Absolute Total np and pp Cross Section Determinations

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- GW SAID NN analyses
- Minimization and Normalization
- SES and LE08
- Amplitudes
- Total Xsections
- Differential Xsections
- Outlook

CSEWG Meeting, BNL, November 2008

What we Look for…

np total Xsections are important in many applications
[Its Xsections are used in determining the flux of incoming neutrons of different neutron induced reactions]

- Astrophysics [(n, γ), (n, α) and others]
- Transmutation of nuclear waste [(n, f), (n, γ) and others] energy generation
- Conceptual design of an innovative nuclear reactor being carried out in the course of the Generation IV initiative [(n, f), and neutron-actinoid elastic and inelastic scattering and others]

- Increasing quality of neutron-induced nuclear reaction measurements requires a high quality *standard* for np Xsections, reproducing total np Xsections with an accuracy of 1 % or better ($E < 20$ MeV)

- The need for neutron data $E > 20$ MeV (up to hundreds of MeV) with accuracy better than 10 % leads to the requirement of Xsection data for the np *reference* reaction with uncertainties at the few percent level

GW SAID (Scattering Analysis Interactive Dial-in) Facility

[http://gwdac.phys.gwu.edu/]

[ssh -C -X said@gwdac.phys.gwu.edu [no passwd]

Center for Nuclear Studies
Data Analysis Center

- CNS DAC Home
- CNS DAC [SAID]
- CNS Home

Partial-Wave Analyses at GW

[See Instructions]

- Pion-Nucleon
- Kaon-Nucleon
- Nucleon-Nucleon
- Pion Photoproduction
- Pion Electroproduction
- Kaon Photoproduction
- Eta Photoproduction
- Pion-Deuteron (elastic)
- Pion-Deuteron to Proton+Proton

Analyses From Other Sites

- Mainz (MAID – Analyses)
- Nijmegen (Nucleon-Nucleon OnLine)
- Hamburg (Inversion OnLine)

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CNS DAC Services [SAID Program]

- The Virginia Tech Partial-Wave Analysis Facility (SAID) has moved to GW!
- New features are being added and will first appear at this site. Suggestions for improvements are always welcomed.
- Once fully operational, this web page will become the main entry for the full range of services presently available through SAID.

Instructions for Using the Partial-Wave Analyses

The programs accessible with the left-hand side navigation bar allow the user to access a number of features available through the SAID program. Contact a member of our group if you are unfamiliar with the SSH version. If you enter choices which are unphysical, you may still get an answer (accordance with the `garbage in, garbage out' rule). Please report unexpected garbage-out to the management.

Note: 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).

All programs expect energies in **MeV** units. All of the solutions and potentials have limited ranges of validity. Some are unstable beyond their uppe energy limits. Extrapolated results may not make much sense.
Increments: The programs will not allow an arbitrary number of points to be generated. As a rule, stay below **100**.

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The George Washington University
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SAID NN History (GW, VPI, LLNL)

R.A. Arndt, W.J. Briscoe, I.I. Strakovsky, and R.L. Workman, *Updated analysis of NN elastic scattering to 3 GeV*, Phys. Rev. C **76**, 025209 (2007).

R.A. Arndt, I.I. Strakovsky, and R.L. Workman, *Nucleon-nucleon elastic scattering to 3 GeV*, Phys. Rev. C **62**, 034005 (2000).

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R.A. Arndt, I.I. Strakovsky, and R.L. Workman, *Updated analysis of NN elastic scattering data to 1.6 GeV*, Phys. Rev. C **50**, 2731 (1994).

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R.A. Arndt, R.H. Hackman, and L.D. Roper, *Nucleon-Nucleon Scattering Analyses. 3. np Phase Shift Analyses, Complex Structure and Multiple Solutions at 50-MeV and 325-MeV*, Phys. Rev. C **15**, 1021 (1977).

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M.H. Mac Gregor, R.A. Arndt, and R.M. Wright, *Determination of the nucleon-nucleon scattering matrix. IX. (n,p) analysis from 7 to 750 MeV*.Phys. Rev. **173**, 1272 (1968).

