Nucleon-Nucleon Interactions from the Quark Model

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Talk Outline

- Review NN Models and the Force
- The 3P0 Model of NNm Coupling Constants and Form Factors
- One Gluon Exchange
- Oxford Model of NN Force (Initial Results)
  - Phase Shifts
  - Deuteron
  - Nuclear Matter
  - Looking at the Potential
- Conclusions, Thoughts, etc.

What is the NN Force

- Nucleons are made of Quarks
- Quarks interact via Quantum Chromodynamics (QCD)
- QCD is confining
  - Nucleons are color singlets
  - QCD is non-perturbative
- NN (hadron-hadron) force is an artifact of QCD interactions between the quarks of the nucleons.
  - Colored van der Waals(?)

Understanding the NN Force, My Questions

1) What are the low-energy degrees of freedom of QCD between the nucleons?

2) Why are those d.o.f. *the* d.o.f. for QCD?

3) How are those d.o.f. driven by the microscopic quark/gluon dynamics?

4) Why is QCD expressed by those drivers?

Understanding the NN Force, My Questions

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4) Why is QCD expressed by those drivers?

χEFT is an answer to 1) and 2) (sort of)

CD-Bonn, Av18, Nijm-I don't attempt to answer these questions. They are (very good) quantitative parameterizations of the NN Force.

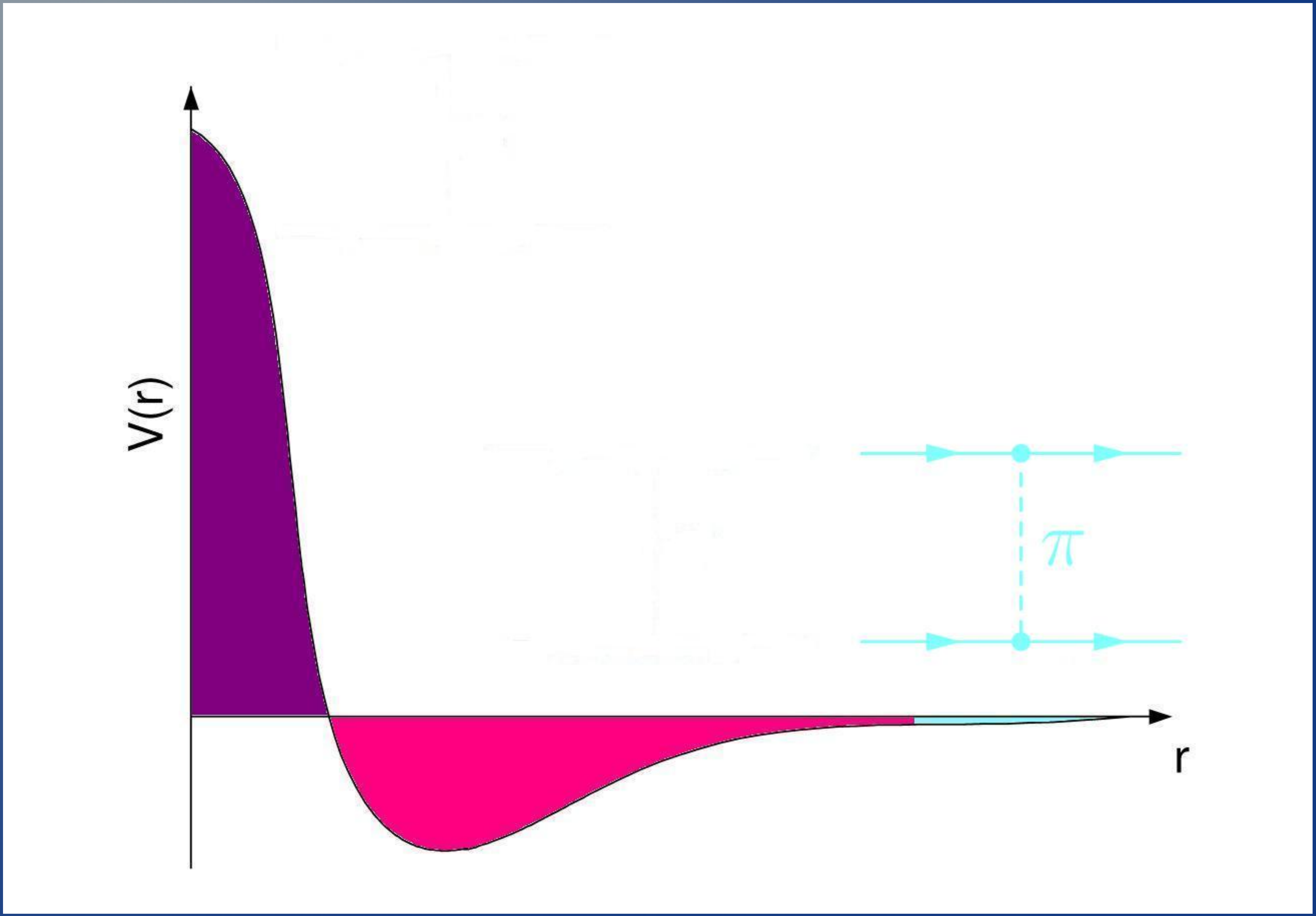
Understanding the NN Force, My Questions

1) What are the low-energy degrees of freedom of QCD between the nucleons?
2) Why are those d.o.f. *the* d.o.f. for QCD?
3) **How are those d.o.f. driven by the microscopic quark/gluon dynamics?**
4) Why is QCD expressed by those drivers?

NN Models and Quarks/Gluons

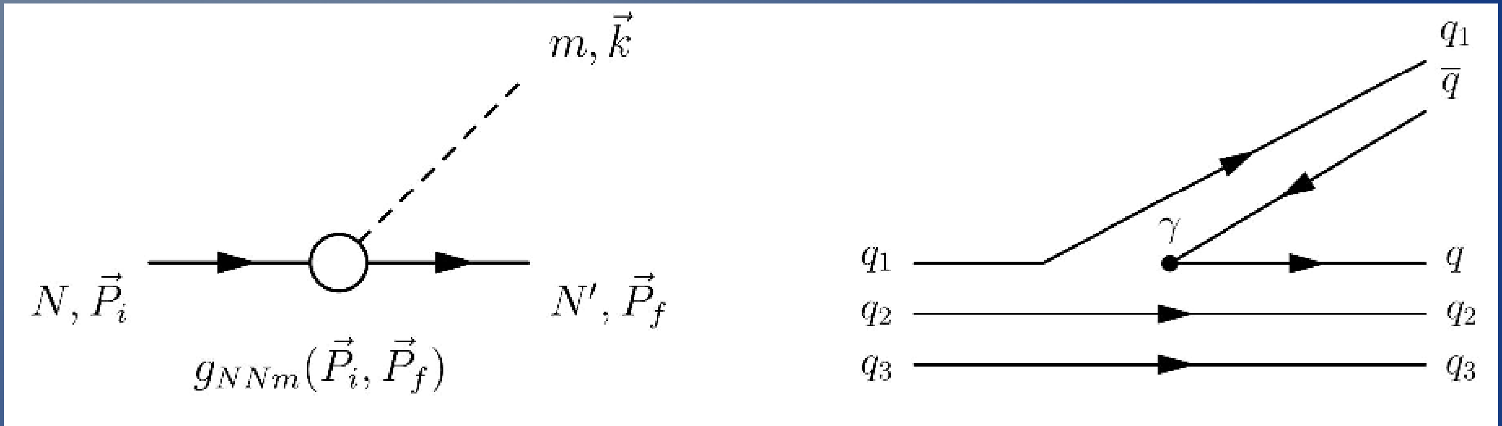
- NN Models take little guidance from quark/gluon substructure of nucleons.
- These models work!
- QCD is non-perturbative $\Rightarrow$ a proper derivation of NN forces is impossible.
- Constituent Quark Model often estimates strong physics
  - 3P0 Decay Model
  - Quark Cluster Model studies of One Gluon Exchange
- Can the Quark Model help us understand NN Dynamics?

