Workshop on Data Compilation, IAEA, Vienna, May 25th, 2011

"Systematic studies of nuclear reactions using EXFOR" --- from a viewpoint of a database user ---

- Contents:
  - Introduction
    - EXFOR and  $\sigma_R$  etc
  - An ex. of systematic analyses: necessity of "HE" data
    - BS Approxi. of nuclei
  - $\sigma_{NN}^{total}$  in EXFOR
  - Summary

The black-sphere picture as a reference frame

A. Kohama (RIKEN Nishina C.)



Ref. *Phys. Rev.* **C69**, 064316 (2004). *Phys. Rev.* **C72**, 024602 (2005). *J. Phys. Soc. Japan* **76**, 044201 (2007). *Phys. Rev.* **C78**, 061601 (2008).

### Self-introduction

- I am ...
  - a nuclear theorist majoring nuclear reactions.
- Research interest:
  - Nuclear radii, density distributions, ...
- Approach:
  - Based on the systematic analyses of plenty of reaction data involving stable nuclei, we lighten up the structure and reaction mechanism of unstable nuclei.

- I am a "Data lover".
  - One of the heavy-users of EXFOR.
  - Members of JCPRG and N.
     Otsuka helped me in collecting data including "missing" data.
  - Prof. Kato has suggested me to join this WS.



# EXFOR is powerful

- Databases support systematic analyses
  - use EXFOR
  - Data:  $d\sigma_{\rm el}(p+A)/d\Omega$ ,  $\sigma_{\rm R}(p+A)$ ,  $\sigma_{\rm R}(A+A)$ , ...
- EXFOR is very powerful for our systematic analyses.



# Key Quantities

- ☆ Scattering amplitude:  $f_{pA}(q)$ .
- Differentiated quantities:
- ► Differ. cross sec.:  $d\sigma_{el}/d\Omega = |f_{pA}(q)|^2$ . sensitive to density distribution (radius, diffuseness)
- Analyzing power: A<sub>y</sub>.

- Integrated quantities:
- Total elas. scat. cross sec.:  $\sigma_{el} = \int d\Omega / f_{pA}(q) |^2.$
- Total cross sec.:  $\sigma_{tot} = (4\pi/k) Im f_{pA(pN)}(q).$
- Total reac. cross sec.:  $\sigma_R = \sigma_{tot} - \sigma_{el}$ . sensitive to radius and diffuseness. Tail?
- > Interaction cross sec.:  $\sigma_{I} = \sigma_{R} - \sigma_{inel}$ . structure info.!

# Importance of $\sigma_R$

- Physics side:
  - Nuclear geometrical size, eg.,  $r_m$
  - Isotope dep. of  $r_m$  $\rightarrow$  Sym. Energy coef. L
  - − Energy dependence
    → density distribution?

- Practical side:
  - Estimation of the reaction rate in simulation codes:
    - eg., FULKA, GEANT, PHITS (Particle and Heavy Ion Transport code System). http://phits.jaea.go.jp/

For PHITS, see
# H. Iwase, K. Niita and T. Nakamura, J. Nucl. Sci. Technol. 39, 1142 (2002).
# K. Niita, T. Sato, H. Iwase, H. Nose, H. Nakashima, L. Sihver, Radiat. Meas. 41, 1080 (2006).



# Fraunhofer diffraction in Optics

 $\operatorname{int}$ **Diffraction with a hole** embedded in an infinitely extended screen.

• Diffract. pattern:  $|f(q)|^2$ Diffraction of He-Ne Laser = 632.8 [nm].  $(slit width) = 250 [\mu m].$ Thanks to Y. Matsuo (RIKEN) for this experiment. Photo by K. Oyamatsu. Feb.20, 2004

 $f(q) = ipa J_1(qa) / q.$ 

Ref. "The Classical theory of fields" L. D. Landau & E. M. Lifshitz

#### The contemporary black-sphere model and the black-sphere cross section formula

in collaboration with K. Iida (Kochi U.) and K. Oyamatsu (Aichi Shukutoku U.)





Phys. Rev. C69, 064316 (2004).

"Kurotama" in Japanese

#### The contemporary black-sphere model Estimate only the strong interac. contribution.

- Determine the blacksphere radius as;
- Geometrical cross section:  $\sigma_{BS} = \pi a^2$ .

 $-a = 1.2135 A^{1/3}$  fm for  $T_p > 800$  MeV.





#### No parameter!



# $\sigma_R$ in EXFOR

- Total reaction cross section
  - = non-elastic cross section (NON)
  - = total cross section
    (TOT)
  - total elastic cross section ("EL")

- Lots of data have been already compiled incl. very recent ones.
- *cf.* antiproton data
  - Recently compiled
     thanks to the effort of
     N. Otsuka and JCPRG.



