Nuclear EFT and Nuclear Many-Body Problems

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1. Introduction

Examples of phenomena
we are interested in

2. Calculational Methods
(not an exhaustive list)

3. Applications

4. Summary

cf. Talks by
T.-S. Park
and
Young-Ho Song

1. Introduction

⊙ Many astrophysically interesting electroweak processes involving light nuclei and low energy-momentum

⊙ In particular, weak processes related to the Sun

pp fusion

$$p + p \longrightarrow d + e^+ + \nu_e$$

hep fusion

$$^3He + p \longrightarrow {}^4He + e^+ + \nu_e$$

νd reactions (SNO experiments)

$$\nu_e + d \rightarrow e^- + p + p \quad (\text{C.C.})$$

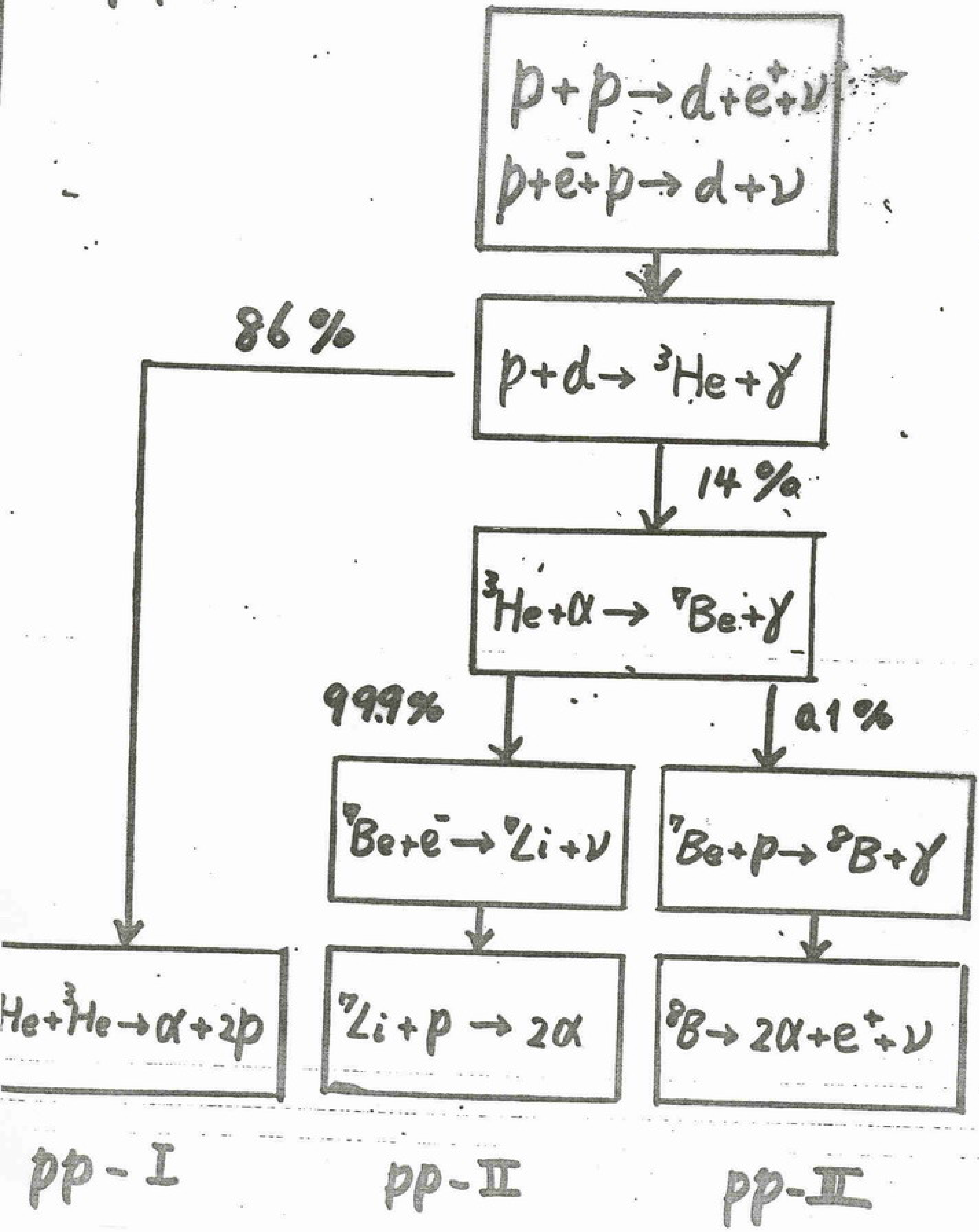
$$\nu_x + d \rightarrow \nu_x + n + p \quad (\text{n.c.})$$

$$x = e, \mu, \tau$$

pp-chain

$p+p+p+p \rightarrow \alpha + 2e^+ + 2\nu_e$

1-3



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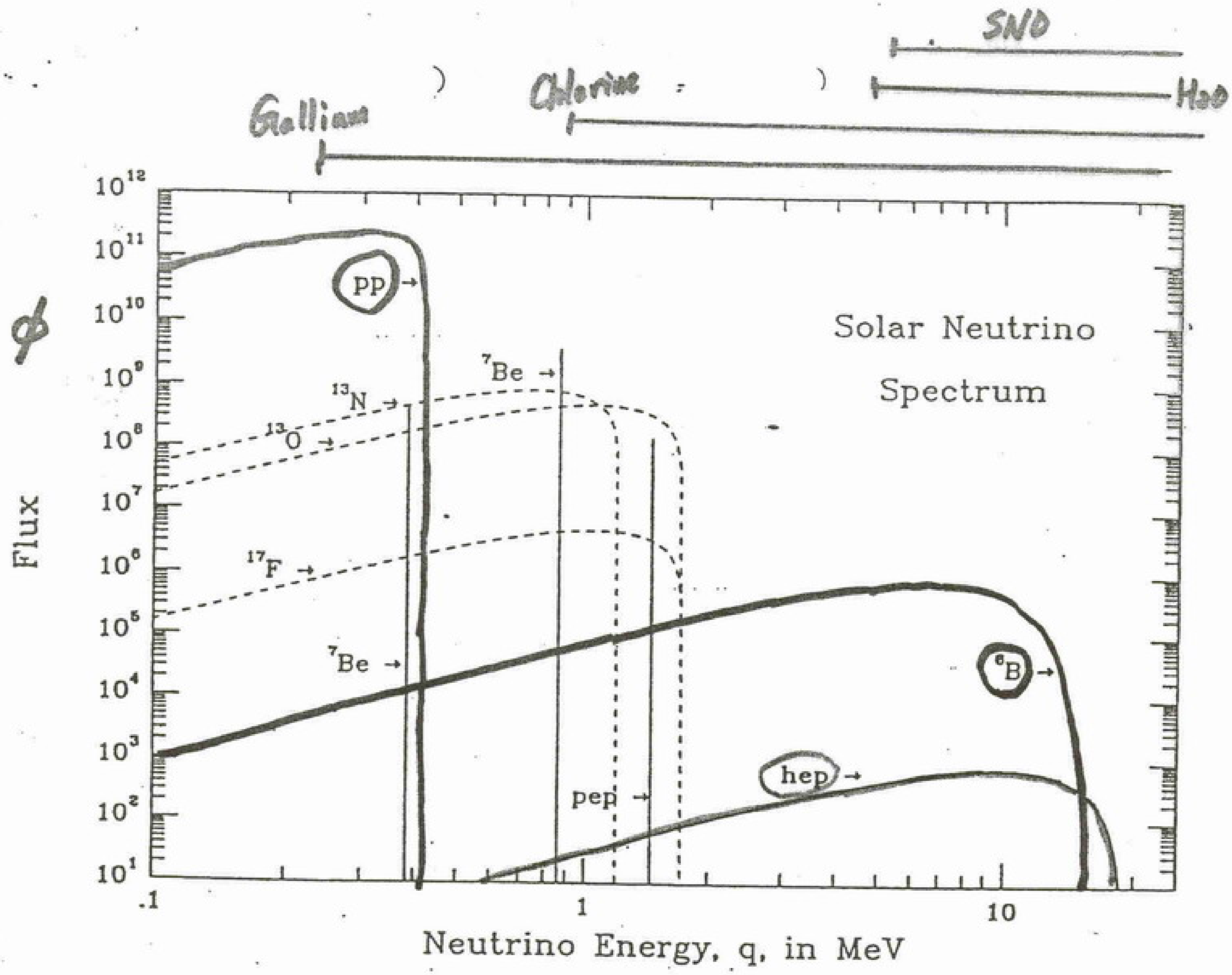
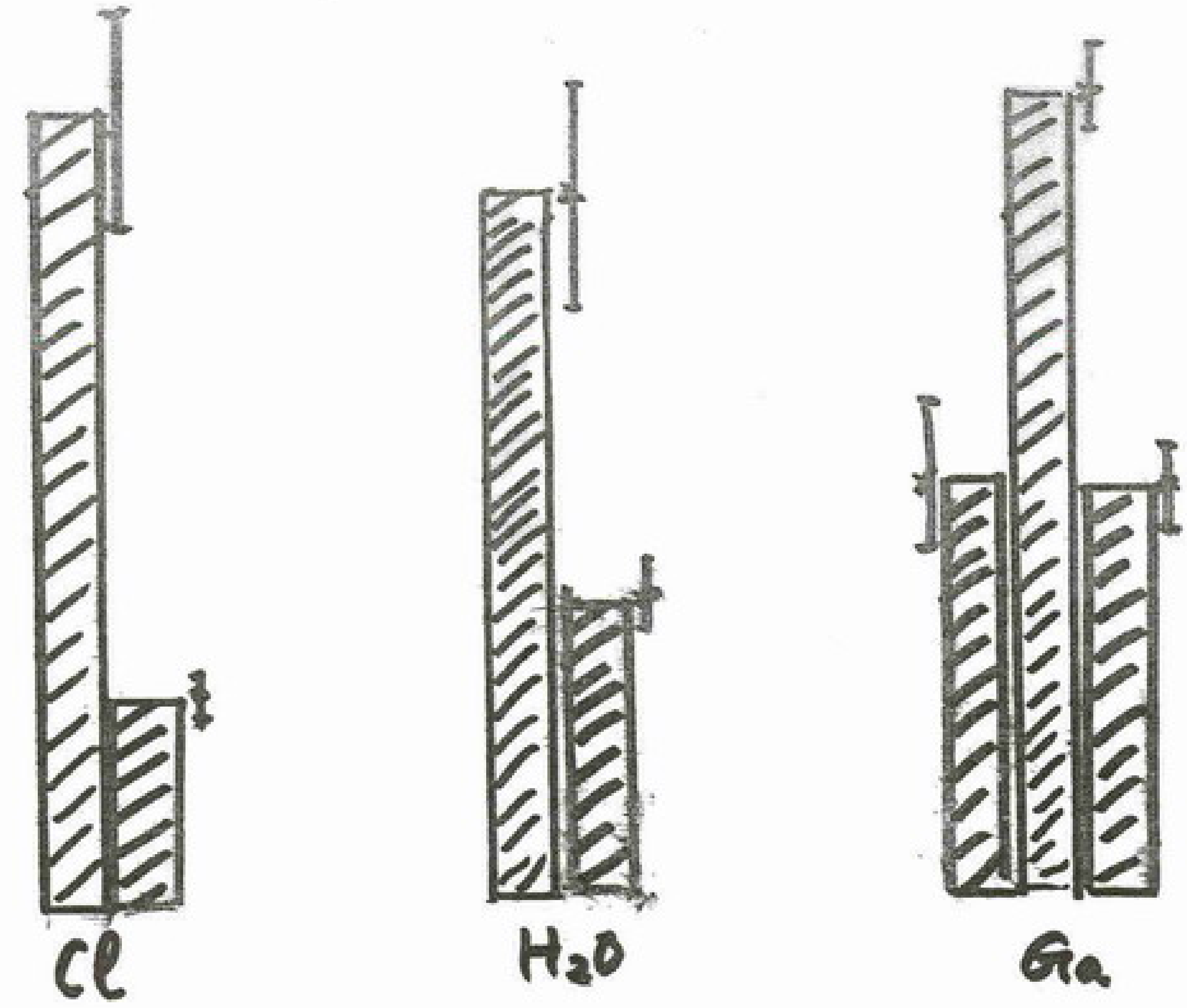