M.H. MacGregor, R.A. Arndt, and R.M. Wright, *Determination of the Nucleon-Nucleon Scattering Matrix. VII. (p, p) Analysis from 0 to 400 MeV,* Phys. Rev. **169**, 1128 (1968).

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GW SAID Fit of NN data

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **76**, 025209 (2007)]

- Energy dependent SP07 and associated Single-Energy Solutions (SES)
- T_p = 0.3 – 3000 MeV T_n = 0.5 – 1300 MeV
- PWs = 17 [Isovector] + 19 [Isoscalar] [J < 8]
- Prms = 147 [I=0,1]
- 2-channel Chew-Mandelstam K-matrix parameterization [included NΔ channel]
- GW PWA have attempted to remain as *model-independent* as possible [no theoretical input]

Reaction	Data	χ^2
pp→pp	12,693	21,496
np→np	24,916	44,463
Total	37,609	65,559

- Low-energy boundaries (beyond database issue)
  - for pp, there is the Coulomb
  - for np, there is the Schwinger (specifically for forward and pol measurements)

Minimization and Normalization Factor [χ^2/Data]

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **76**, 025209 (2007)]

- Modified χ^2 function, to be minimized [systematics plays important role]

$$\chi^2 = \sum_i [\underbrace{(X\theta_i - \theta_i^{exp}) /}\varepsilon_i]^2 + [(X - 1) / \varepsilon_X]^2$$

Modified χ^2 [Norm]

Standard χ^2 [UnNorm]

θ_i^{exp} measured, ε_i stat error, θ_i calculated, X norm const, ε_X its error

Renormalization freedom provides a significant improvement for our best fit results

χ^2/Data	SP07	SP00	SM97	Nijm93	Data	Data
Range (MeV)	Norm/ UnNorm	Norm/ UnNorm	Norm/ UnNorm	Norm/ UnNorm	np	pp
0- 4	2.5/28	2.5/28	2.5/28	3.3/27	63	193
0- 20	1.8/13	1.9/13	2.3/14	2.9/10	468	389
0-200	1.5/ 7	1.5/ 7	1.7/ 7	1.7/ 6	2381	1491
200-400	1.3/ 3	1.3/ 3	1.4/ 3	1.3/ 3	2208	2172
400-600	1.5/ 9	1.4/ 8	1.5/11		2779	3635
600-800	1.5/ 8	1.5/ 8	1.4/11		2529	3974
800-999	1.4/ 3	1.4/ 3	1.4/ 3		2112	3274

- If the systematic uncertainty varies with angle, this procedure may be considered a first approximation

- **SP00** [R. Arndt, IS, and R. Workman, Phys Rev C **62**, 034005 (2000)]
- **SM97** [R. Arndt, C.H. Oh, IS, and R. Workman, Phys Rev C **56**, 3005 (1997)]
- Nijm93 [V.G.J. Stoks *et al*, Phys Rev C **48**, 792 (1993)] [below 350 MeV]

- GW solutions look very stable

Single-Energy Solutions (SES) and LE08

[R. Arndt, W. Briscoe, A. Laptev, IS, R. Workman, arXiv:0806.1198 [nucl-ex]]

We have employed both single-energy (SES) and energy-dependent (Global) solutions over a variety of energy ranges in order to estimate uncertainties

- SES: based on a bin of data spanning a narrow E range [2 – 75 MeV]
  searches 6 to 47 prms
  43 SES have been generated with central E = 5 to 2830 MeV
  # of data in the bin varies from 100 to 2000
  a linearized E dependence is taken, it reducing # of searched prms

- LE08: low-energy fit to 25 MeV
  searches 19 prms, scattering length a, effective range r
  for 3 S-waves & 13 leading prms for S, P, & D waves