Data: W. Bauhoff, *At. Data Nucl. Data Tables*, **35**, 429 (1986). A. Auce *et al.*, *Phys. Rev.* **C 71**, 064606 (2005).

#### The size of the black sphere changes with $T_p$



The region where incident proton probes will change according to the change of the black-sphere radius.

# Which part is probed?

Correspondence of the BS radius to the "real" density.

 $L' \Leftrightarrow \rho_0^{-1} \int_{-\infty}^{\infty} dz' \rho_N(\vec{b}, z')$ 

projectile path length L' $\cong$  mean-free path

 $\langle r^2 \rangle^{1/2}$ 

4 r [fm

 $= 4.64 \, [fm]$ 

<sup>120</sup>Sp

 $n_c$ 

8

6

r = a

• The radius "*a*" can be regarded as a "reaction radius", inside which the reaction with incident protons occurs.

projectile

K.Iida, A.K., K.Oyamatsu, J. Phys. Soc. Japan 76, 044201 (2007).

0.20

0.15

0.10

0.05

0.00

a

 $\rho_0/2$ 

2

Density Distribution  $ho({
m r})~[{
m fm}^{-3}]$ 

### Estimation of the path length L'

$$L'=2\sqrt{R^2-a^2}.$$



- The "real" density is approximated by *the trapezoidal density* with the standard diffuseness.
- D: the surface thickness (= 2.2 fm)

Normalization:

$$A = \frac{4\pi\rho_0}{3} \left( R^3 - \frac{3}{2}DR^2 + D^2R - \frac{1}{4}D^3 \right).$$

### "Optical" depth of nuclei is the key

• Introduce nuclear optical depth:  $\tau = L'/\{1/(\sigma_{pN} n_c)\} = \sigma_{pN} n_c L',$ which is assumed to be  $T_p$ -independent. This is similar to  $\int_{l} dl[\sigma_{pn} n_n(\mathbf{r}) + \sigma_{pp} n_p(\mathbf{r})],$ 

Assume:  $\tau = \mathcal{O}(1)$ , *i.e.*, The black-sphere radius "*a*" corresponds to a radius at which the mean-free path of incident protons is of the order of the length of the penetration.

#### Construction of BS-cross-sect. formula

$$\sigma_R \cong \pi a(T_p)^2 \cong \pi a_0^2 \left(1 + \frac{\Delta a}{a_0}\right)^2.$$

• Express  $\Delta a/a_0$ in terms of  $\Delta \sigma_{pN}/\sigma_{pN0}$ using  $\tau$  being  $T_p$ -indep. *i.e.*,  $\Delta \tau = 0$ , and

$$\Delta\left(\frac{\tau}{\bar{\sigma}_{pN}}\right) = \Delta(n_c L').$$

• 
$$\Delta a = a(T_p) - a_0$$
.

the value at 800 MeV.

$$\Delta X = X - X_0,$$

> 
$$X_0$$
 is  
 $X (= a, \sigma_{pN}, n_c, L')$   
at 800 MeV.

Destination:  $\Delta a/a_0 = \Delta \sigma_{pN}/\sigma_{pN0} \times (T_p$ -independent terms).

#### Formula for reaction cross section

# $T_p$ -dep. is driven by $\sigma_{pN}$ through the nucl. optical depth.

#### **Proton - stable nucleus**

$$\sigma_{\rm R}(T_p, A) = \pi a^2(T_p, A) = \pi a_0^2 \left(1 + \frac{\Delta a}{a_0}\right)^2, \ T_p > 100 \,{\rm MeV}$$

$$\Delta a = \left(\frac{\rho_0 a_0}{D n_{c0}} - \frac{a_0}{L'_0} \frac{dL'}{da}\right|_0^{-1} \frac{\Delta \overline{\sigma}_{pN}}{\overline{\sigma}_{pN0}} a_0$$
  

$$\overline{\sigma}_{pN} = (Z/A)\sigma_{pp} + (1 - Z/A)\sigma_{pn}$$
  

$$X_0 : X(= \overline{\sigma}_{pN}, a, n_c, L') \text{ at } T_p = 800 \text{ MeV}$$
  

$$\Delta X = X - X_0$$
  

$$L' = 2\sqrt{R^2 - a^2}$$
  

$$R = R_0 + D/2 - R_0 (1 + 12R_0^2/D^2)^{-1}$$
  

$$D = 2.2 \text{ fm}, \rho_0 = 0.16 \text{ fm}^{-3}, R_0 = (3A/4\pi\rho_0)^1$$

 $n_{c0} = 0.9(\sigma_{pN0}L_0)$ 

target Larger  $\sigma_{pN}$ 

3

Bird's-eye view

$$\Delta \overline{\sigma}_{pN}^{total} = \overline{\sigma}_{pN}^{total}(T_p) - \overline{\sigma}_{pN0}^{total}.$$

is small for  $T_p > 100$  MeV.