FIG. 2

Solar neutrino flux calculated in SSM
(standard solar model)
J. N. Bahcall

$\phi = \begin{cases} \#\text{ of } \nu\text{'s}/\text{cm}^2\cdot\text{sec MeV} & \text{for continuous spectrum} \\ \#\text{ of } \nu\text{s}/\text{cm}^2\cdot\text{sec} & \text{for line spectrum} \end{cases}$



The solar neutrino problem

SSM prediction

measured value

The solar neutrino problem
prior to the first SNO result (2001)

SNO can detect

$$\nu_e + d \longrightarrow e^- + p + p \quad : \text{CC}$$

$$\nu_x + d \longrightarrow \nu_x + p + n \quad : \text{NC}$$
$$(x = e, \mu, \tau)$$

as well as

$$\nu_e + e^- \longrightarrow \nu_e + e^- \qquad \text{CC+NC}$$

NC is flavor-independent

→ Can determine the total flux of solar neutrinos regardless of their flavors

SNO results

Ahmad et al., P.R.L. 87 (2001) 071301; 89 (2002) 011301; 011302

- ϕ_ν^{total} agrees with ϕ_ν^{total} (SSM)

- $$\frac{\phi_{\nu_e}}{\phi_\nu^{\text{total}}} = 0.34$$

→ Neutrino oscillations

$$\begin{cases} \sigma_{calc}^{cc} \equiv \sigma(\nu_e d \to e^- + p + p)_{calc.} \\ \sigma_{calc}^{nc} \equiv \sigma(\nu_x d \to \nu_x + n + p)_{calc.} \end{cases}$$

important for these considerations

How reliable are they ?

Similar questions for pp and hep.

2. Methodology in nuclear physics
(a very limited list)

◉ SNPA

Standard nuclear physics approach
(potential model)

◉ EFT

Effective field theory

◉ MEEFT (More Effective EFT)
or
EFT*

the latest development

§1 SNPA (Standard nuclear physics approach)

SNPA is based on

$$\underbrace{H^{SNPA} = \sum_i t_i + \sum_{i<j} v_{ij}^{phenom}}_{} + \sum_{i<j<k} v_{ijk}^{phenom} + \cdots$$

or

$$\mathcal{L} = \mathcal{L}^{SNPA}(N, \pi, \Delta, \rho, \omega, \sigma \cdots)$$

H^{SNPA}, $\mathcal{L}^{SNPA}$ determined phenomenologically to reproduce 1-body and 2-body data (up to π threshold)

Once H^{SNPA} is fixed, find realistic wave functions by solving

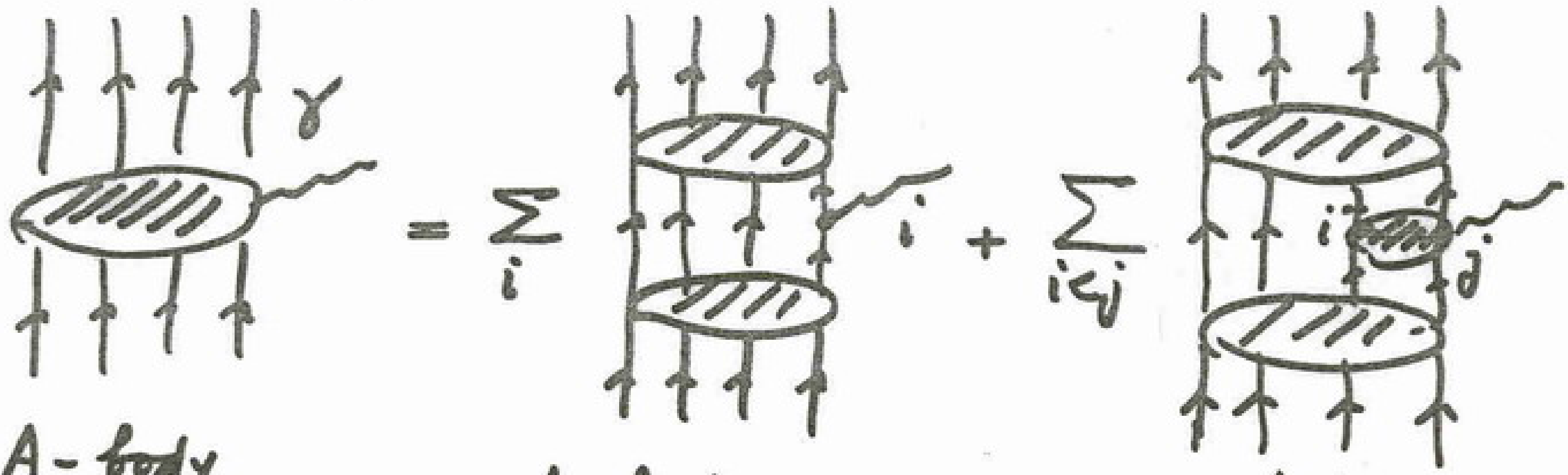
$$H|\Psi_A\rangle = E|\Psi_A\rangle$$

Practically, no approximation up to A = 11 !!

No truncation problems.
No need to employ approximate many-body technique such as RPA, ...

Responses to external probes

(electromagnetic and weak currents)

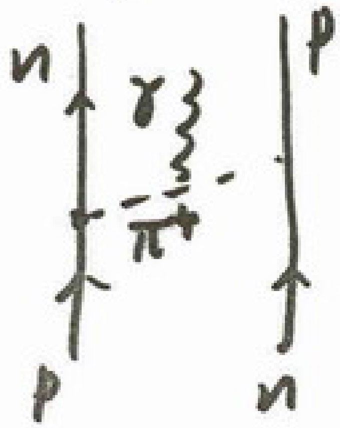


A-body

1-body
Impulse approxim.
IA

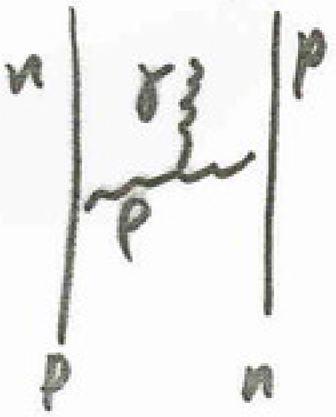
2-body
Exchange current
EXC, MEX

Example of EXC



$\mathcal{L}_{NN\pi}$, $\mathcal{L}_{NN\rho}$, $\mathcal{L}_{N\Delta\pi}$, etc.

$\mathcal{L}_{\gamma\pi\pi}$, etc.

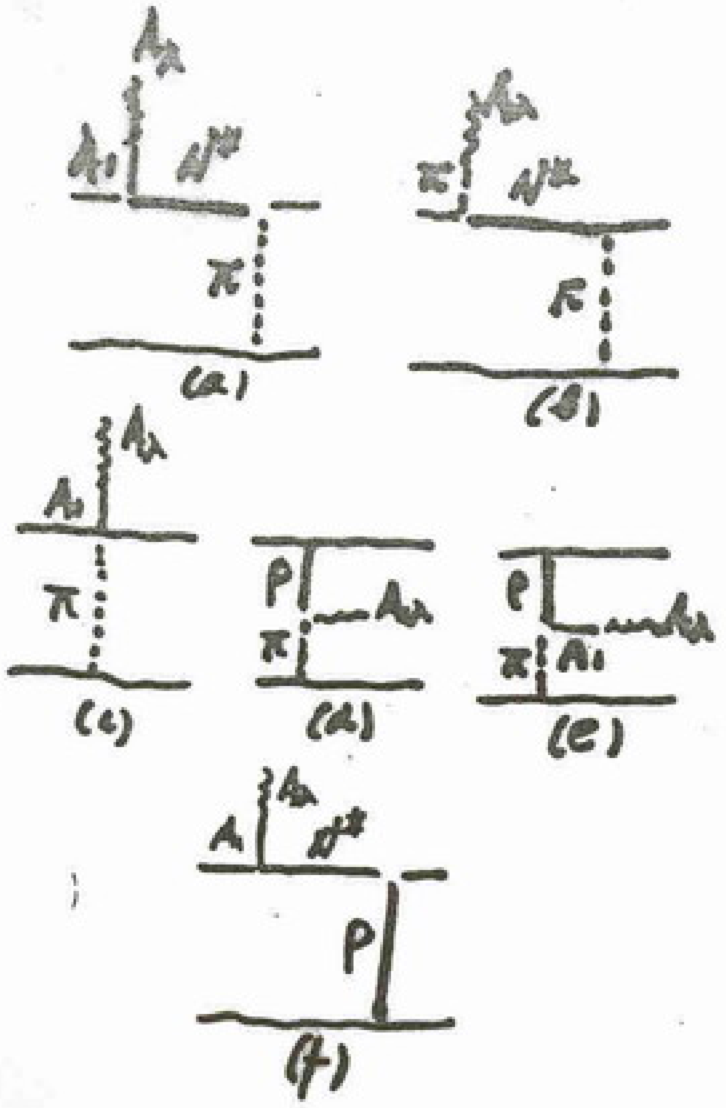


determined

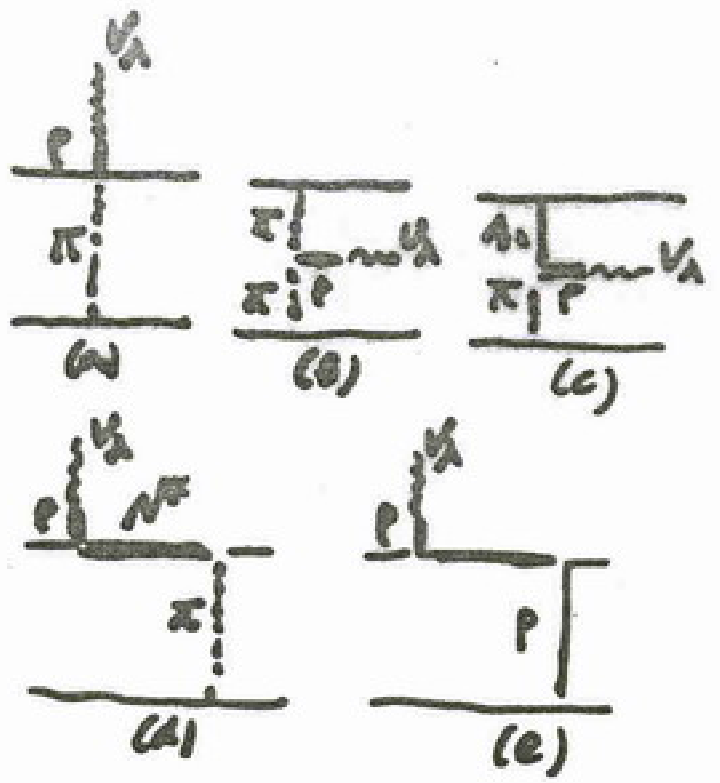
phenomenologically

to satisfy

CVC, PCAC, current algebra, etc.