Schematic Picture of NN Forces



3P0 Model and Effective Strong 3-Point Vertices

$$H_{^3\mathrm{P}_0} = \gamma \sigma . \vec{p} \, |q\bar{q}\rangle \langle 0|$$



$$\text{Equating the Two} \Longrightarrow g_{NNm}\left(q^2\right) = \cdots$$

3P0 NNm Coupling Constants

$$g_{\mathrm{NN}\pi} = \gamma 40\sqrt{3}\pi^{3/4} m_N \sqrt{m_\pi} \frac{\beta^{3/2}(4\beta^2+\alpha^2)}{(3\beta^2+\alpha^2)^{5/2}}$$

$$g_{\mathrm{NN}\sigma} = \gamma 108\sqrt{2}\pi^{3/4} \frac{\alpha^4\beta^{5/2}\sqrt{m_\sigma}}{(\alpha^2+3\beta^2)^{5/2}}$$

3P0 Coupling Constants and Form Factors

$$g_{NN\pi} = \gamma 40\sqrt{3}\pi^{3/4} m_N \sqrt{m_\pi} \frac{\beta^{3/2}(4\beta^2+\alpha^2)}{(3\beta^2+\alpha^2)^{5/2}}$$

$$\mathcal{F}_S = \exp\left\{ -\frac{(\vec{P}_i+\vec{P}_f)^2}{24(3\beta^2+\alpha^2)} - \frac{(\vec{P}_i-\vec{P}_f)^2}{6\alpha^2} \right\}$$

$$g_{NN\sigma} = \gamma 108\sqrt{2}\pi^{3/4} \frac{\alpha^4\beta^{5/2}\sqrt{m_\sigma}}{(\alpha^2+3\beta^2)^{5/2}}$$

$$\mathcal{F}_P = \left(1+\frac{4\beta^2+\alpha^2}{12\alpha^2(\alpha^2+3\beta^2)}(\vec{P}_f-\vec{P}_i)^2\right) \exp\left\{ -\frac{(\vec{P}_i+\vec{P}_f)^2}{24(3\beta^2+\alpha^2)} - \frac{(\vec{P}_i-\vec{P}_f)^2}{6\alpha^2} \right\}$$

Parameter Free Relations Among Coupling Constants

$$g_{NN\eta(')} = \frac{3}{10\sqrt{2}} \left(\frac{m_{\eta(')}}{m_\pi} \right)^{1/2} g_{NN\pi}$$

$$g_{NN\omega} = \frac{9}{10} \left(\frac{m_\omega}{m_\pi} \right)^{1/2} g_{NN\pi}$$

$$g_{NN\rho} = \frac{1}{6} \left(\frac{m_\rho}{m_\omega} \right)^{1/2} g_{NN\omega}$$

$$g_{NNa_0} = \frac{1}{3} \left(\frac{m_{a_0}}{m_\sigma} \right)^{1/2} g_{NN\sigma}$$

$$\kappa_\omega = -\frac{3}{2}$$

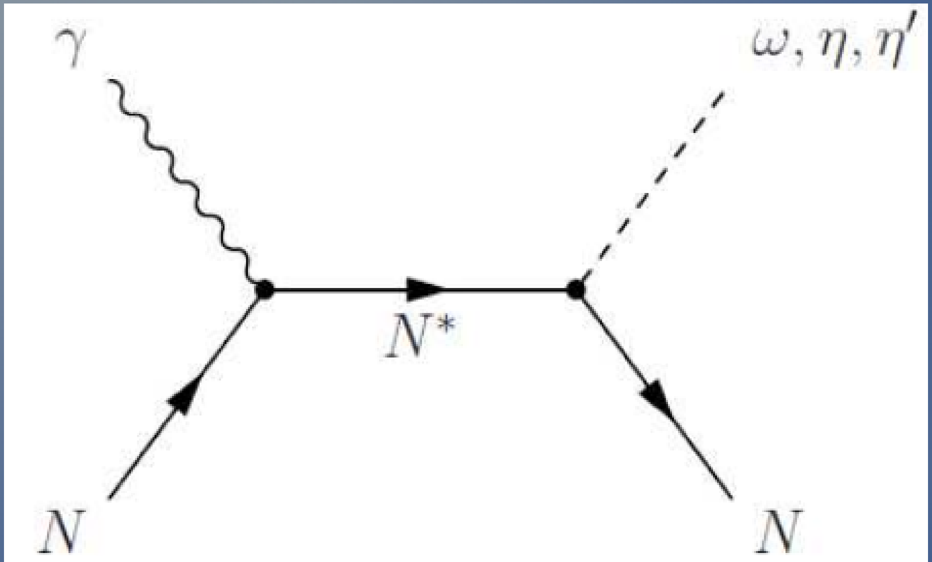
$$\kappa_\rho = +\frac{3}{2}$$

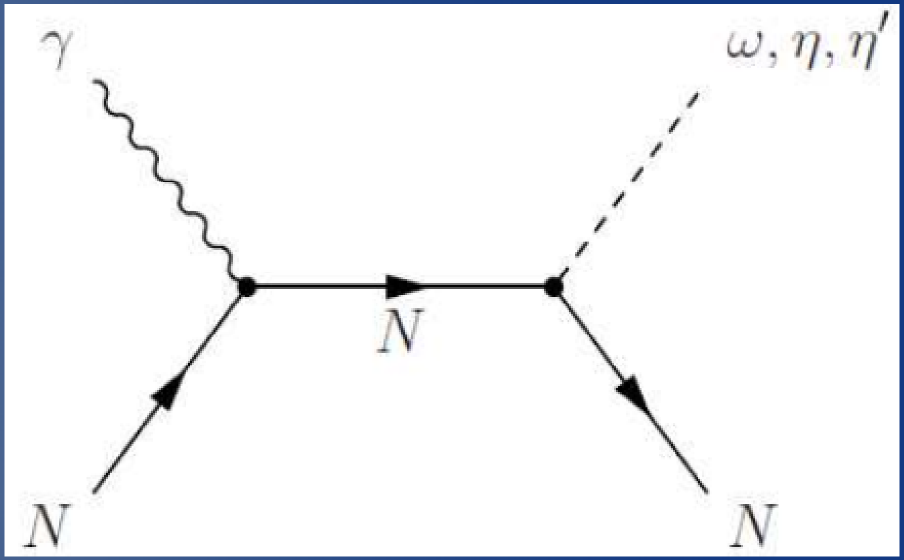
Numerical Values of Coupling Constants

Coupling	This Work	This Work	Paris	Nijmegen'93	CD-Bonn
$g_{NN\pi}$	14.2	[13.5]	[13.3]	13.3	[13.1]
$g_{NN\eta}$	6.0	5.7	–	9.8	–
$g_{NN\eta'}$	7.9	7.5	–	10.5	–
$g_{NN\sigma}$	5.0	N/A	–	17.9	(7.3; 14.9)
g_{NNa_0}	2.7	N/A	–	3.3	–
$g_{NN\omega}(\gamma_\mu)$	30.2	28.7	12.2	12.5	15.9
$g_{NN\rho}/g_{NN\omega}(\gamma_\mu)$	+.33	+.33	–	0.22	0.20
$\kappa_\omega(\sigma_{\mu\nu}/\gamma_\mu)$	–3/2	–3/2	–0.12	0.66	0
$\kappa_\rho(\sigma_{\mu\nu}/\gamma_\mu)$	+3/2	+3/2	–	6.6	6.1

Downum et al. Phys. Lett. B (638) 455-460 (2006). (With a π correction.)

CLAS Measurement!