No energy dependent adjustable parameter

— different from fitting formulas

From K. Iida



cf. PHITS



In the EXFOR manual,

"a less complete compilation of charged-particle-induced reaction data."

Based on the discussion with N. Otsuka (IAEA)



You will find "Cross Sections and related quantities".



### E-dep. of p+n total cross sections



#### "observable" or "deduced value"?

- $\sigma_{pp}^{\text{total}}$ > It is an ill-definition
  - It is an ill-defined quantity, not an observable.
     It is a deduced quantity.
    - Due to the coulomb interaction, it must be diverge.
    - Procedure of Coulomb subtraction should be accompanied by some uncertainties.

- $\sigma_{np}^{\text{total}}$  or  $\sigma_{pp}^{\text{total}}$   $\succ$  "n on p" is an observable.
  - This serves as the standard values of cross sections.
    - The highest incident energy is limited.
  - "p on n" is not an observable.
    - It is a deduced quantity.
      - The target will be deuterons. The contribution from the target proton should be subtracted out.

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# My current concern with $\sigma_{NN}^{\ total}$

- Below the π-threshold:
   (total) = (elastic)
- While in EXFOR even below π-threshold;
  - 1-H-1(N,EL)1-H-1,,SIG,1-H-1(N,TOT),,SIG
  - Different data sets appear, but the same sets should appear.
- At high energy,  $\sigma_{pn}^{\text{total}} \approx \sigma_{np}^{\text{total}}$ ?

- Extrapolation is inevitable
  - EL: integrated angular distribution of elastic differential cross section.
     Extrapolation to zero degree to subtract the Coulomb.
  - TOT: Extrapolation of angular distribution of elastic differential cross section to zero degree and adopt the optical theorem.

I believe that  $\sigma_{NN}^{total}$  is important as a measure of the strength of NN-int. and hope to be compiled properly.

### EXFOR is powerful and evolving DB

- I have illustrated an example of the systematic analyses of high energy processes using EXFOR.
  - Compilation of high energy data is very helpful.
  - Please be careful for high energy data and for reactions involving particles other than nucleons.
- Message: Databases, such as EXFOR, must be evolving forever with the users.
  - Nuclear reaction data is one of the valuable common properties of human being!
- Special thanks to N. Otsuka (IAEA) & the members of Nuclear Reaction Data Centre (JCPRG) @ Hokkaido Univ. for the data collection.

# Thank you very much!



# Backup slides

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# C1-H2(2-HE-6,NON),S1G) Quantity: [CS] Cross section       # (2-HE-6(F,IOH),S1G) Quantity: [CS] Cross section         # Process: [NON] Nonelastic (= total minus elastic)       # (2-HE-6(F,IOH),S1G) Quantity: [CS] Cross section         # Process: [LO] Harding (= CS] Cross section       # Process: [NON] Nonelastic (= total minus elastic)         # Process: [LO] Harding (= CS] Cross section       # Process: [NON] Nonelastic (= total minus elastic)         # Process: [LO] Harding (= CS] Cross section       # Process: [NON] Nonelastic (= total minus elastic)         # Process: [LO] Harding (= CS] Cross section       # Process: [NON] Nonelastic (= total minus elastic)         # Catheder calculation       See RE-REF.         Integration       See RE-REF.         Integration       See RE-REF.         Integration       Glauber calculation         REL-REF       (N, .6. ) Alkhazov+ .0, NP/A, 712, 269, 2002)         Datai of clauber calculation       Section         REP-RDE       1 3         REMOMIN       1 3         REMOMIN       1 3         REMOMIN       3         Atta       6         Data       161.3         198.9       MB         MB MB       MB         MB MENT       3         MBMENTET       3         MBMENT       3		#(2-HE-6(P,TOT),,S	IG,,MSC) Quar	ntity: [CS] Cr	oss section		# /2 UE	(PTOCESS: [IUI	J IOCAL MCC) Output	itui lool on		
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<pre>#(1++1(2+HE-6,E)1++1,SIG,MSC) Quantity:[CS] Cross section # Process: [Lt[Edits cattering #(2+HE-6(PEL)2+HE-6,SIG,MSC) Quantity:[CS] Cross section # Modifier: [MSC] Approximate definition only, see text General purpose modifier for ANALYSIS # Iffective nucleon-nucleon parameters was used in Glauber calculation. See REI-REF. IDerived from extrapolated 0 deg angular differential cross section with the optical theorem Clotal cross section inus elastic cross section 3# xtrapolation of angular differential cross section 3# xtrapolation of angular differential cross section 3# xtrapolation of angular differential cross section (A0493.006) to 0 deg by the Glauber model and integration. # U, C.D. Althacovt, J, NP/A, 712, 269, 2002) Detail of Glauber calculation BRE-NNLYS (IABLE).Table 2 (Office) (IABLE).Table 2 (Office) 1 3 EN NDATA 6 1 DATA 1 EP-T DATA 2EDP-T 2DATA SERP-T 3 NB N</pre>		#(2-HE-6(P,NON),,	SIG) Quantity:	[CS] Cross se	ection		*(T-U-T	(Z-HE-6,NON),;	(I Manalactia /	ty: [CS] Cro	iss section	
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Fig. 1. Calculated  $p^{6}$ He elastic-scattering cross sections at  $E_{p} = 721$  MeV versus the four-momentum transfer squared, taking into account either the single-scattering term (curve 1), or multiple-scattering terms (curve 2), or all scattering terms (curve 3). The experimental data [1,2] (dots) are also displayed.