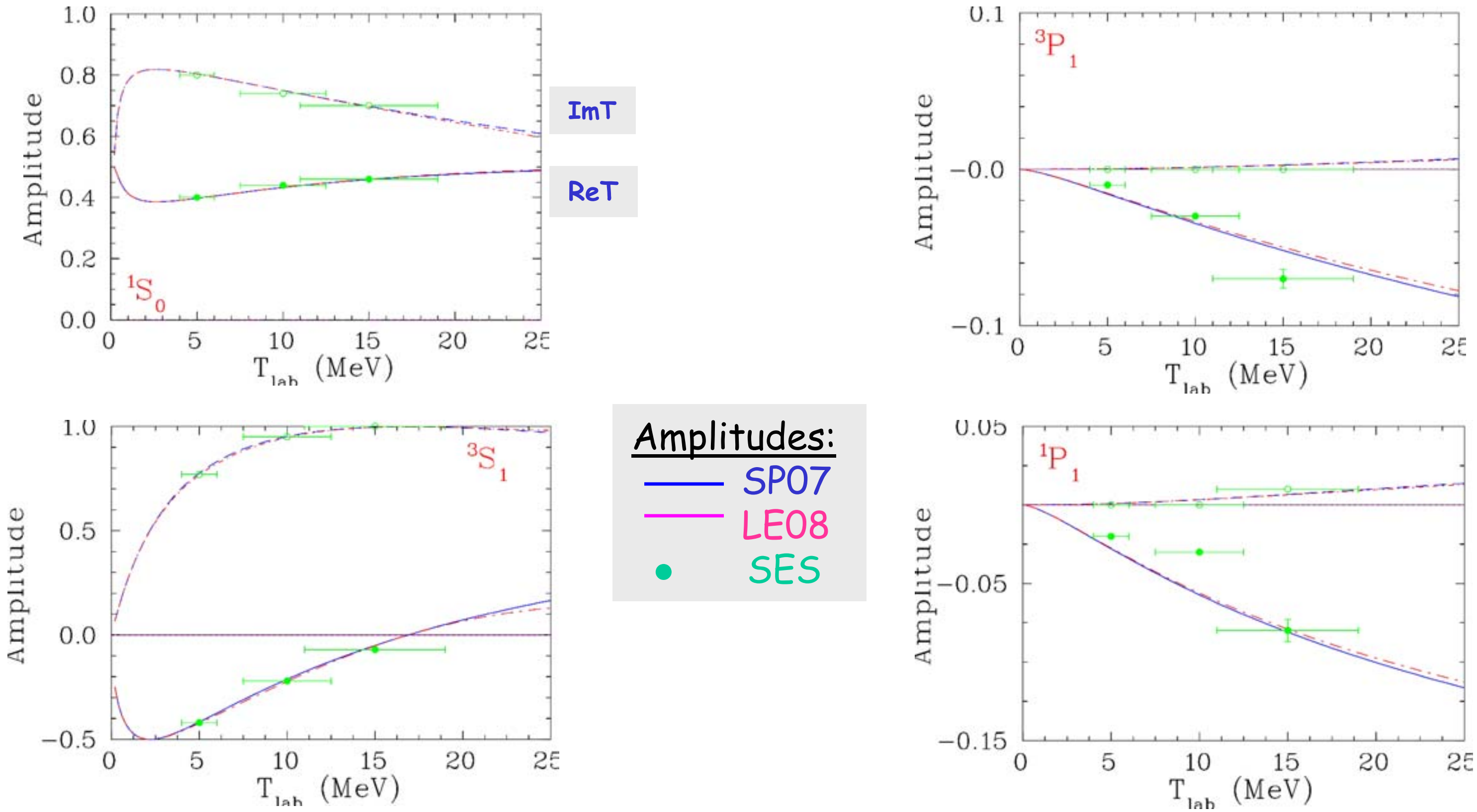
  It results: χ^2/pp = 722/391 & χ^2/np = 634/631

- Systematic deviation between SES and global fits is an indication of
  - missing structure in the global fit
  - possible problems with a particular dataset

- An Diagonal Error Matrix generated in the SES [and LE08] fits
  It can be used to estimate the overall uncertainties for global fit

Partial Waves [$^{2I+1}L_J$] for SP07

- **Overall**: the amplitudes found in GW fits to 1000 MeV have remained stable against the addition of new measurements for many years