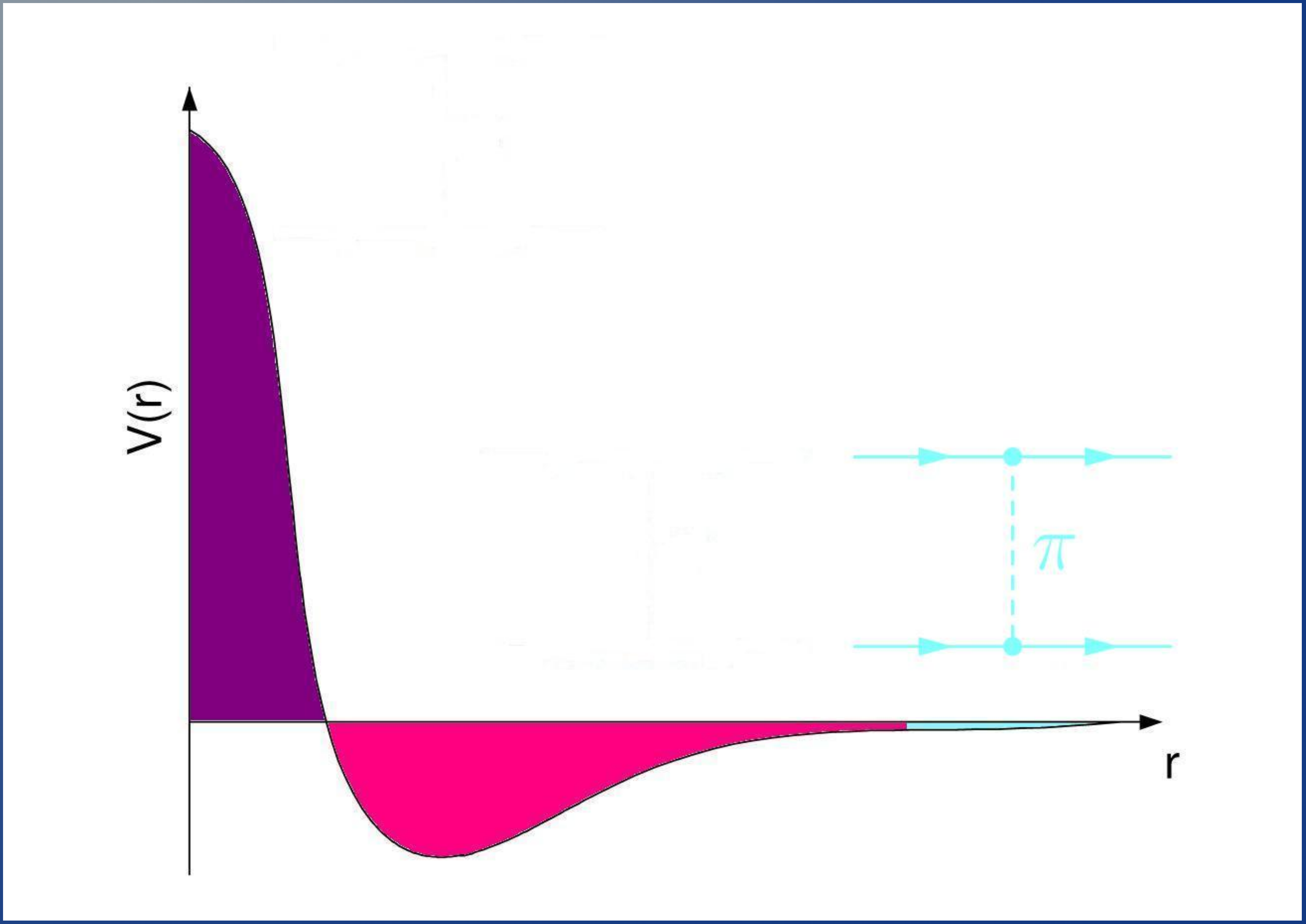
- Mike Williams reports (2007):

$$g_{\mathrm{NN}\omega} = 1.04$$

$$\kappa_\omega = -2.10$$

- Which is significantly different than our values for the coupling constant, but not the ratio.

Back to NN Force Schematic



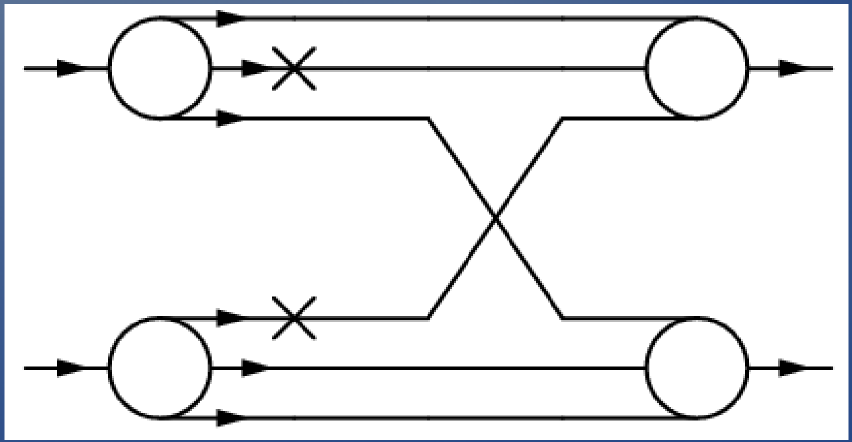
Quark Cluster Model Studies of One Gluon Exchange

- Date back to Liberman in 1977.
- Uses the Breit-Fermi Hamiltonian for perturbative QCD effects and a confining potential for non-perturbative QCD effects.
- Solve the Schrödinger Equation
- Extract a potential.
- They find: Tensor, Coulomb, Central and Spin-Orbit forces approximately cancel.
- Therefore, spin-spin contact interaction dominates.

Simple OGE Potential

Barnes et al. PRC 48 539(1993)

$$H_{\mathrm{OGE\ Hyp}} = \sum_{i<j;i,j=1}^{3} -\frac{8\pi\alpha_S}{3m_i m_j}\vec{s}_i.\vec{s}_j \sum_{a=1}^{8} \frac{\lambda_i^a}{2}\frac{\lambda_j^a}{2}$$



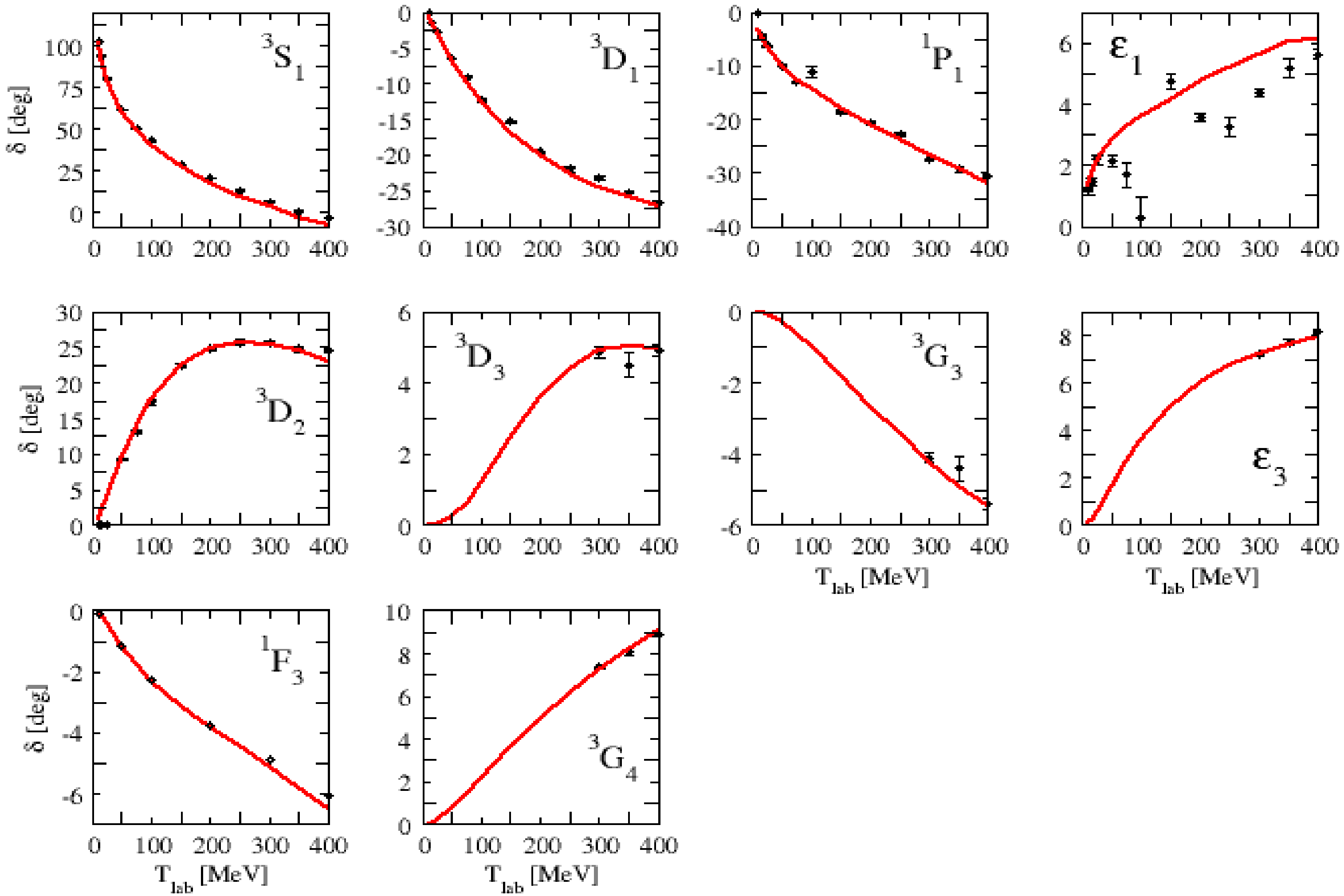
$$\mathcal{V}_{\mathrm{OGE+CI}} = \frac{\alpha_S m}{3m_q^2}\sum_{n=1}^{8}\omega_n\eta_n \exp\left\{-A_n {p_i}^2 - C_n {p_f}^2 + B_n \vec{p}_i.\vec{p}_f\right\}$$