Exchange currents for A_λ



Exchange currents for V_λ

$\mathcal{M} = \langle \Psi_f | J | \Psi_i \rangle$

IA + EXC (derived phenomenologically)

Use of "realistic" wave functions obtained by solving exactly

$H^{SNPA} | \Psi \rangle = E | \Psi \rangle$.

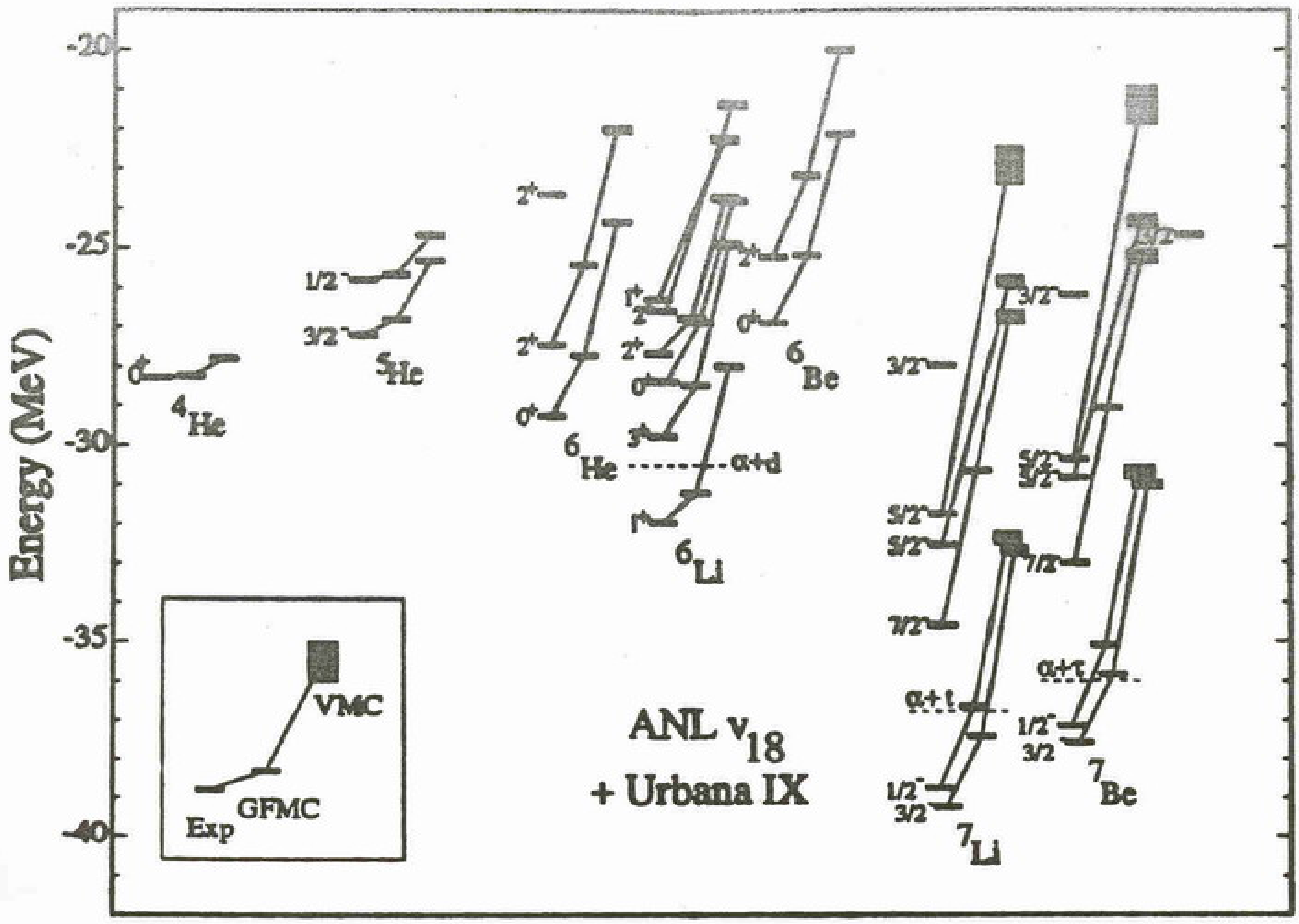
→

SNPA

Great success !!

see e.g.,

Carlson and Schiavilla, Rev. Mod. Phys. 70 ('98) 743.



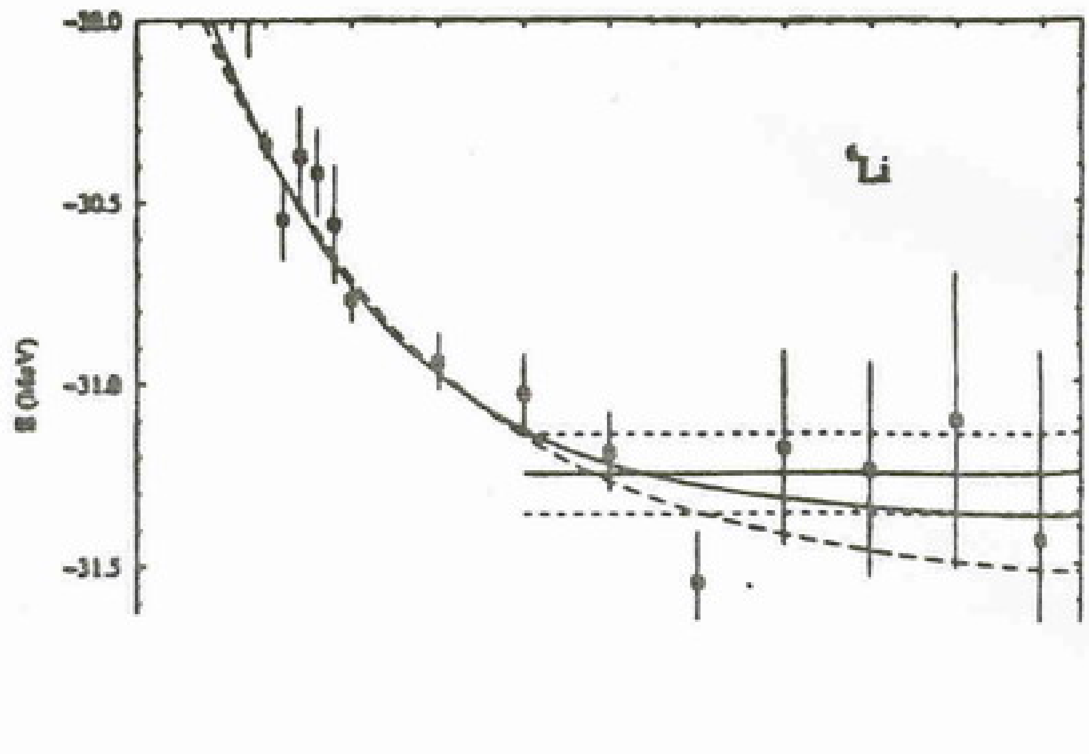
Color) Energy spectra of $A=4$–7 nuclei, obtained in variational Monte Carlo (VMC) and Green's-function Monte Carlo calculations with the Argonne v_{18} two-nucleon and Urbana model IX three-nucleon interactions. Both the central value one-standard-deviation error estimate are shown. GFMC results are a variational bound obtained by averaging from τ 06 MeV^{-1}.

.8. Thus this calculation yields approximately ds of the experimental spin-orbit splitting in

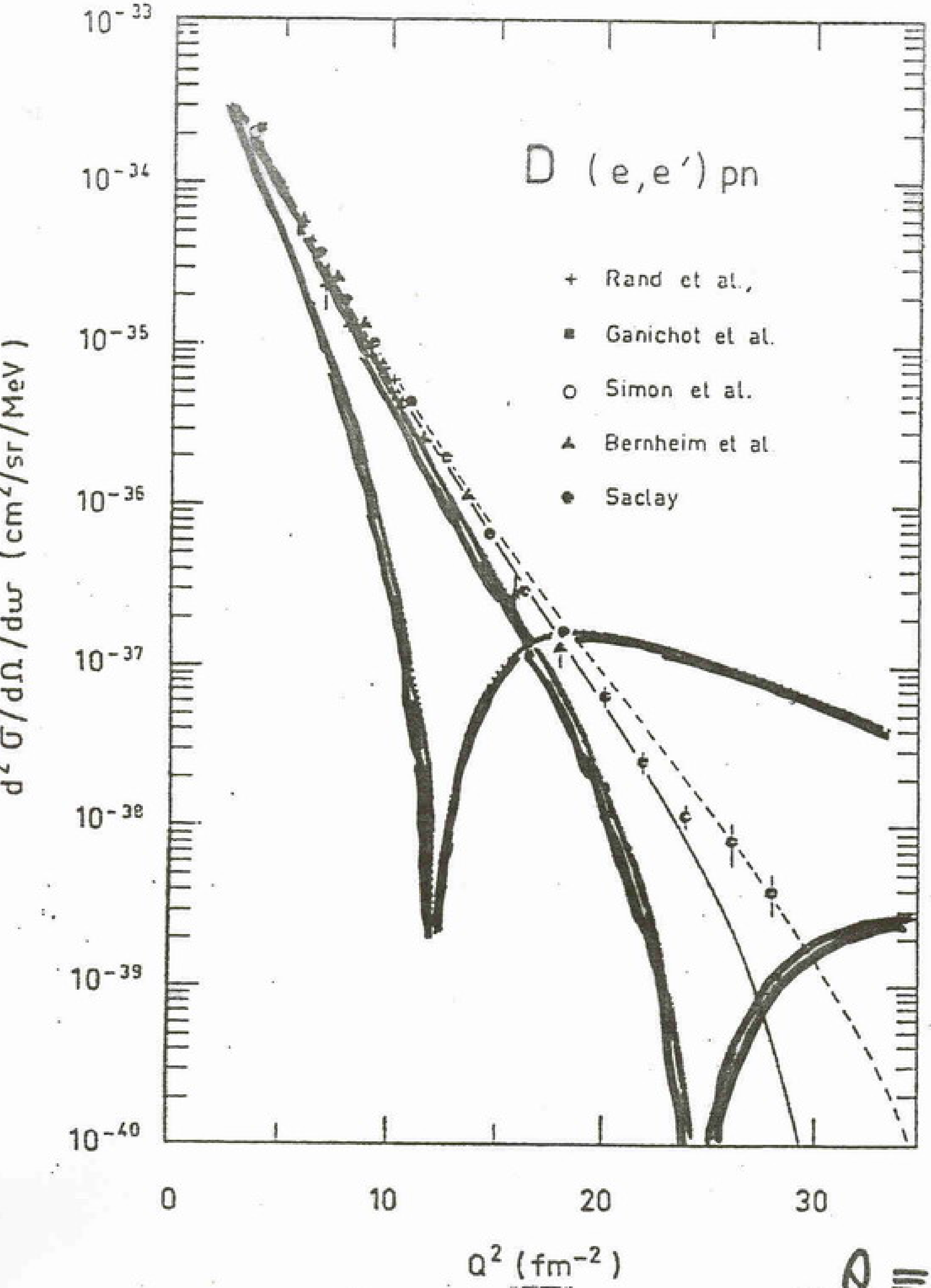
's-function Monte Carlo calculations produce a decreasing upper bounds to the true energy as ation time τ is increased. For ^{5}He, the calculapear to be well converged—indeed, little depenpon τ is seen for any observable for $\tau>0.03$ Hence the only uncertainty remaining is the dewhich the difference between the full isospinent Hamiltonian and a simpler static v_8 model reated in perturbation theory. While this is ap· quite a good approximation in $A=3$ and 4, for ystems it remains to be tested.