#### Applications to other hadronic probes

### $\sigma_{pp} vs. \sigma_{pbarp}$



• pbar + p

12 40. Plots of cross sections and related quantities



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Add	ar le co ch	e field				
4	AP,EL	AP, NON	<u>AP,X</u>			
2	KN, A	DIN THE	DIM NON	DIM DIM N	DIN TOT	
3	PIN, EL PIN Y	PIN, INL	PIN, NON	PIN, PIN+N	PIN, 101	
4	PIP.EL	PIP.INL	PIP.PIN	PIP.PIP	PIP.X	
5	G,2A	G,2P	G, ABS	G, D	G, EL	
	G, INL	G,N	G,N+A	G,N+P	G,N+P+A	
	G,N+X	G,P	G,P+A	G,P+N	G, PAI	
	<u>G, PIO</u>	<u>G, TOT</u>	<u>G,X</u>			
6	<u>N,0</u>	N, 2A	<u>N,2N</u>	N,2N+A	<u>N,2N+D</u>	
	N, 2N+P	<u>N, 3N</u>	N,A	N, A+ZN	N, A+D	
	N, A+N	N, A+N+P N, D +N	N, A+N+P+T	N, ABS	N, D	
	$\frac{N, D+X}{N + 2}$	$\frac{N}{N+N}$	N N+ 0+N	N N+0+P	N N+0+P+T	
	N,N+D	N,N+P	N, N+P+A	N, N+P+A+T	N,N+P+N	
	N, N+P+N+A	N,N+P+T	N,N+T	N.NON	N, P	
	N, P+2N	N, P+A	N, P+D	N, P+N	N, P+N+A	
	N, P+N+A+T	N, P+N+T	N,P+T	N,SCT	N, T	
	N, T+P	N, T+P+N	N, THS	N, TOT	N,X	
7	D,2-HE-2	D,2N+P	D,3-LI-6	D,3-LI-7	D, A	
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	P,PIP+N+X	P,PIP+X	P,T	P, TOT	P,X	
	P,X+2P	P,X+3P	P,X+P	P,X+PI	P,XN+4P	<b>_</b>
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• These options have never been appeared before!

#### pbar + A elastic scattering



### $\sigma_{\rm R}$ of antiproton + A



V. Ashford et al., Phys. Rev. C 30, 1080 (1984).

# Do we know $\sigma_{NN}^{total}$ precisely?

- One may say "Yes!", but ...
- $\sigma_{NN}^{total}$  is important, because it is a measure for the strength of the NN interaction.
- Practically, we need  $\sigma_{NN}^{total}$  for

$$f(0) = \frac{i + c_0}{4\pi} \sigma_{\rm NN}^{\rm total} |\boldsymbol{p}|.$$

- NN scattering amplitude
   4<sup>*π*</sup>
   in the conventional multiple scattering theories,
   eg., KMT, Glauber.
- The contemporary black-sphere model needs  $\sigma_{NN}^{\ \ total}$  .
  - the formula is now being implemented to PHITS.

# The SAID (SP07)

- The on-line Scattering Analysis Interactive Dial-in (SAID) facility.
- The SAID program gives several estimations of observables based on the partial-wave analyses of the latest compilation of nucleon-nucleon scattering data.