Oxford Model

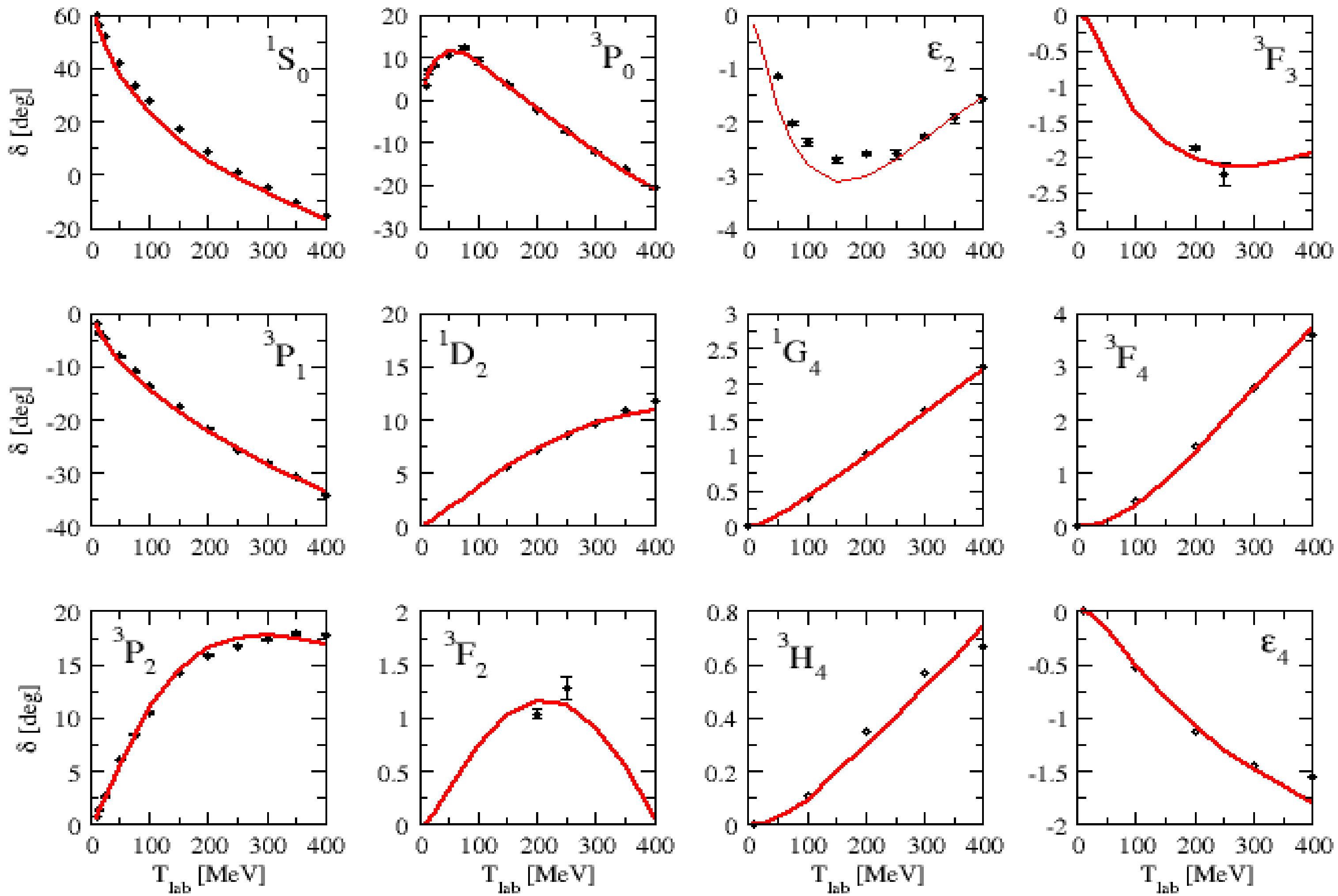
$$\mathcal{L}_{\mathrm{Oxf}} = -ig_{\mathrm{NN}\pi}\mathcal{F}_S\bar{\psi}\gamma_5\vec{\tau}\psi\cdot\vec{\pi} - ig_{\mathrm{NN}\sigma}\mathcal{F}_S\bar{\Psi}\Psi\sigma + i\mathcal{V}_{\mathrm{OGE+CI}}[\bar{\psi}\bar{\psi}\psi\psi].$$

- Wanted to try a simple model
- Introduced Charge Independence Breaking and Charge Symmetry Effects.
- χPT says interactions are NN contact and π exchange
  - OPE
  - OGE + CI for contact
  - OSE for 2π Attraction
- See if we could fit the data...
  - Additional Repulsion Required (OOE)

T=0 Phase Shifts



T=1 Phase Shifts



Scattering Lengths and Effective Ranges by Channel

	Oxford	CD-Bonn	Nijmegen I	Argonne v18	Experiment
			$^1S_0$		
a^C_{pp}		-7.8154		-7.8064	-7.8149(29)
r^C_{pp}		2.773		2.788	2.769(14)
a^N_{pp}	-17.365	-17.4602		-17.164	
r^N_{pp}	2.886	2.845		2.865	
a^N_{nn}	-18.949	-18.9680		-18.818	-18.9(4)
r^N_{nn}	2.859	2.819		2.834	2.75(11)
a^N_{np}	-23.85	-23.7380		-23.084	-23.74(2)
r^N_{np}	2.753	2.671		2.703	2.77(5)
			$^3S_1$		
a^N_t	5.46	5.4196	5.4194	5.402	5.419(7)
r^N_t	1.77	1.751	1.7536	1.752	1.753(8)

Deuteron Results

Property	Oxford	CD-Bonn	Nijmegen I	Argonne v18	Experiment
B_D[MeV]	2.224574	2.224575	2.224575	2.224575	2.224575(9)
A_S[fm$^{1/2}$]	0.8913	0.8846	0.8841	.8850	0.8848(9)
η	0.0261	0.0256	0.0253	.0256	0.0256(4)
$\sqrt{\langle r^2 \rangle}$[fm]	1.975	1.966	1.9666	1.967	1.971(6)
Q_d[fm^2]	0.2856	0.270	0.2719	.270	0.2859(3)
P_D [%]	5.56	4.85	5.664	5.76	

Nuclear Matter

Imagine a Volume V with A nucleons. We assume that the system has periodic boundary conditions and has translational invariance. The the limit as V and A $\rightarrow\infty$ but $\rho=A/V$ = constant of this matter is called Nuclear Matter.

Two variables:

- Density (ρ)
- Proton Fraction: x_p

$X_p=1/2$ is Symmetric Nuclear Matter (SNM)

$X_p=0$ is Pure Neutron Matter (PNM)

X_p=else is Asymmetric Nuclear Matter (ANM)

We are interested in E/A, the Equation of State (EOS).