nitial sets of calculations for $A=6$–7 have reeen completed (Pudliner *et al.*, 1995, 1997), and 's are quite encouraging. Figure 7 compares the

Similar calculations in $A=4$ and 5 show that the results are well converged. Statistical fluctuations that occur in all path-integral calculations of fermion systems (Schmidt and Kalos, 1984) limit the calculations to τ



Auffret et al., Phys. Rev. Lett. 55('85) 1362



$E_{np} = 1.5$ MeV

$Q \equiv p_e - p_{e'}$

—— impulse

—— pion-exchange theory

- - - - $\pi + \rho$ J. Mathiot,

—— full ($\pi + \rho + \Delta$) N.P. A412 ('84) 201

2-5'''

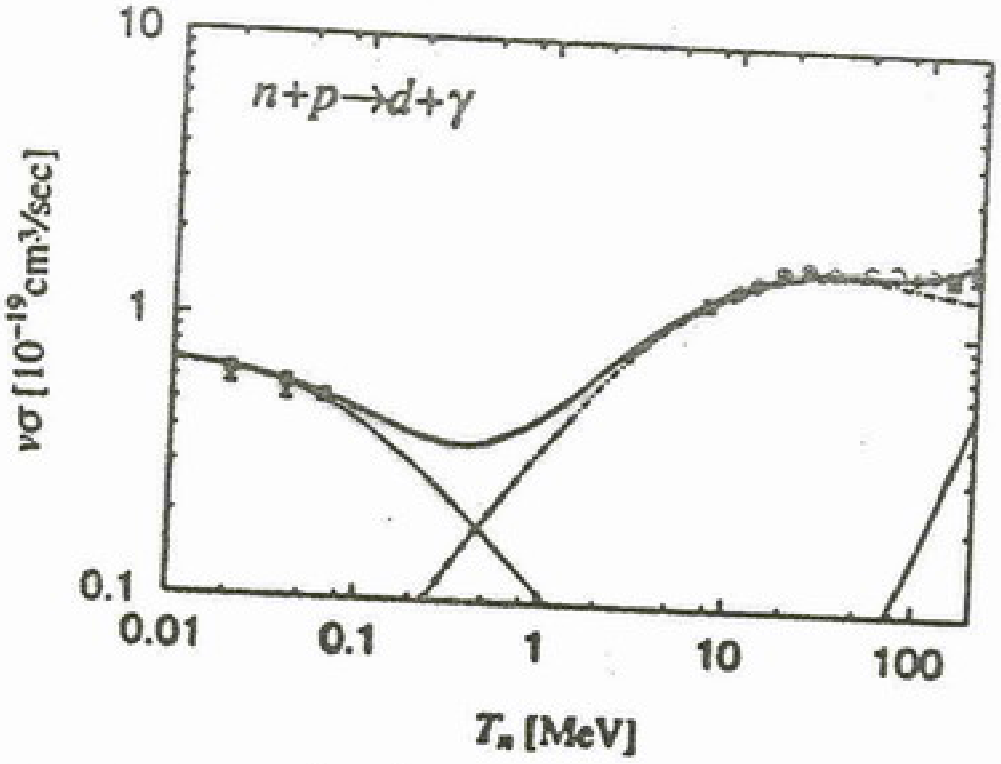


FIG. 1. Total cross section for radiative neutron capture. The solid curve corresponds to the results of our full calculation including the IA and exchange currents and all the multipole amplitudes. The dashed and dash-dotted curves show the individual contributions of the magnetic-dipole and electric-dipole amplitudes, respectively. The data are taken either from the neutron capture reaction itself [43], or from its inverse process [44,45], with the use of detailed balance for the latter.

ANLV18 used

2-3

2-5

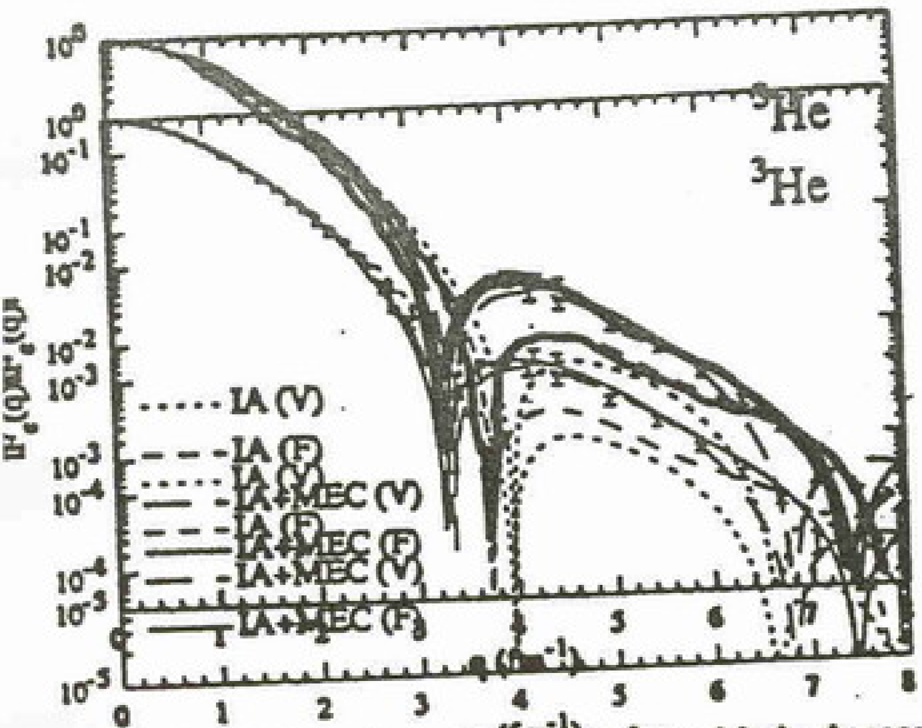


FIG. 8. Charge form factor $|F_c(q)|$ for ^{3}He with the Argonne v_{14} + Urbana VIII Hamiltonian calculated in impulse approximation (IA) and with meson-exchange-current (IA + MEC) contributions for both variational (V) and Faddeev (F) wave functions.

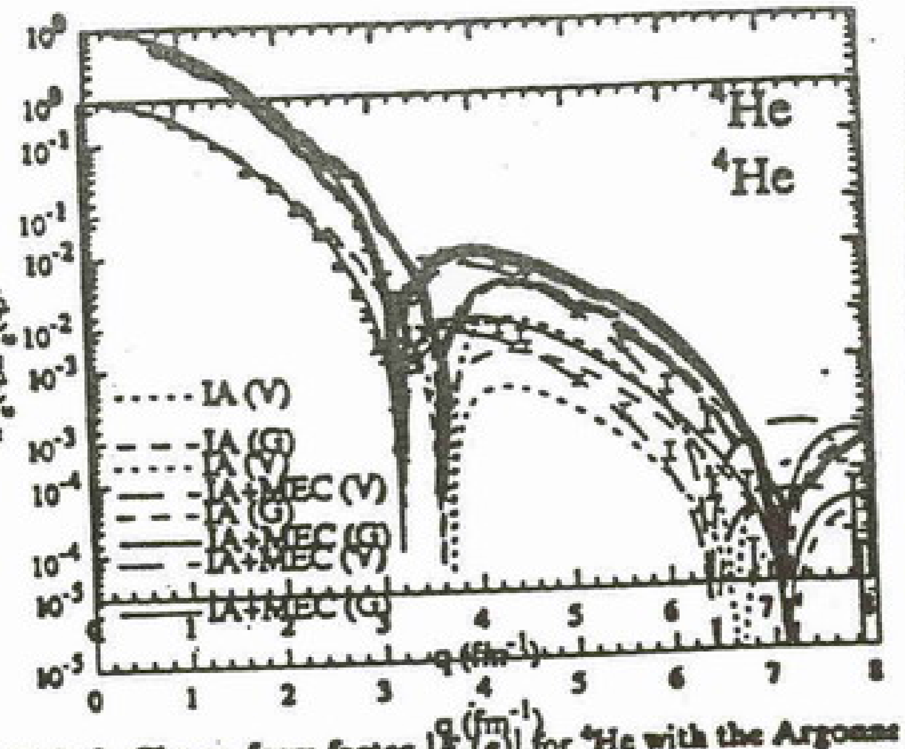


FIG. 9. Charge form factor $|F_c(q)|$ for ^{4}He with the Argonne v_{14} + Urbana VIII Hamiltonian calculated in impulse approximation (IA) and with meson-exchange-current (IA + MEC) contributions for both variational (V) and Green's function Monte Carlo (G) wave functions.

Despite its great successes,

there is still room for a new approach

based on "effective field theory (EFT)":

at least for certain classes of nuclear

phenomena.

§2 EFT (Effective field theory)

◎ How is SNPA related to QCD ?

The fundamental theory of strong interactions for quarks and gluons

vs. nuclei composed of hadrons

Does SNPA respect the symmetries of QCD ?
in particular, chiral symmetry ?

◎ Do we have a guiding principle in choosing v_{ij} (phenom) ?

What is an expansion parameter ?
What is a measure of errors in SNPA ?

◎ Why do we need "high-energy" information (up to $E_{cm} \sim 150$ MeV) to understand "low-energy" phenomena ?

We wish to formulate a nuclear theory in which

(i) the symmetries of QCD are respected,

(ii) there is a well-defined expansion scheme,

(iii) the separation of low- and high-energy scales is clear.

→ Nuclear Effective Field Theory (EFT)

S. Weinberg, Phys. Lett. B 251 ('90) 288

↓

Explosion of research activities

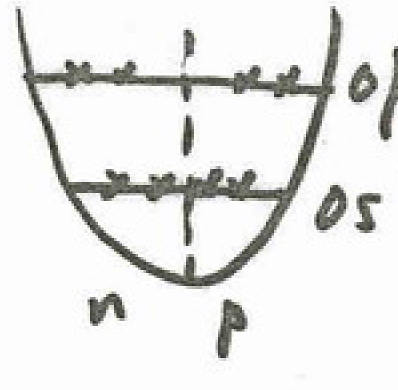
For a recent review, see, e.g.,

P. Bedaque & U. van Kolck,
Ann. Rev. Nucl. Part. Sci., 52, 339 (2002)

The basic idea of EFT is <u>not</u> <u>foreign</u> to nuclear physics

Cohen-Kurath's treatment of p-shell nuclei

$$|\Psi^{A}_{true}\rangle \cong |(0s)^4(0p)^{A-4}\rangle$$



$$|\Psi^{A}_{true}: \alpha TJ\rangle = \sum_{k} |(0p)^{A-4}\alpha TJ : k\rangle C_k$$

$$\text{"}H_{true}\text{"} \rightarrow H_{p\text{-shell}} = \sum t_i + \sum_{\alpha,\alpha'} |(0p)^2\alpha' TJ\rangle \langle (0p)^2\alpha' TJ|\tilde{H}|(0p)^2\alpha TJ\rangle \cdot \langle (0p)^2\alpha TJ|$$

$$H_{true} \equiv H_{SNPA}$$

The model Hamiltonian

characterized by "low-energy constants" (LEC's)

$$h_{\alpha\alpha'}(JT) \equiv \langle (0p)^2\alpha TJ|\tilde{H}|(0p)^2\alpha' TJ\rangle$$

$h_{\alpha\alpha'}(TJ)$ subsumes "high-energy" physics

core polarization

Δ-excitation, etc.