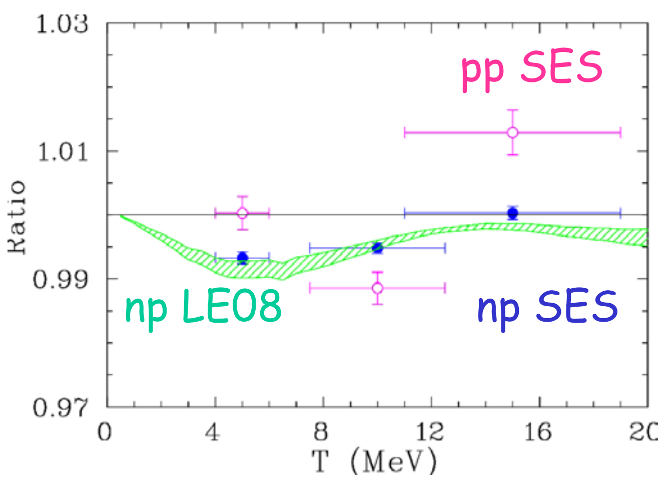


- $ImT - T^*T < ImT$ [unitarity limit], which not a problem – we are below pion threshold

Low-Energy np and pp Total Xsection Ratio

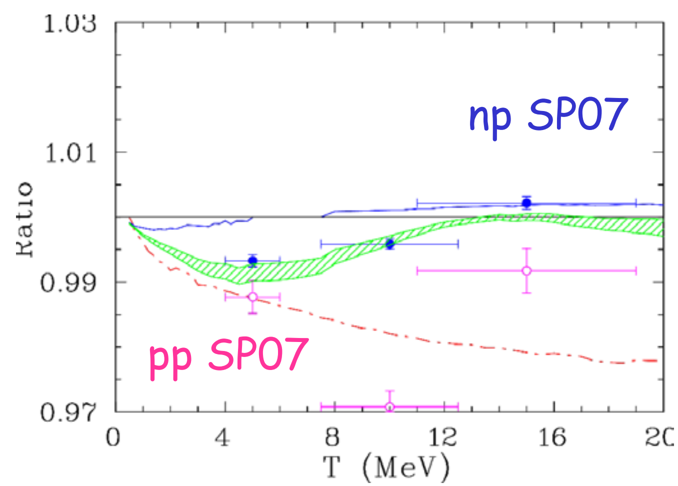
As cross sections change rapidly near threshold, we have chosen to display the agreement between various fits in terms of ratios

- SES & LE08 to SP07



- Deviations are
  - within 1 % for np
  - within 2 % for pp

- SES & LE08 & SP07 to Nijm93

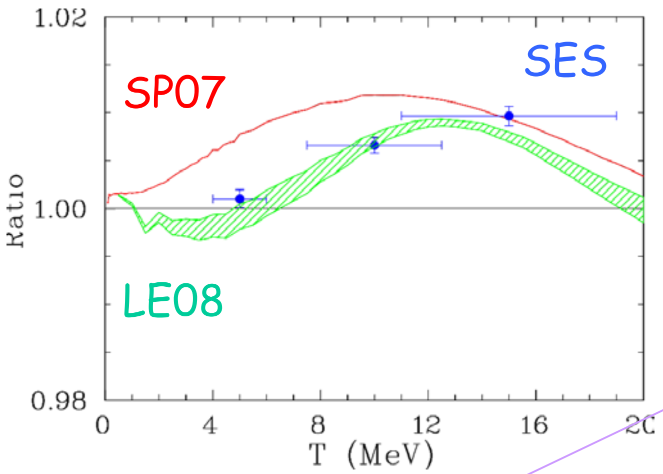


- Low-Energy Nijm93 is
  - agreed within 0.3 % for np
  - up to ~2 % above for pp