Properties of Nuclear Matter from Heavy Nuclei

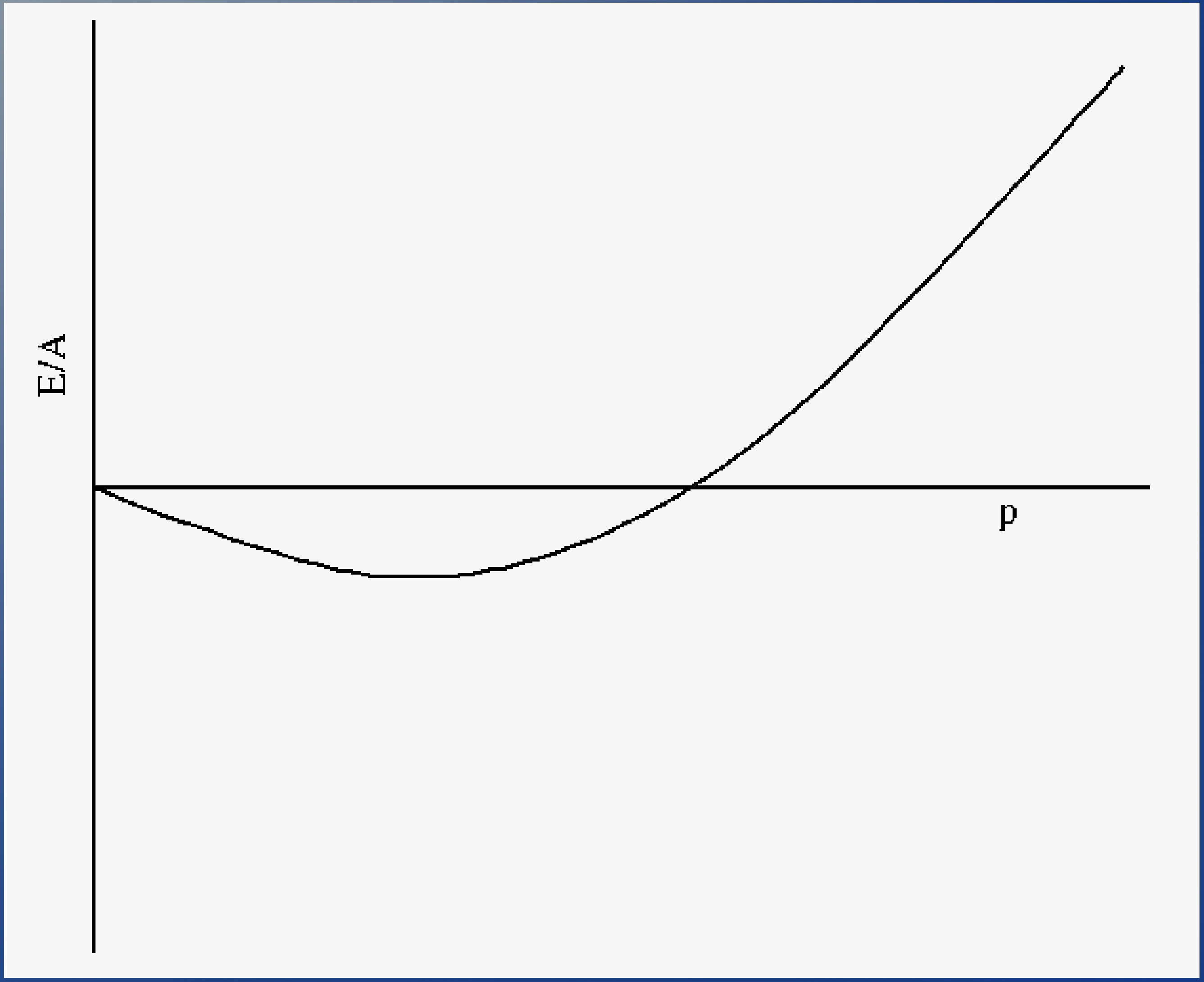
$$\frac{E}{A} = a_1 + a_2 A^{-\frac{1}{3}} + a_3 x_p^2 A^{-\frac{10}{3}} + a_4 (1-2x_p)^2 + a_5 A^{-\frac{7}{4}}$$

$$\lim_{A\to\infty} \frac{E}{A}\Big|_{x_p=\frac{1}{2}} = a_1 \approx -16.1\mathrm{MeV}$$

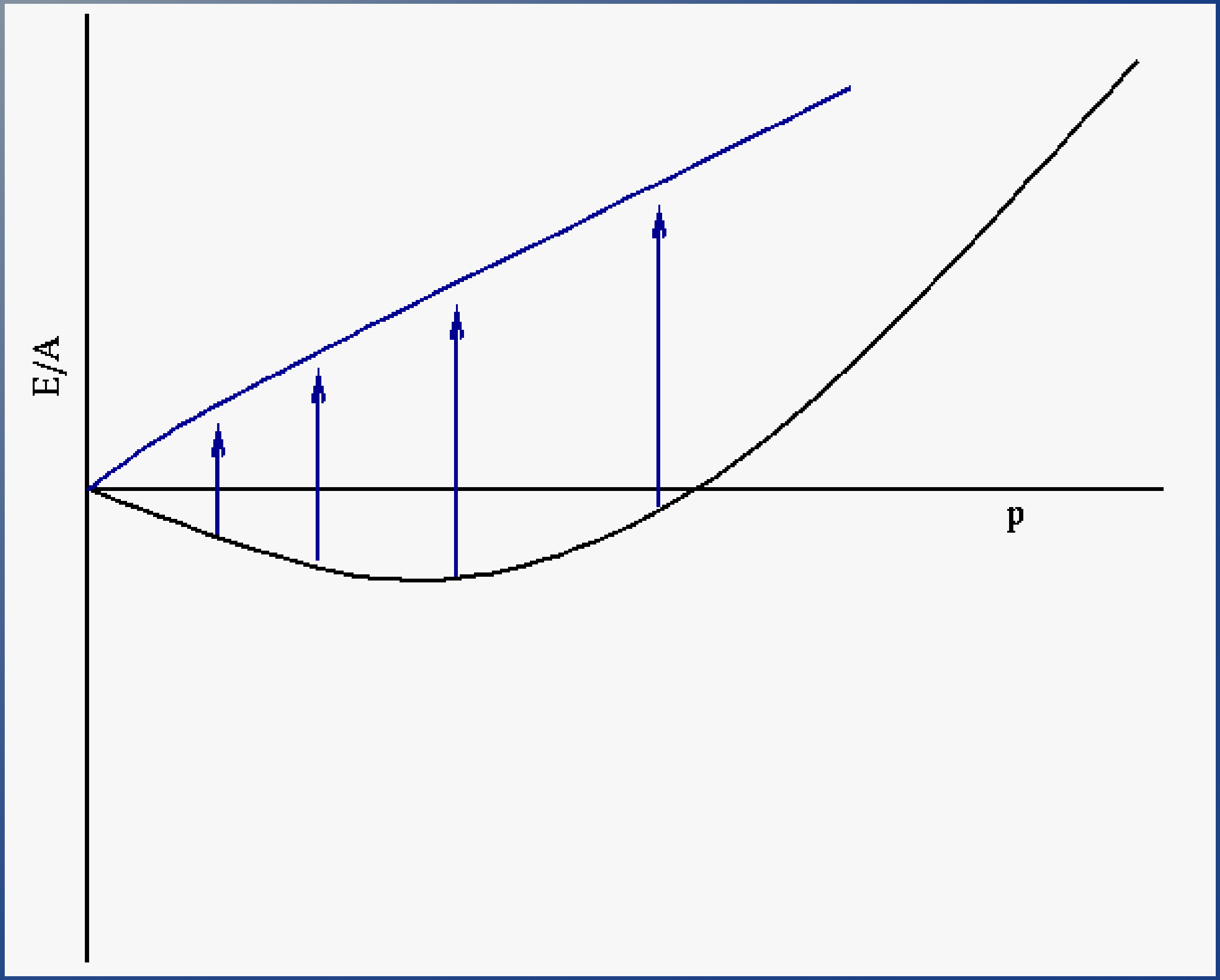
$$\lim_{A\to\infty} \frac{\partial^2}{\partial x_p^2}\frac{E}{A} = 8a_4 \Rightarrow \frac{1}{8}\lim_{A\to\infty}\frac{\partial^2}{\partial x_p^2} = a_4 \approx 23\mathrm{MeV}$$

$$\lim_{A\to\infty} \frac{\partial^2}{\partial x_p^2}\frac{E}{A} \approx \lim_{A\to\infty}\frac{E}{A}\Big|_{x_p=\frac{1}{2}} - \lim_{A\to\infty}\frac{E}{A}\Big|_{x_p=0}$$

