy α-particle scattering. We predict shallow potentials for ^{12}C scattering from light targets but deeper potentials for heavier targets.

Unified description of the nucleus



For new data!



new data from Guo Bing.

The end

Thanks for attention!