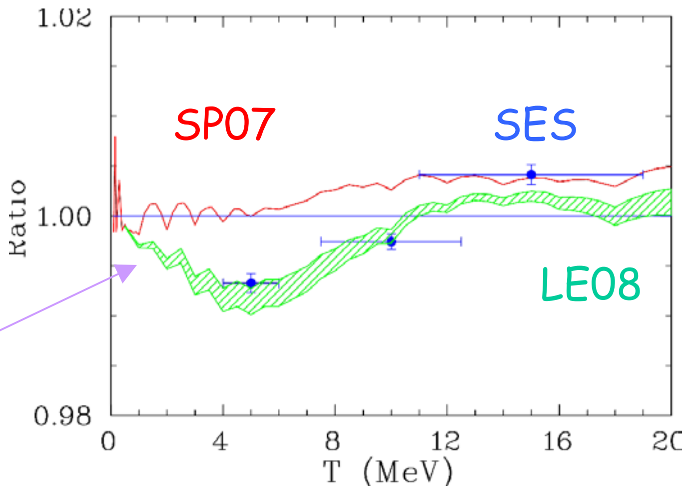
Nijm93 [V.G.J. Stoks *et al*, Phys Rev C **48**, 792 (1993)]

Low-Energy np Total Xsection Ratio

• SP07, SES & LE08 to ENDF/B



• SP07, SES & LE08 to JENDL



- Slightly better agreement is found with JENDL than with ENDF/B
- Wiggles reflect a lack of smoothness in JENDL

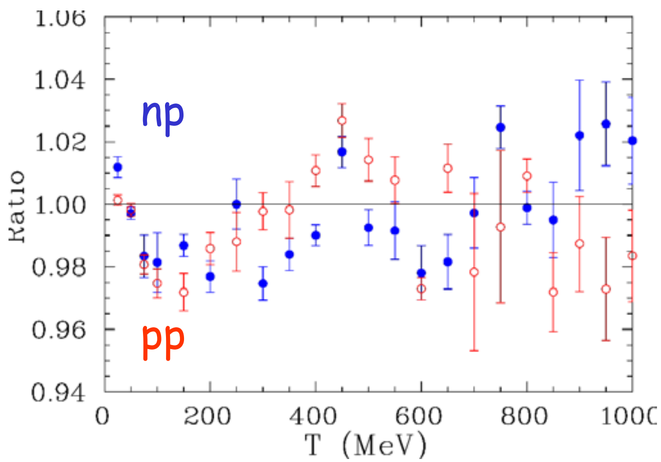
[SP07 and LE08 are smooth functions of Energy]

- ENDF/B is systematically below SP07, LE08, and Nijm93 (< 1 %)
- JENDL and SP07 & LE08 agreed at the level of 0.5 %

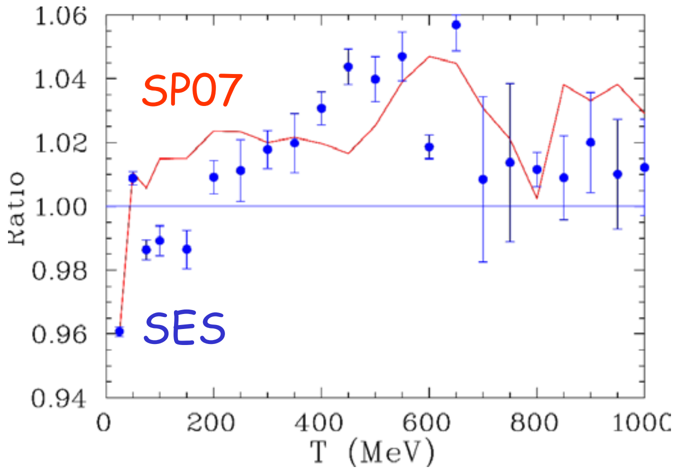
ENDF/B-VII.0: www.nndc.bnl.gov/endf
JENDL-3.3: wwwndc.jaea.go.jp/jendl/j33/j33.html