Qualitative EOS for SNM



Change of EOS from SNM to PNM

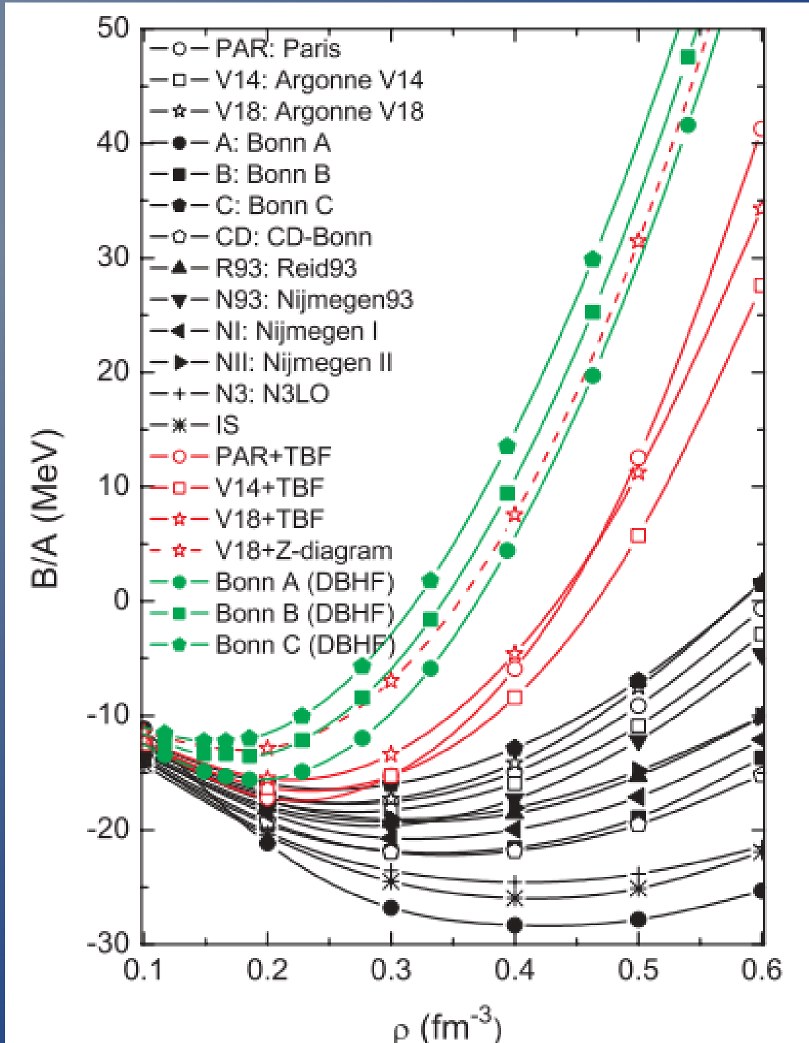


Calculating the EOS

$$H\psi = (T + V)\psi = E\psi$$

- Need to solve the many body Schrödinger equation.
- Non-trivial but technical.
- First person to try perturbation theory techniques to nuclear matter: Brueckner. Hence the Brueckner Hartree Fock formalism.

Formalism and Interaction Matter!

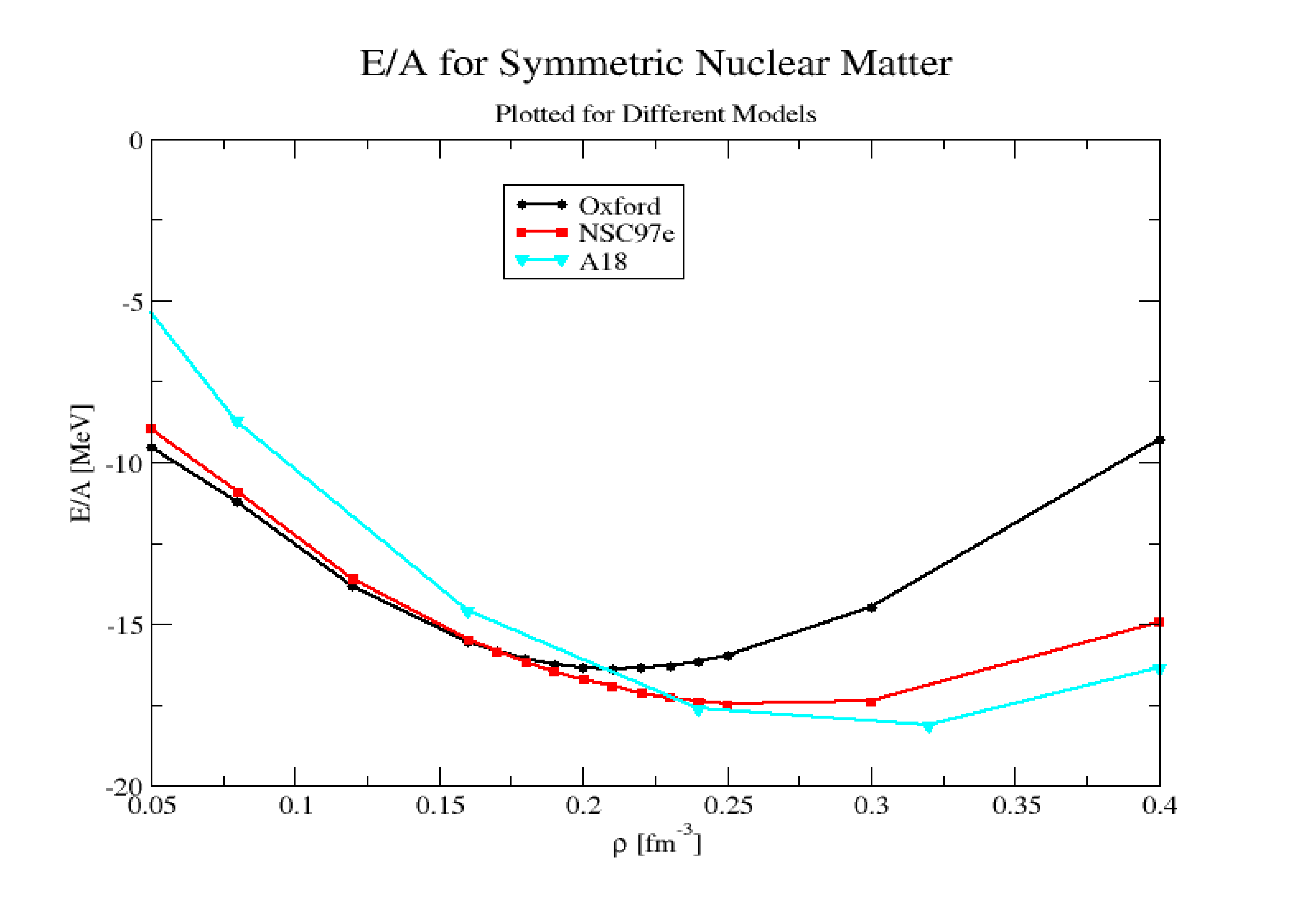


PHYSICAL REVIEW C **74**, 047304 (2006)

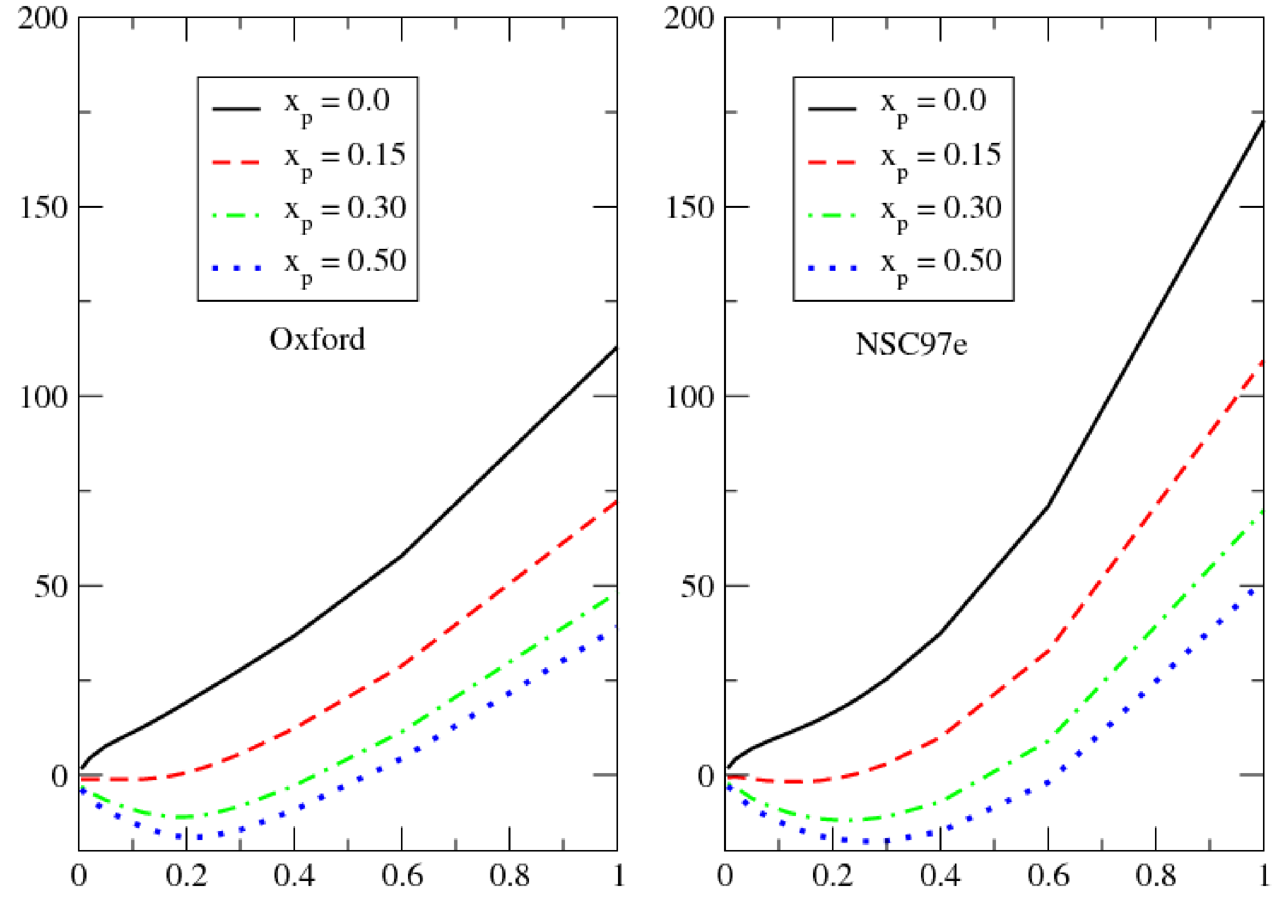
Nuclear matter saturation point and symmetry energy with modern nucleon-nucleon potentials