Use the observed energy spectra of p-shell nuclei to fix LEC's

→ prediction for the remaining levels

F-5-6
8-9-2

a nucleonic observable $\mathcal{O}_N$

(Transition operator)

In general

$$\langle f:\text{full} | \sum_{i=1}^{A} \mathcal{O}_N(i) | i:\text{full} \rangle$$

$$\neq \langle f:P | \sum_{i=1}^{A} \mathcal{O}_N(i) | i: \cancel{\text{full}}\, P \rangle$$

This difference is called the

Core-polarization effect

Furthermore

$$\hat{\mathcal{O}} \xrightarrow{\text{Truncation to } P} \sum_{i=1}^{A} \mathcal{O}_N(i)$$

in the world of $\mathcal{L}_{\text{hadron}}$

In general, we expect some deviation from $\underbrace{\sum_{i=1}^{N} \mathcal{O}_N(i)}$

Impulse approx.

$\Rightarrow$ meson-exchange currents (MEC)

effective transition operator method

① Choose for $|A\rangle$, $|B\rangle$ reasonably realistic wave functions.

② $$\langle B ||| \sum_{i=1}^{N} \mathcal{O}_i ||| A\rangle = \sum_{\substack{B', A' \\ b, a}} [B \{| B' \times b] \cdot [A \{| A' \times a] \times \langle b ||| \mathcal{O} ||| a\rangle$$

single-particle label

③ cfp's many-body problem part

assumed to be given by the model w.f.

④ $\langle b ||| \mathcal{O} ||| a\rangle$ acquires modifications due to

i) more complicated components in w.f.

ii) explicit degrees of mesons

⑤ $$\vec{\tau}\vec{\sigma} \longrightarrow g_L^{eff} \vec{\tau}\vec{l} + g_A^{eff} \vec{\tau}\vec{\sigma} + g_P^{eff} [Y_2(\hat{r}) \times \vec{\sigma}]^{(1)}$$

⑥ Determine g_L^{eff}, g_A^{eff}, g_P^{eff} through χ^2-fitting to the available data

⑦ Predict $\langle B ||| \vec{\tau}\vec{\sigma} ||| A\rangle$ for unknown transitions

References for ETOM

2-9-84

B.A. Brown and B.H. Wildenthal
Atom. Data Nucl. Data Tables, 33 ('85) 347

A. Arima, K. Shimizu, W. Bentz and H. Hyuga,
Adv. Nucl. Phys. 18 ('87) 1

I.S. Towner, Phys. Rep. 155 ('87) 263

2-9-85

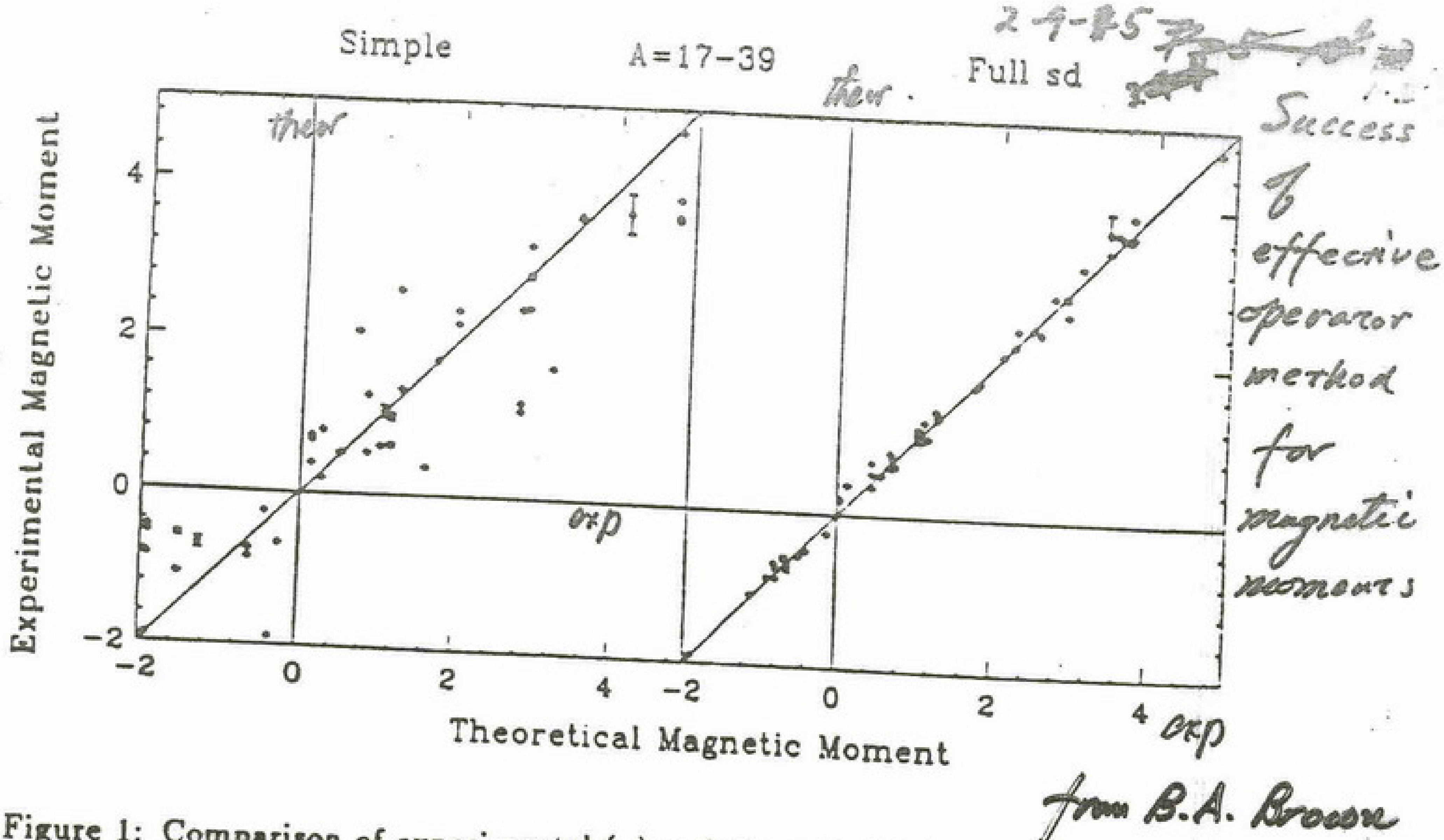


Figure 1: Comparison of experimental (y) and theoretical (x) magnetic moments for 1s0d-shell nuclei. The theoretical values for the right-hand side were obtained with the full 1s0d-shell basis, and those on the left-hand side were obtained with only the largest component in the wave function (corresponding to the extreme single-particle model). Free nucleon g-factors are used in both cases.

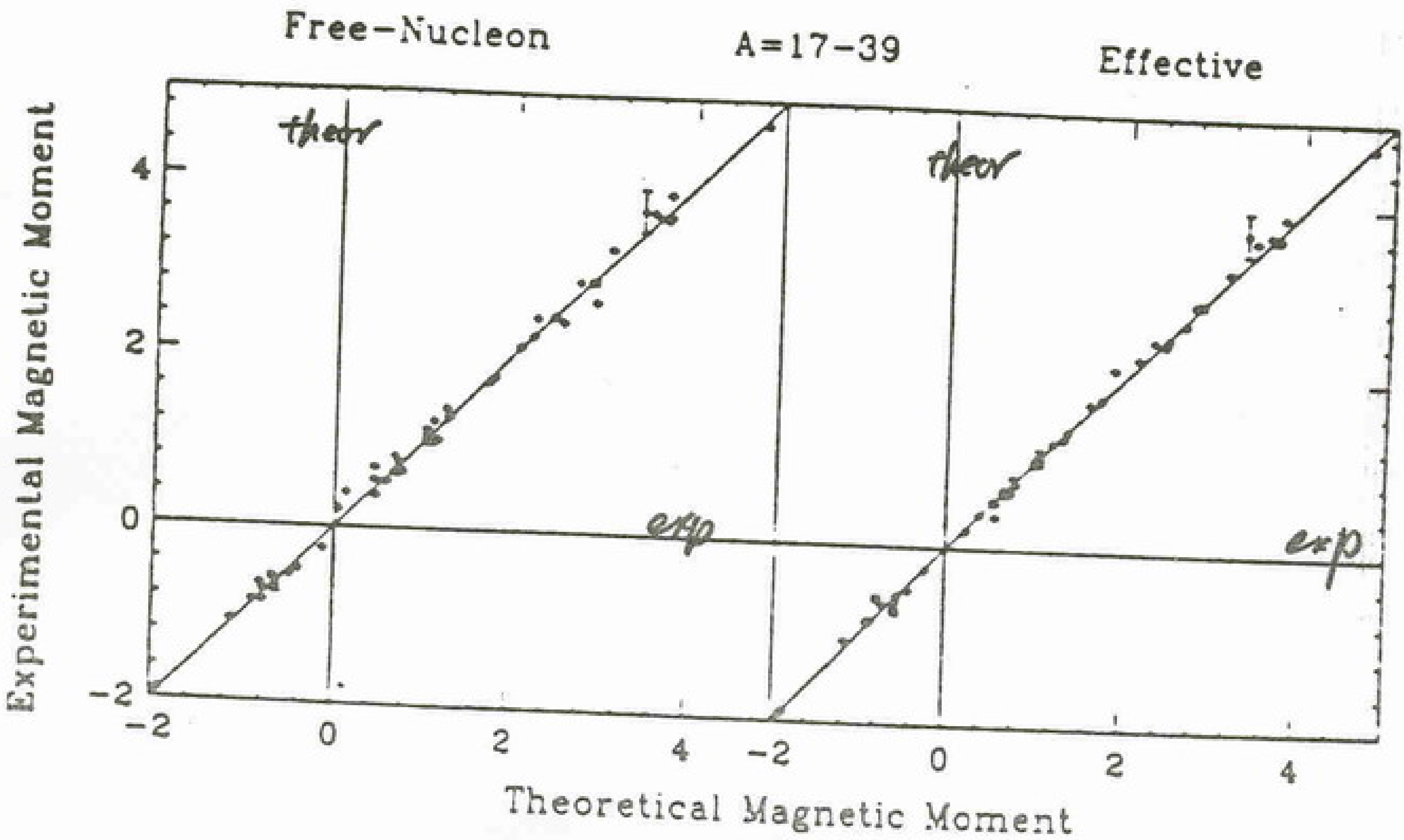


Figure 2: Comparison of experimental (y) and theoretical (x) magnetic moments for 1s0d-shell nuclei. The theoretical values for both sides were obtained with the

- The problems of SNPA persist in this type of "conventional" effective operator methods

  - What is the expansion parameter ?
  - Are the one-body operators sufficient ?
  - Non-hermiticity due to truncations ?

  etc. ...

Back to our case !!

Suppose we are interested in nuclear phenomena characterized by an energy-momentum scale Q, say, $Q \lesssim m_\pi$ (pion mass).