High-Energy np and pp Total Xsection Ratio

• SES to SP07



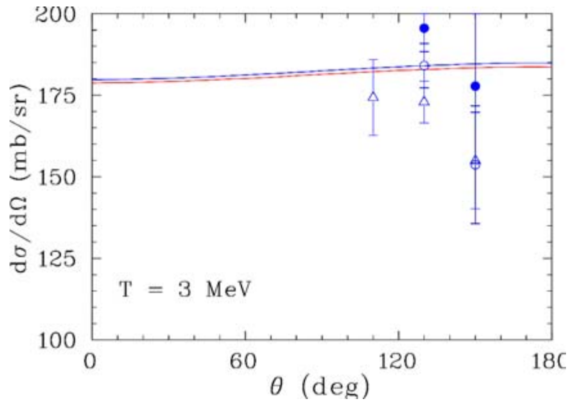
• SP07 & SES to JENDL



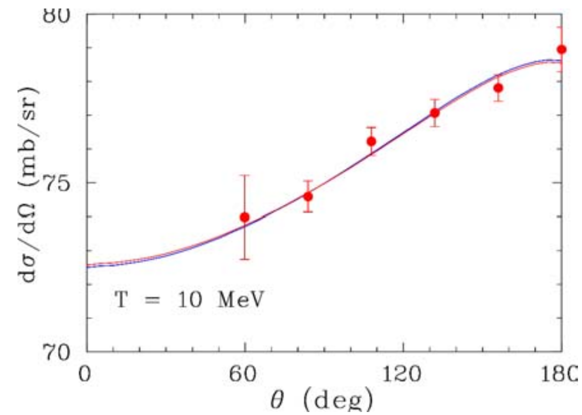
• At energies up to 1000 MeV, ratios of the grid of SES to SP07 differ from unity by less than 3 %