PHYSICAL REVIEW C 76, 025209 (2007)

#### Updated analysis of NN elastic scattering to 3 GeV

R. A. Arndt, W. J. Briscoe, I. I. Strakovsky, and R. L. Workman

Center for Nuclear Studies, Department of Physics, The George Washington University, Washington, D.C. 20052, USA (Received 18 June 2007; published 16 August 2007)

A partial-wave analysis of *NN* elastic scattering data has been updated to include a number of recent measurements. Experiments carried out at the Cooler Synchrotron (COSY) by the EDDA Collaboration have had a significant impact above 1 GeV. Results are discussed in terms of the partial-wave and direct-reconstruction amplitudes.

### SAID (SP07)

#### ARNDT, BRISCOE, STRAKOVSKY, AND WORKMAN

PHYSICAL REVIEW C 76, 025209 (2007)



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[See Instructions] Pion-Nucleon Pion-Pion-Nucleon Kaon-Nucleon Nucleon-Nucleon	Instructions for Using the Partial-Wave Analy	/ses			
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Analyses From Other Sites Mainz (MAID – Analyses) Nijmegen (Nucleon-Nucleon OnLine) Bonn-Gatchina (Partial-Wave Analysis)	<b>Note</b> : These programs use HTML forms to run the SAID code. If unfamiliar with the options, run the default setup first. The output is an (edited) echo of an interactive session which would have resulted had you used the SSH version. If the default example fails to clarify the specific task you have in mind, we can help (just send an e-mail message).				
P.W.A	All programs expect energies in <b>MeV</b> units. All of the validity. Some are unstable beyond their upper energies. Increments: The programs will not allow an arbitration of the programs will not allow and programs wi	he solutions and potentials have limited ranges of ergy limits. Extrapolated results may not make much ary number of points to be generated. As a rule, stay			
πN PWA Workshop May 24-27, 2011	below 100. ACKNOWLEDGMENTS				
Washington, D.C.	The <b>CNS Data Analysis Center</b> is partially funded Jefferson Lab, with strong support from the GW No	l by the U.S. Department of Energy and the Thomas rthern Virginia Campus.			
William J. Briscoe Ron L. Workman	Washington University	http://gwdac.phys.gwu			

•

## Which curve is more appropriate? Fitting vs. SAID

About 10 % deviation between the two!



Fitting: C. A. Bertulani and C. De Conti, Phys. Rev. C 81, 064603 (2010).

PHYSICAL REVIEW C 81, 064603 (2010)

#### Pauli blocking and medium effects in nucleon knockout reactions

C. A. Bertulani<sup>1,\*</sup> and C. De Conti<sup>2,†</sup>

<sup>1</sup>Physics Department, Texas A&M University-Commerce, Commerce, Texas 75428-3011, USA <sup>2</sup>Campus Experimental de Itapeva, Universidade Estadual Paulista, 18409-010 Itapeva, SP, Brazi (Received 12 April 2010; published 3 June 2010)

• "We study medium modifications of the nucleonnucleon (*NN*) cross sections and their influence on the nucleon knockout reactions. ..."

$$\sigma_{pp} = \begin{cases} 19.6 + 4253/E - 375/\sqrt{E} + 3.86 \times 10^{-2}E \\ \text{(for } E < 280 \text{ MeV}), \end{cases}$$

$$32.7 - 5.52 \times 10^{-2}E + 3.53 \times 10^{-7}E^3 \\ -2.97 \times 10^{-10}E^4 \\ \text{(for } 280 \text{ MeV} \leqslant E < 840 \text{ MeV}), \end{cases}$$

$$50.9 - 3.8 \times 10^{-3}E + 2.78 \times 10^{-7}E^2 \\ + 1.92 \times 10^{-15}E^4 \qquad \sigma_{np} \end{cases}$$
(for 840 MeV \leq E \leq 5 GeV)

#### Least-squares fit to the data



# It is hard to distinguish...: p+C

- Two curves
- We use
  - the same  $a_0$
  - Two parameterizations
    - SAID (SP07)
    - Fitting by Bertulani

![](_page_48_Figure_7.jpeg)

Data:

R. F. Carlson, At. Data Nucl. Data Tables, 63, 93 (1996).

A. Auce et al., Phys. Rev. C 71, 064606 (2005).

E > 100 MeV/nucl. Coulomb int. can be neglected.

![](_page_49_Figure_0.jpeg)

#### Application to A+A reactions works

![](_page_50_Figure_1.jpeg)

### Water diffraction

![](_page_51_Picture_1.jpeg)

出典:フリー百科事典『ウィキペディア(Wikipedia)』

http://ja.wikipedia.org/wiki/%E6%B0%B4%E9%9D%A2%E6%B3%A2