Relevant degrees of freedom

ψ_N : nucleon (fields)

ϕ : pion (field)

$\Rightarrow$

We should be able to describe our low-energy phenomena in terms of ψ_N and ϕ.

$$\mathcal{L}_{QCD}(q, \bar{q}, A_\mu) \overset{\text{related}}{\longleftrightarrow} \mathcal{L}_{EFT}(\underbrace{\psi_N, \bar{\psi}_N, \phi}_{\varphi\text{ : denoted collectively}})$$

$$\int [dq][d\bar{q}][dA_\mu]\, e^{i\int d^4x\, \mathcal{L}_{QCD}(q, \bar{q}, A_\mu)}$$

$$= \int [d\varphi]\, e^{i\int d^4x\, \mathcal{L}^{eff}(\varphi)}$$

Write down all possible monomials consisting of ψ_N, $\bar{\psi}_N$ and ϕ and their derivatives that are consistent with the symmetyies of QCD (chiral symmetry, etc.)
Hermiticity preserved.

$\vec{\nabla}\phi \leftrightarrow Q$: typical momentum of the system

→ Expansion in $\frac{Q}{\Lambda}$ ($\Lambda \simeq 1\,\mathrm{GeV}$)

A small quark mass m_q
makes the mass of a Goldstone boson m_π
deviate from 0

m_π/Λ also appears as an expansion parameter

⇒ χPT (chiral perturbation theory)

if the nucleon is treated as almost static

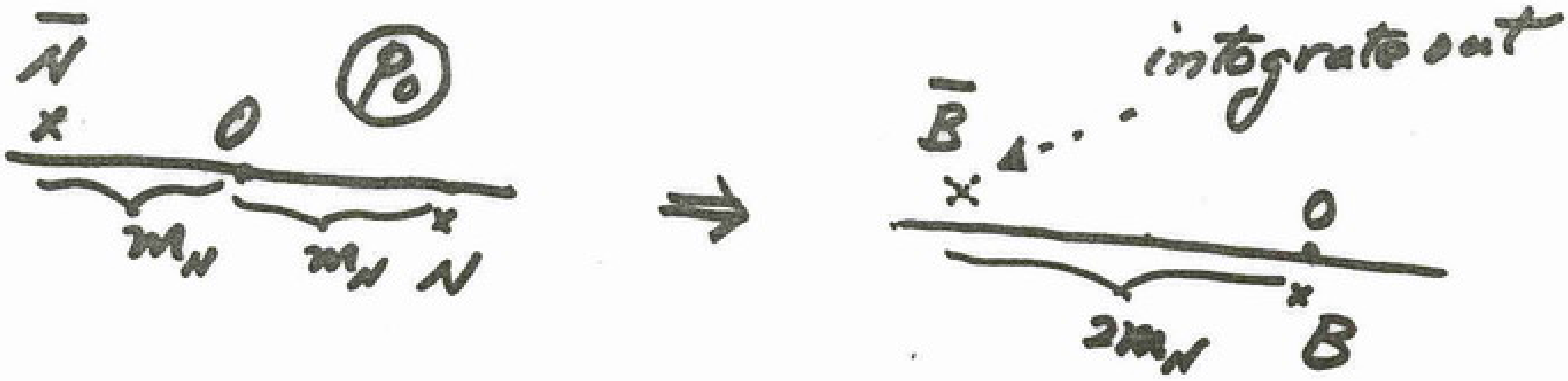
→ HBχPT (heavy baryon χPT)

HBF (Heavy Baryon Formalism) 2-12

cf Heavy Quark Formalism

$$N \longrightarrow B(x) \equiv e^{i(v\cdot x)m_N} N(x)$$

$$v \equiv (1,0,0,0)$$



$$\mathcal{L}(N,\bar{N}) \Longrightarrow \mathcal{L}_{eff}(B)$$

$$B = (P_+ + P_-)B \equiv B_+ + B_-$$

upper comp.

lower comp.

$$P_\pm \equiv \frac{1}{2}(1 \pm \not{v})$$

$$B_- \propto \frac{1}{m} B_+$$

$$\mathcal{L}_{eff}(B) \Longrightarrow \mathcal{L}_{eff,eff}(B_+) \equiv \mathcal{L}_{HBF}(B_+)$$

$\frac{\partial}{\partial t} N \sim m_N N$ large !

$\frac{\partial}{\partial t} B \sim (m_N - m_N)$ small !

⊙ The coefficient of certain terms may not be known.

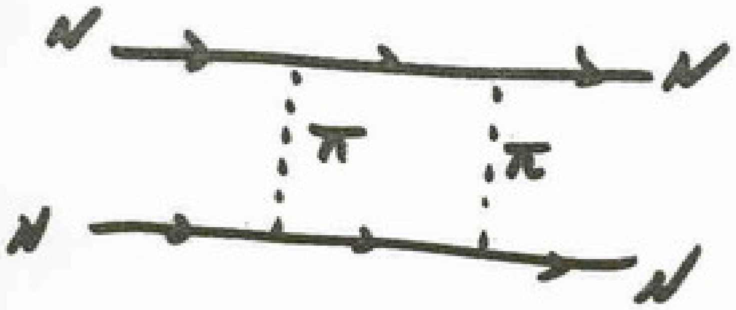
↔ Low-energy constants (LEC's) need to be fixed empirically.

χPT successfully used for the pion sector and 1-nucleon sector (πN scattering, μ-p capture, etc.)

How about A-nucleon systems ($A \geqq 2$) ?

→ Nuclear χPT à la Weinberg — cf van Kolck, thesis

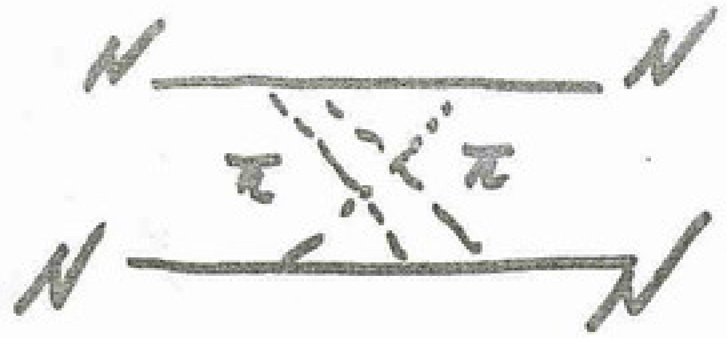
"Dangerous" intermediate states



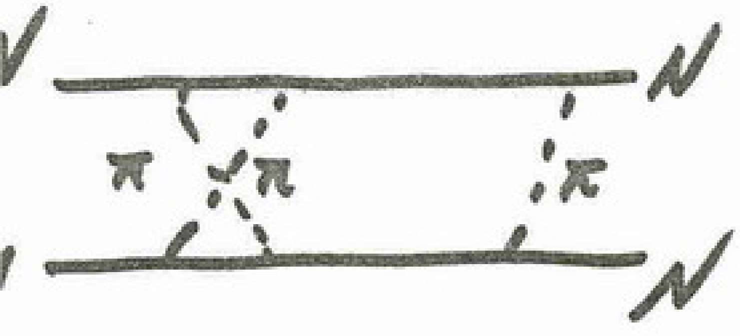
Very low excited states possible in nuclei !!