• Above 180 MeV, SAID np Xsections are larger than JENDL by up to 5 %

Low-Energy np Diff Xsections

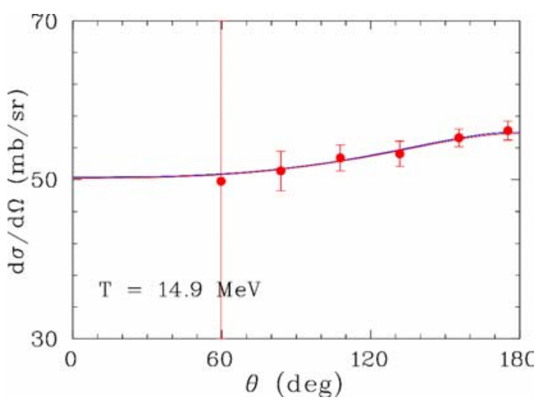


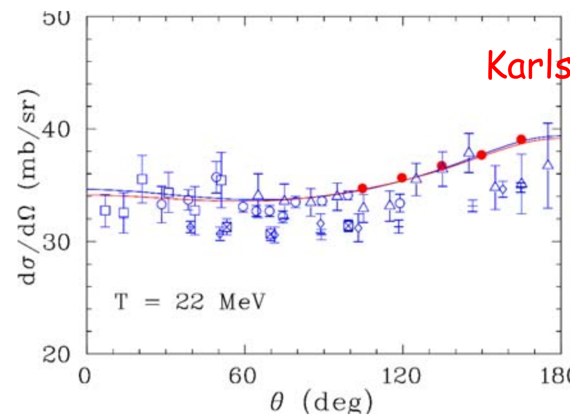
SP07
LE08



Ohio02

Prlm
Ohio08



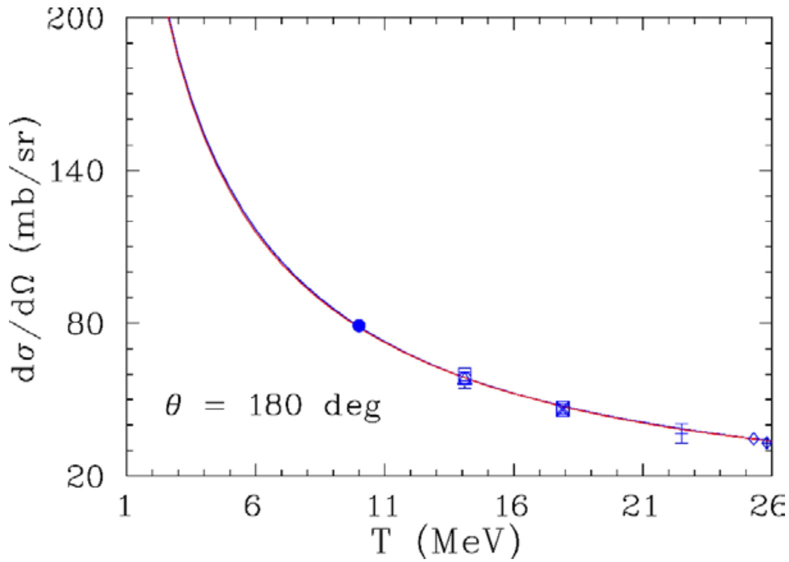


Karlsruhe90

- Angular distributions are more favorable for PWA

np Low-Energy Backward Scattering

- Looks attractive from the experimental point of view



SP07
LE08

- No Schwinger
- Less Systematics

Outlook

- We have generated fits to describe the total np and pp Xsections below 1000 MeV
- The fits have been both energy dependent (SP07, LE08) and SES

- The uncertainties associated with our total np Xsections below 20 MeV are clearly less than 1 %
- The agreement between SP07, JENDL, and the Nijmegen analysis, suggests an uncertainty of 0.5 % or less for the np case

- For the pp Xsections, uncertainties are larger; systematic disagreements are evident in comparison with the Nijmegen PWA
- At very low energies, the main problem stems from lack of relevant pp data
- At low energies, the various determinations also agree at the few-percent level

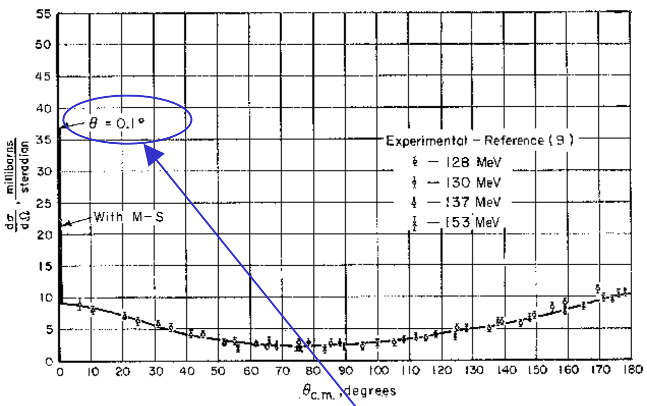
- The advantage of the GW parameterization is
  - its smooth energy dependence and
  - coverage from threshold up to high energies
- We also have capability to modify the GW fits
  - to either generate SES centered on a particular energy or
  - produce lower-energy fits when a specific energy region is of interest

- We will continue to update both GW energy-dependent and SES if the new measurements become available

Schwinger [Magnetic Moment interaction in NN]

[J. Schwinger, Phys Rev **55**, 235 (1939)]

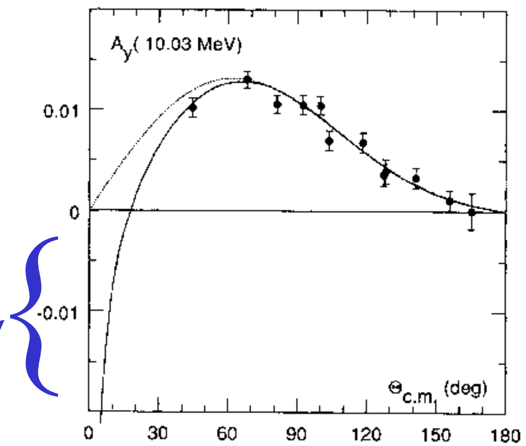
- NP Dif Xsection



- Large sensitivity:
  - very small angles
  - Pol measurements

[Hogan & Seyler, Phys Rev C **1**, 17 (1970)]

- NP Pol Measurements



We finally mention that for the *np* analysis we can also make the approximation as used by Arndt *et al.*[11,12] for including the MM interaction. In that case, the MM scattering amplitude is included in all partial waves, but the partial-wave nuclear amplitudes are not adjusted for this. We then find $\chi^2_{min}=433.4$, which is almost as good as the more complete treatment discussed in this paper.