Z. H. Li,[1] U. Lombardo,[2] H.-J. Schulze,[3] W. Zuo,[4] L. W. Chen,[1] and H. R. Ma[1]

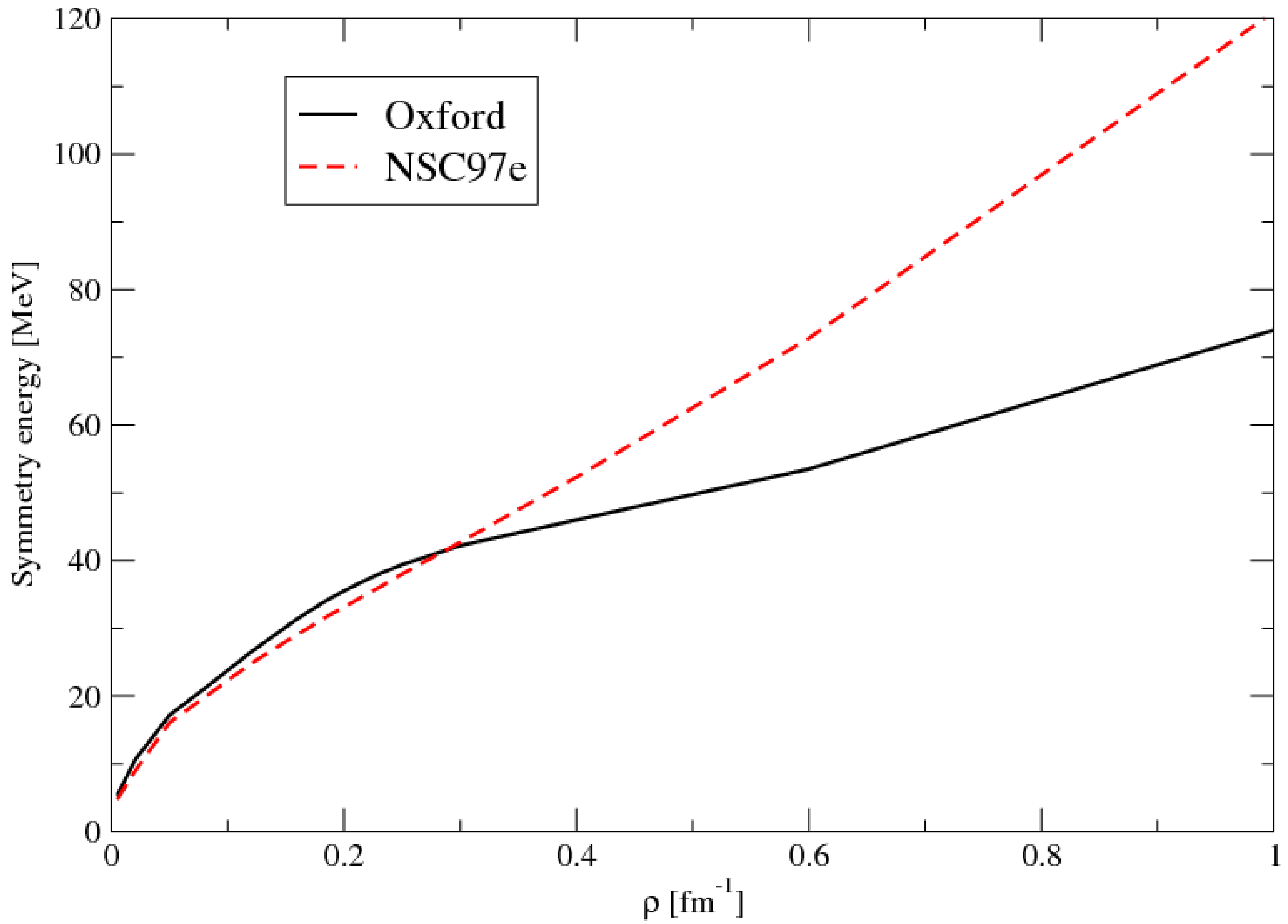
EOS Results


E/A for Symmetric Nuclear Matter
Plotted for Different Models
Oxford
NSC97e
A18
E/A [MeV]
0
-5
-10
-15
-20
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
ρ [fm^-3]

EOS Results (Cont'd.)