→ Perturbation breaks down

→ Reducible and irreducible diagrams. treat them separately

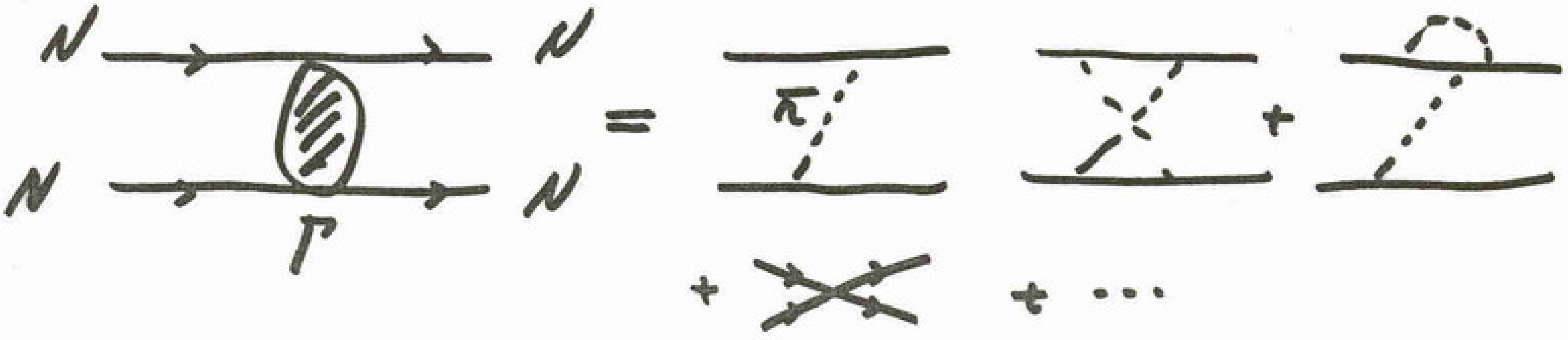


irreducible



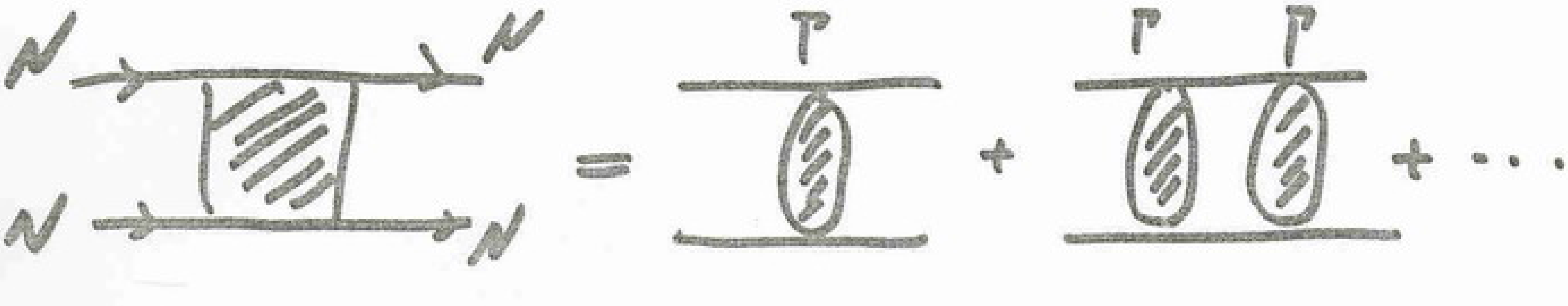
reducible

- Apply χPT to irreducible diagrams
  e.g., N–N force

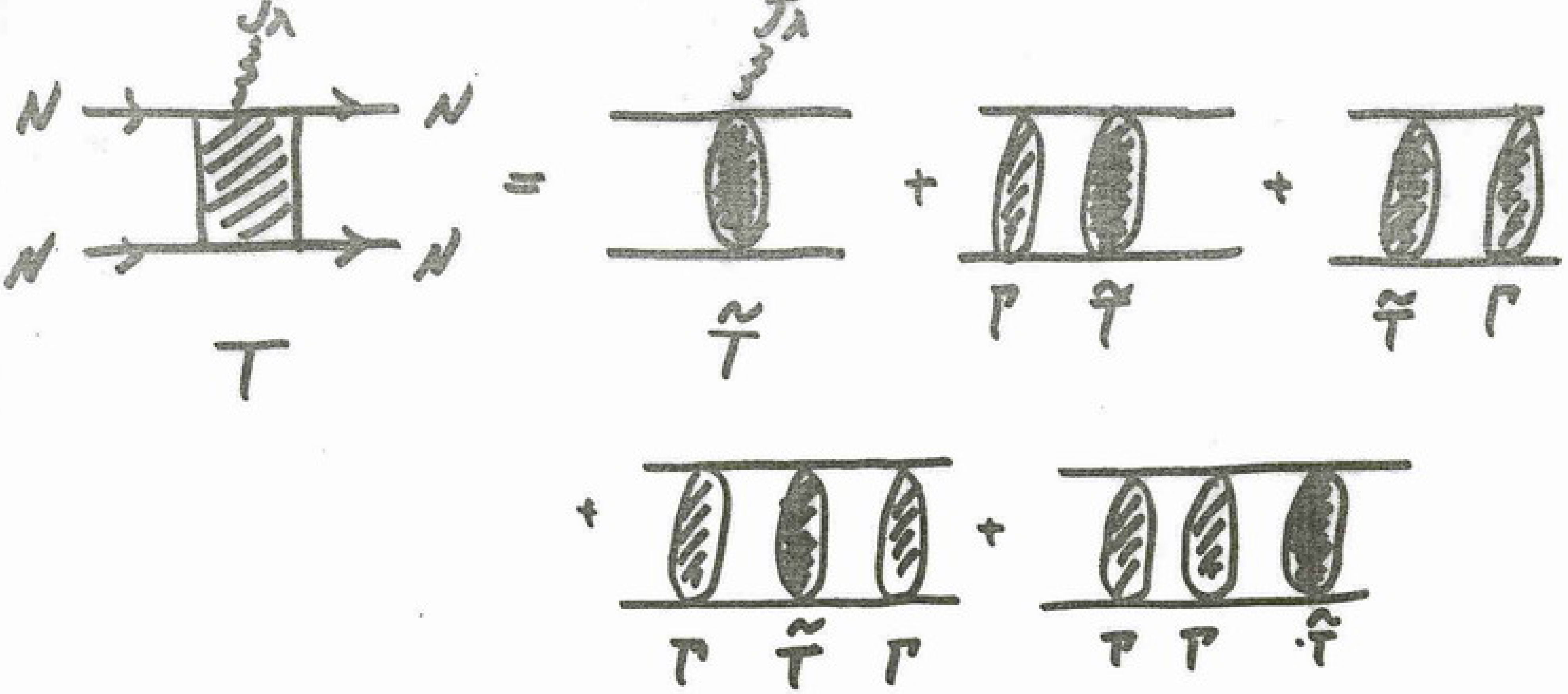


within a given order of χ expansion

Use Γ as a potential in
Lippman-Schwinger eq. or Schrödinger eq.



For electroweak probes



$\tilde{T}$: irreducible diagrams

$$T = \langle \tilde{\Psi}_f | \tilde{T} | \tilde{\Psi}_i \rangle$$

$|\tilde{\Psi}_i\rangle$, $|\tilde{\Psi}_f\rangle$: distorted waves obtained by solving

$$(H_0 + \Gamma)|\tilde{\Psi}\rangle = E|\tilde{\Psi}\rangle .$$

If carried out faithfully,

$\Rightarrow$ an "ab initio" calculation

Criticism of Weinberg counting

→ PDS (power divergence subtraction) KSW

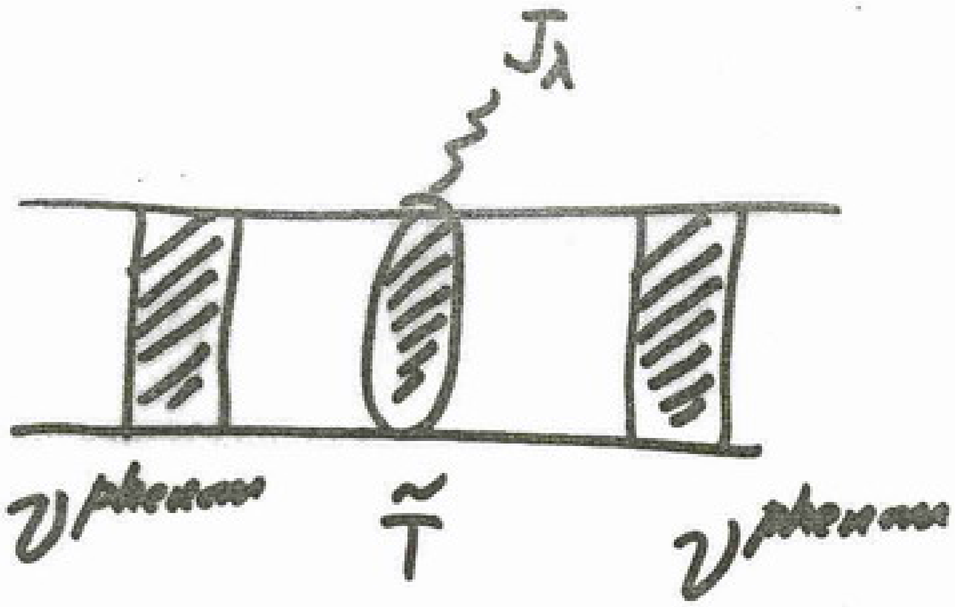
M. Lutz, hep-ph/9606301 ;
U. van Kolck, Mainz 1997 ;
D. Kaplan, M. Savage and M. Wise
Nucl. Phys. B534('98) 329;
Phys. Lett. B424('98) 390.

Careful study of the convergence properties of W and KSW countings.

S. Beane, P. Bedaque, M. Savage & U. van Kolck,
Nucl. Phys. A700, 377 (2002).

In practice,

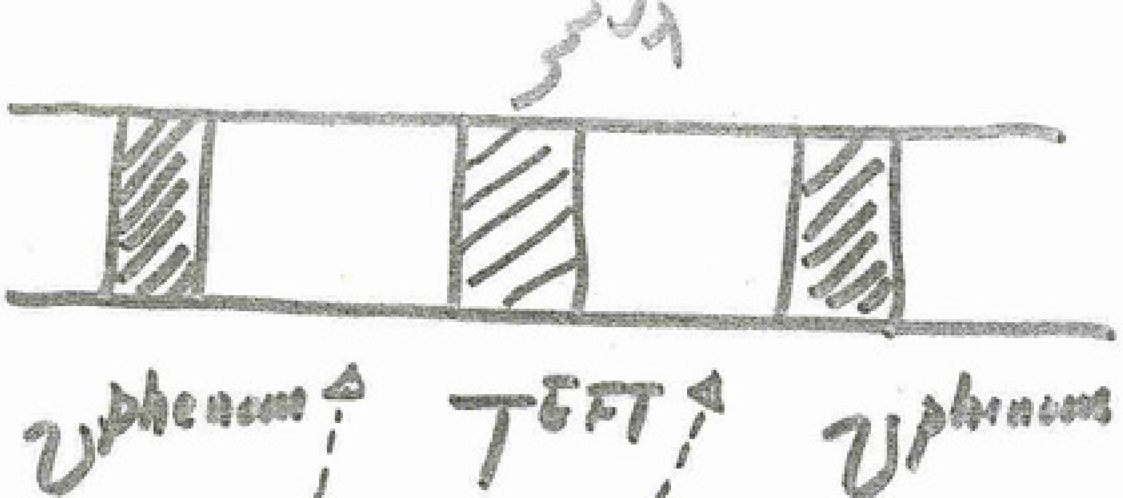
hybrid nuclear χPT



(i) $|\hat{\Psi}_i\rangle$, $|\hat{\Psi}_f\rangle$ calculated with the use of a phenomenological potential, v^{phenom}.

"Realistic potential" $\to$ reasonably reliable

(ii) $\tilde{T}$: transition operator controlled by χPT



high momentum components creep into our regime

Introduce a cut-off parameter Λ (cf. Lepage)

$$e^{-\vec{q}^{\,2}/\Lambda^2}$$

⊙ $m_\pi \ll \Lambda \lesssim \Lambda_{QCD} \lesssim m_\rho$ $\qquad \Lambda = 500\,\text{MeV} \sim 800\,\text{MeV}$

⊙ Mismatch between V^{EFT} & V^{phenom}
off-shell effects
Higher order effects ....

→ Λ dependence

→ Λ independence serves as a measure of soundness hybrid EFT

MEEFT (More effective EFT)

or EFT*

$\mathcal{J}^{EFT}$ often involves (an) unknown LEC(s).

How to handle this problem?

Can be explained better with the use of concrete examples.

We consider here

νd, pp fusion and hep fusion

3. Applications

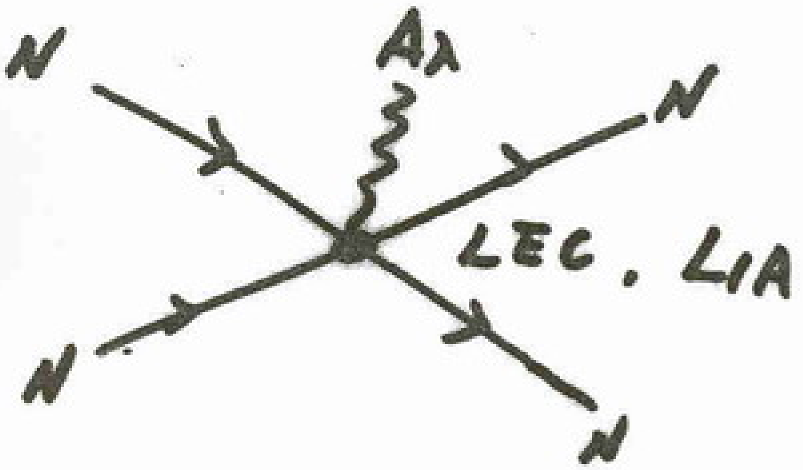
$\sigma(\nu d)$

SNPA calc.