[Stoks & de Swart, Phys Rev C **42**, 1235 (1990)]

- There are no such forward measurements, we are safe

NN Database below 25 MeV

- PP = 391 Unpol = 339 Pol = 52

$d\sigma/d\Omega$	[339]:	0.3 - 20 MeV,	10 - 110 deg
P	[44]:	5 - 18 MeV,	15 - 90 deg
A_{yy}	[5]:	10 - 23 MeV,	75 - 90 deg
A_{xx}	[3]:	11 - 23 MeV,	90 - 90 deg

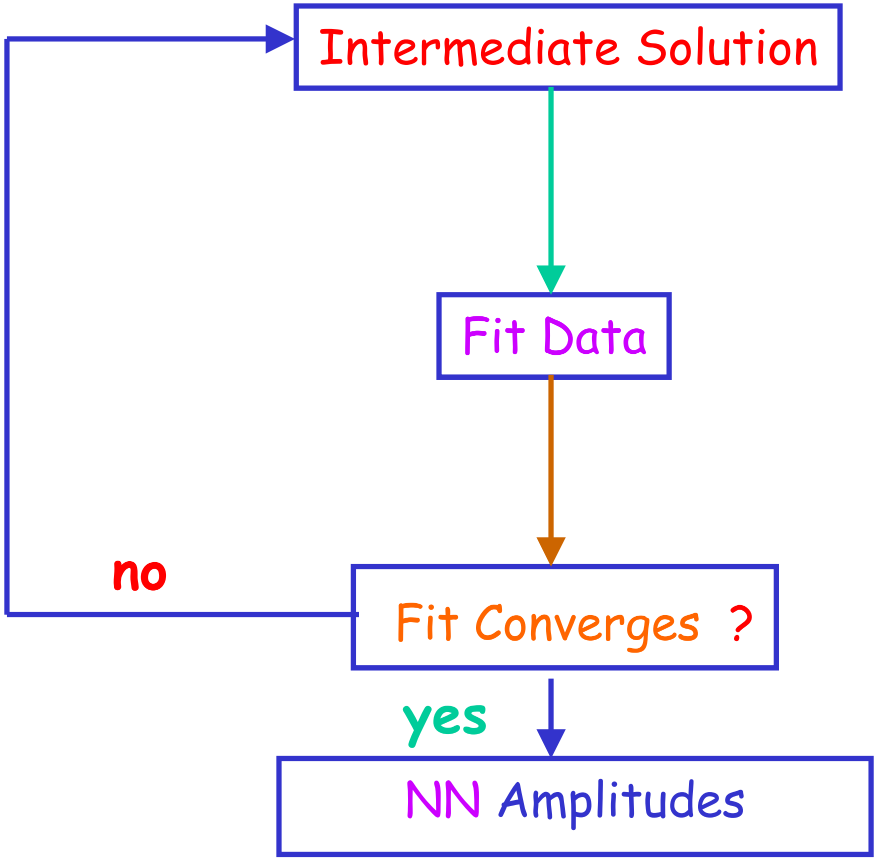
- There is NO σ^t at low-energies
- Full angular coverage is an issue

- NP = 630 Unpol = 397 Pol = 233

σ^t	[221]:	0.5 – 25 MeV	
$\Delta\sigma_T$	[13]:	4 - 17 MeV	
$\Delta\sigma_L$	[7]:	5 - 20 MeV	
$d\sigma/d\Omega$	[176]:	3 - 25 MeV,	12 - 180 deg
P	[190]:	8 - 25 MeV,	21 - 170 deg
A_{yy}	[21]:	14 - 25 MeV,	60 – 174 deg
D_T	[2]:	16 - 17 MeV,	132 – 133 deg

- Pol measurements is important part of constraint
- It allows to determine small multipoles

NN Analysis Flow Chart



Cook until DONE !