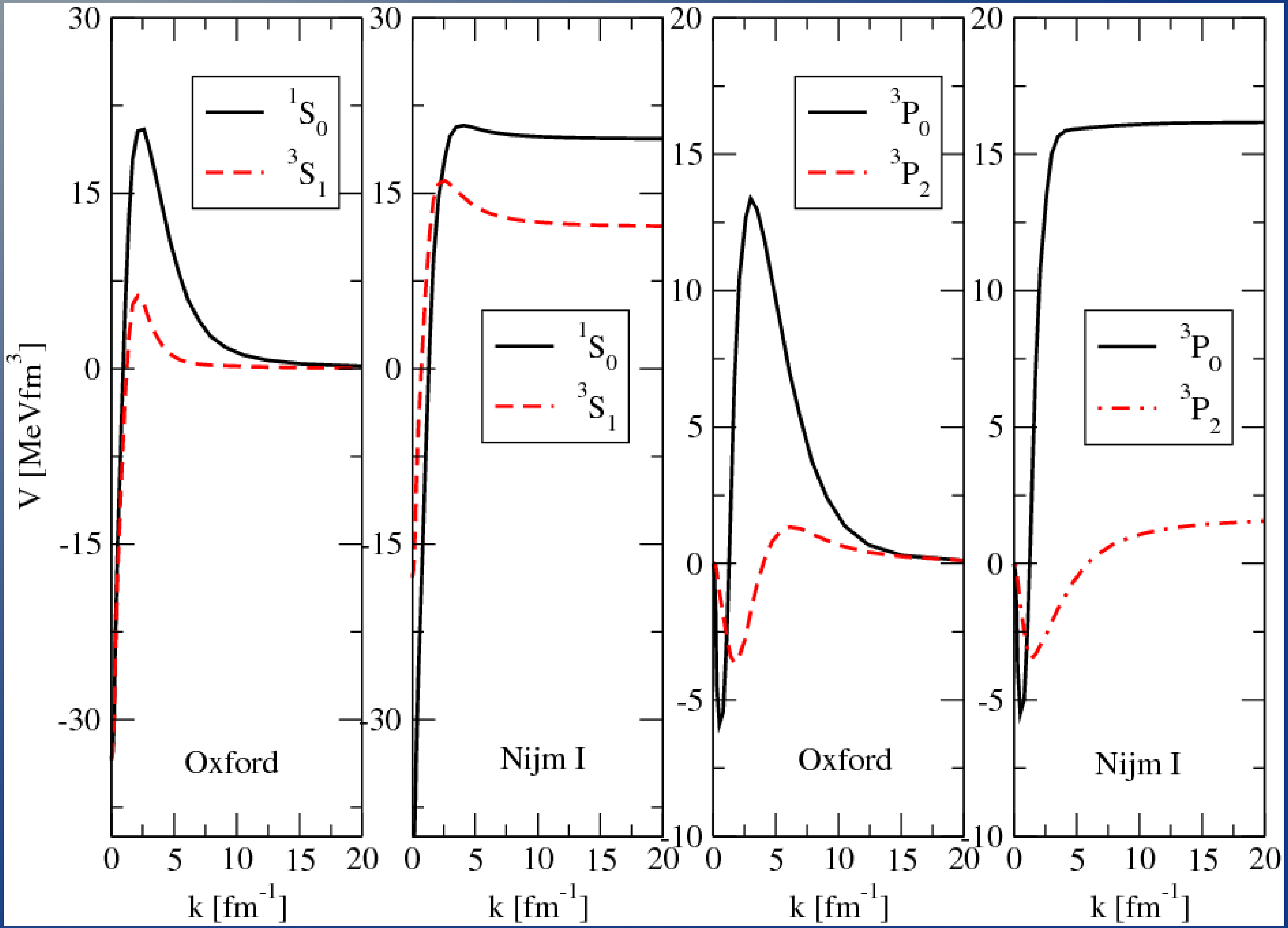
Symmetry Energy



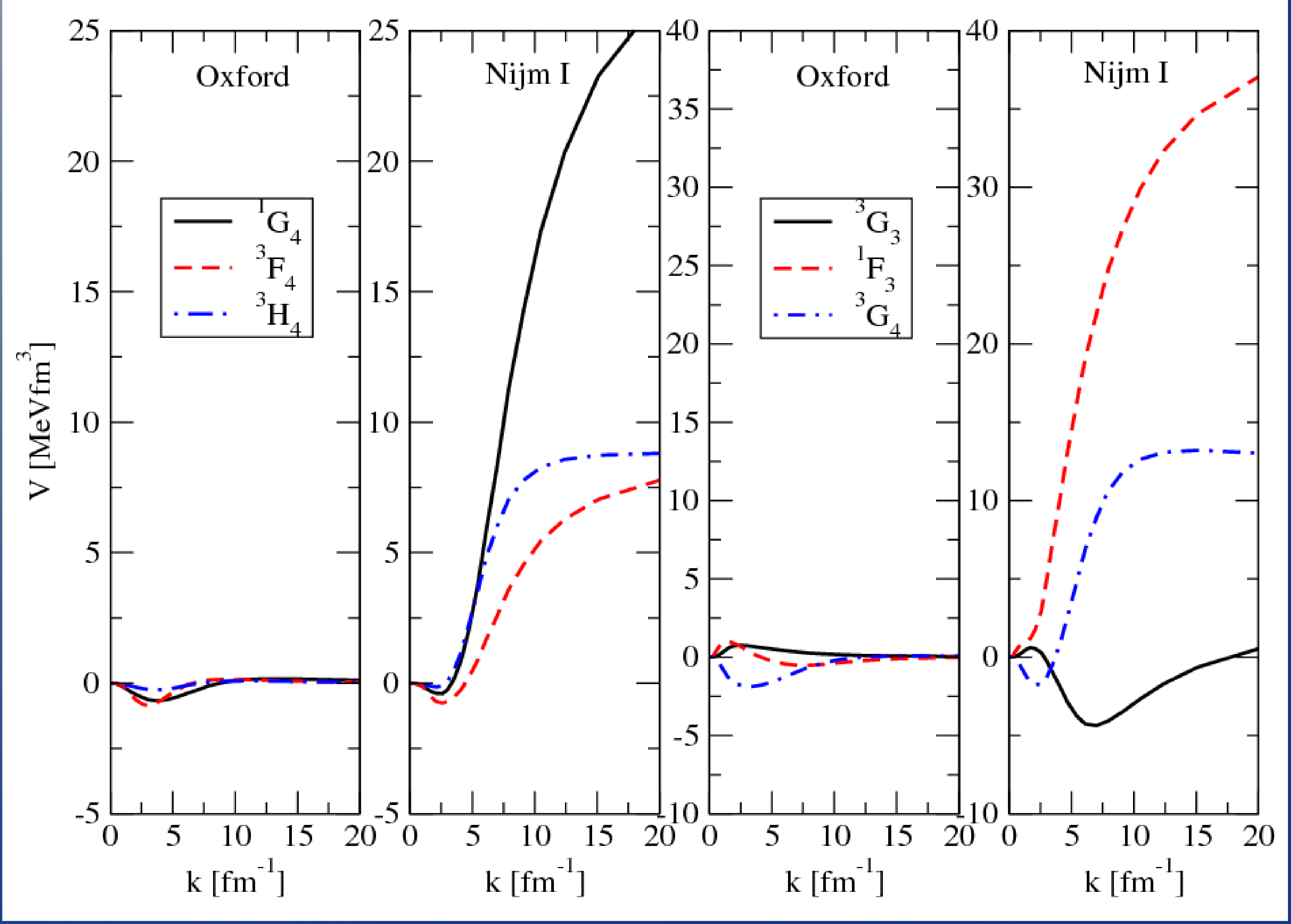
Comparison of EOS Results

Property	Oxf.	CD-Bonn	Nijm I	Av18	Expt.
$\rho_0[\mathrm{fm}^{-3}]$	0.25	0.374	0.348	0.259	0.16
$E/A[\mathrm{MeV}]$	-16.02	-21.9	-20.7	-17.3	$\approx$-16
$E_{\mathrm{sym}}[\mathrm{MeV}]$	38.0	31.1	30.5	29.9	

Oxford and Nijmegen Potential by Partial Wave



Oxford and Nijmegen Potential by Partial Wave (Cont'd.)



What I'm Doing – Parameters

Force Component	Parameters			
OGE+CI (Core)	α_{S}	α_{Core}	m_q	
OPE (π)	$g_{\mathrm{NN}\pi}$	α_π	β_π	
OSE (σ)	$g_{\mathrm{NN}\sigma}$	α_σ	β_σ	m_σ
OOE (ω)	$g_{\mathrm{NN}\omega}$	α_ω	β_ω	

What I'm Doing – Parameters

Force Component	Parameters			
OGE+CI (Core)	$\alpha_{\mathrm{S}}= 1.0$	$\alpha_{\mathrm{\ Core}}= 0.7$ GeV	$m_q= .33$ GeV	
OPE (π)	$g_{\mathrm{\ NN}\pi}= 13.0$	$\alpha_\pi= 0.4$ GeV	$\beta_\pi= 0.6$ GeV	
OSE (σ)	$g_{\mathrm{\ NN}\sigma}= 6.0$	α_σ=0.5 GeV	β_σ=0.5 GeV	$m_\sigma= * * *$ GeV
OOE (ω)	$g_{\mathrm{\ NN}\omega}= * * *$	$\alpha_\omega= 0.4$ GeV	$\beta_\omega= 0.4$ GeV	

- Literature Values:
  - $\alpha_S = 0.6 – 1.4$
  - α = 0.25-0.4 GeV
  - β = 0.3-0.4 GeV
  - $g_{NN\pi} \approx 13.0$
  - m_q = 0.3-0.4 GeV

Partial Wave Parameters

Partial Wave Channel	$m_\sigma (GeV)$	$g_{NN\omega}$
$^1S_0$	0.407	0.0
$^3P_0$	0.450	12.0
$^1P_1$	0.540	14.0
$^3P_1$	0.490	10.5
$^3S_1$	0.501482	0.0
$^3D_1$	0.431	0.0
ε_1	0.501482	0.0
$^1D_2$	0.455	0.0
$^3D_2$	0.620	0.0
$^3P_2$	0.635	0.0
$^3F_2$	0.440	12.5
ε_2	0.440	12.5
$^1F_3$	0.600	14.0
$^3F_3$	0.455	0.0
$^3D_3$	0.520	0.0
$^3G_3$	0.520	0.0
ε_3	0.520	0.0
$^1G_4$	0.440	0.0
$^3G_4$	0.650	0.0
$^3F_4$	0.520	0.0
$^3H_4$	0.520	0.0
ε_4	0.520	0.0

Thoughts, Conclusions, etc.

- The most significant failure of the model is the necessity of including an ad-hoc ω exchange in some P-waves.
- The range of parameter variation by partial wave, while not extreme, is disappointing.
- We can alter the physics of the model self-consistently to explore other mechanisms (2π exchange, etc.)

Thoughts, Conclusions, etc. (Cont'd.)

- The ability of the simple and constrained model to well reproduce so many observables connected to the NN interaction is surprising and encouraging.
- The model raises important physics issues:
  - Non-locality
  - ρ exchange
  - High momentum behavior, etc.
- Work continues.

End of Talk

Thank you for your attention!

Questions?

Feedback?