S. Nakamura et al., Phys. Rev. C 63 ('01) 034617

EFT calc. (power divergence subtraction, PDS)
Butler, Chen and Kong, Phys. Rev. C 63 ('01) 035501

"L_{1A}" is unknown



BCK optimized L_{1A} to reproduce $\sigma(\nu d\text{: SNPA})$

→ Agreement within 1% for all the channels
and for all energies up to 20 MeV

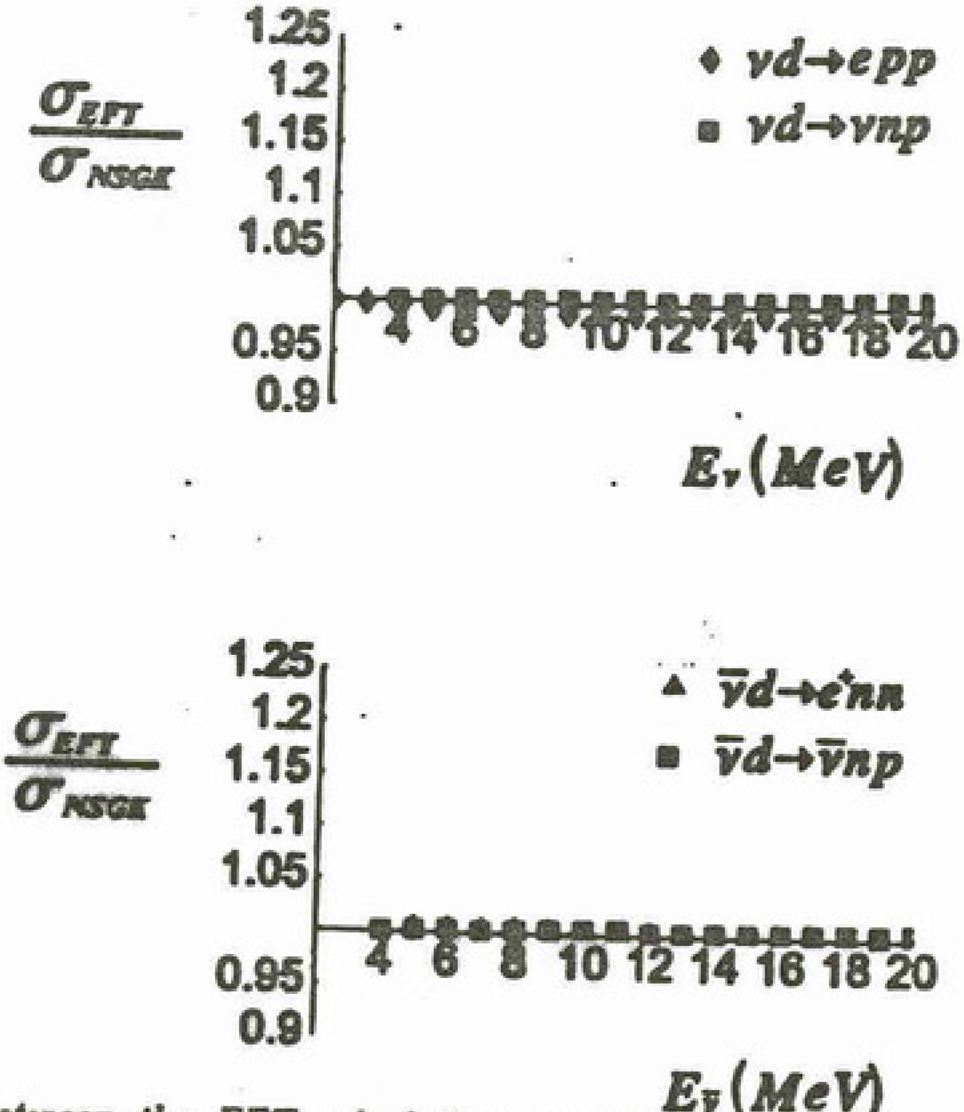


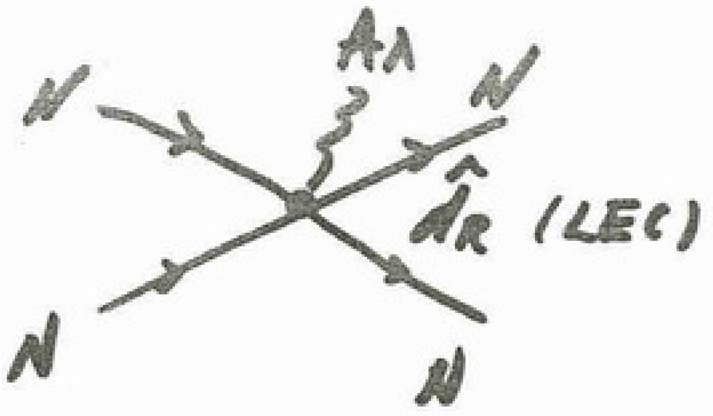
FIG. 11. *Ratios between the EFT calculation at NNLO and the potential model result of NSGK [12]. The upper graph compares the two channels of ν-d scattering, and the lower graph the two channels of ν-d scattering. Agreement is better than 1% over the whole range of energies shown, for a single value of $L_{1,A} = 5.6\ fm^3$.*

	$a^{^1S_0,pp}$ (fm)	$r_0^{^1S_0,pp}$ (fm)	$a^{^1S_0,nn}$ (fm)	$r_0^{^1S_0,nn}$ (fm)	$a^{^1S_0,np}$ (fm)	$r_0^{^1S_0,np}$ (fm)	ρ_d (fm)
This Work	-7.82	2.79	-18.5	2.80	-23.7	2.73	1.764
NSGK	-7.815	2.78	-18.5	2.83	-23.73	2.69	1.767

TABLE III. *Effective range parameters as used in our work and NSGK [12].*

EFT* or MEEFT (More effective ...)

T.-S. Park et al., nucl-th/0106025, 0107012
Phys. Rev. C 67 (2003) 055206



Based on hybrid χPT, but the LEC, $\hat{d}_R$, controlled by nuclear data.

The same vertex features in

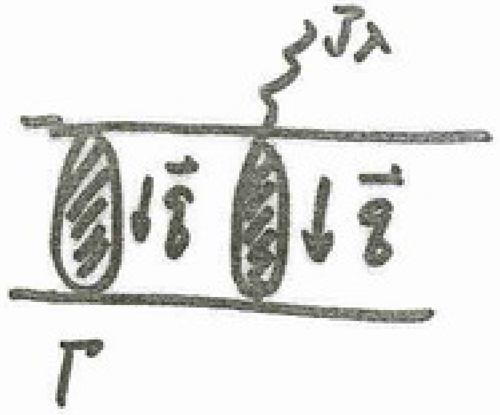
$$t \rightarrow {}^3He + e^- + \bar{\nu}_e$$

- Γ_t^β well known.
- High-precision wave functions available for A = 3

→ Parameter-free calc. of $\sigma(\nu d)$ and $\sigma(pp)$, $\sigma(Hep)$.

Cut-off independence,

a measure of the reliability of the formalism



$|\vec{q}| < \Lambda$ cut-off

2-body and 3-body systems share the same short-range physics

$\sigma(\nu d)_{EFT^*}$

Nakamura et al., Nucl. Phys. A707('02) 561
Ando et al., Phys. Lett. B555('03) 49.

$\sigma(\nu d)_{EFT^*} = \sigma(\nu d)_{SNPA}$

within ~1%

Λ-dependence of $\sigma(\nu d)_{EFT^*}$ ~ 0.1%

for Λ = 500 MeV ~ 800 MeV

Γ^{β}_{t} ~ 0.5% uncertainty

The same approach applied to pp

$$p + p \to e^+ + d + \nu_e$$

Park et al., Phys. Rev. C 67 ('03) 055206

Astrophysical S-factor

$$S_{pp}(0) = 3.94 \times (1 \pm 0.004) \times 10^{-25}\ \text{MeV} \cdot \text{b}$$

improvement in accuracy by a factor of ~ 10

hep and hen

$$^3He + p \longrightarrow {}^4He + e^+ + \nu_e$$

$$\underline{E_\nu^{max} = 18.8\,MeV} \;!!$$

But ϕ_ν(hep) is tiny.

→ diagnostic purposes

Anomaly (?) seen in the $\phi_\nu(^8B)$ spectrum at Super-K ?

see 3-4'

$$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e \ (99.75\%) \qquad p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e \ (0.25\%)$$

$$\downarrow$$

$${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$$

$$\downarrow$$

$${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow \alpha + 2p \ (86\%) \qquad {}^3\mathrm{He} + \alpha \rightarrow {}^7\mathrm{Be} + \gamma \ (14\%) \qquad {}^3\mathrm{He} + p \rightarrow \alpha + e^+ + \nu_e$$

$$\downarrow$$

$${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e \ (99.85\%) \qquad {}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma \ (0.15\%)$$

$${}^7\mathrm{Li} + p \rightarrow 2\alpha \qquad {}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$$

$${}^8\mathrm{Be}^* \rightarrow 2\alpha$$

Figure 1: Solar thermonuclear reactions in the *pp*-chain and their branching ratios. The *Hep* branching ratio is of the order of 0.01% or less.

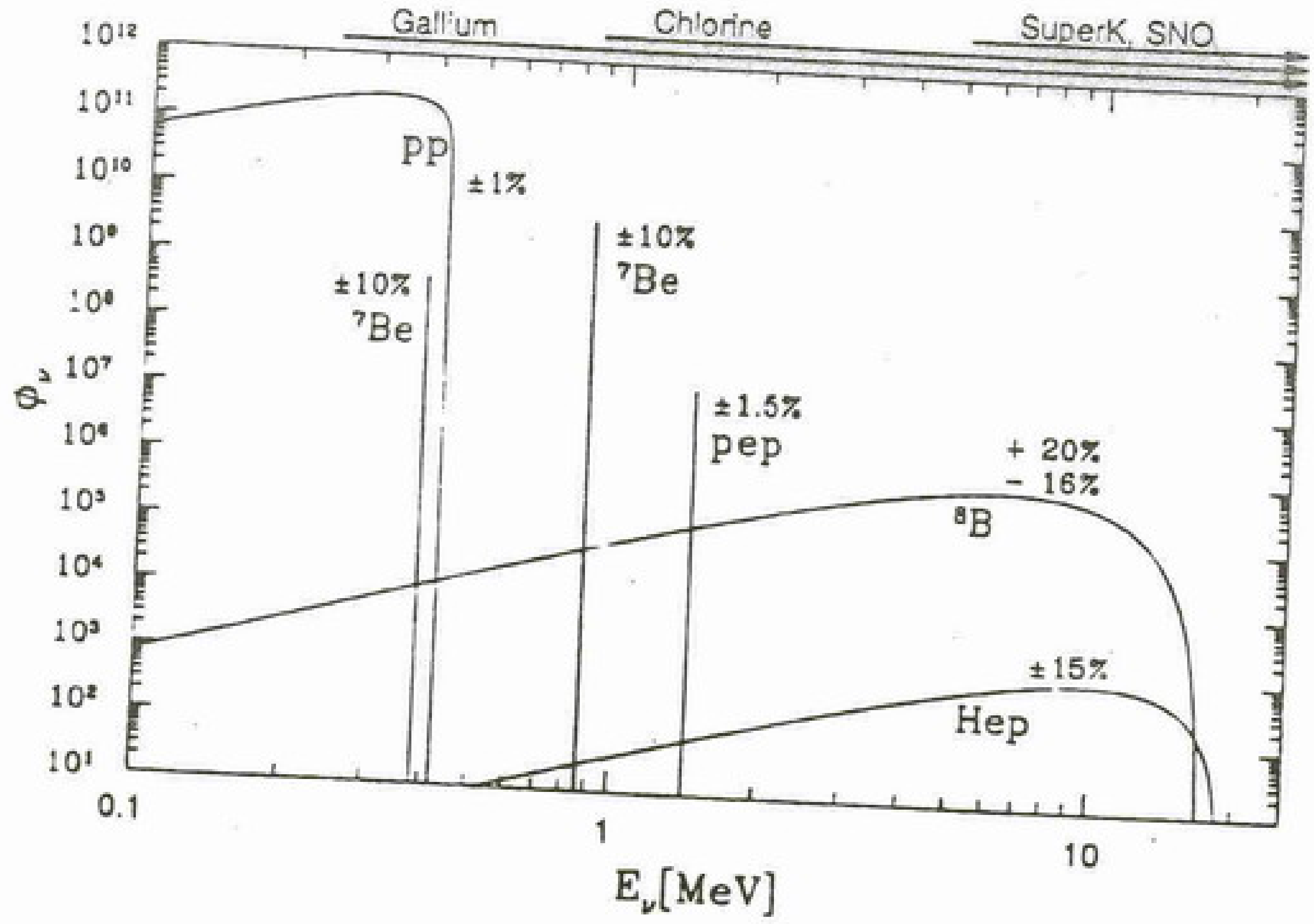
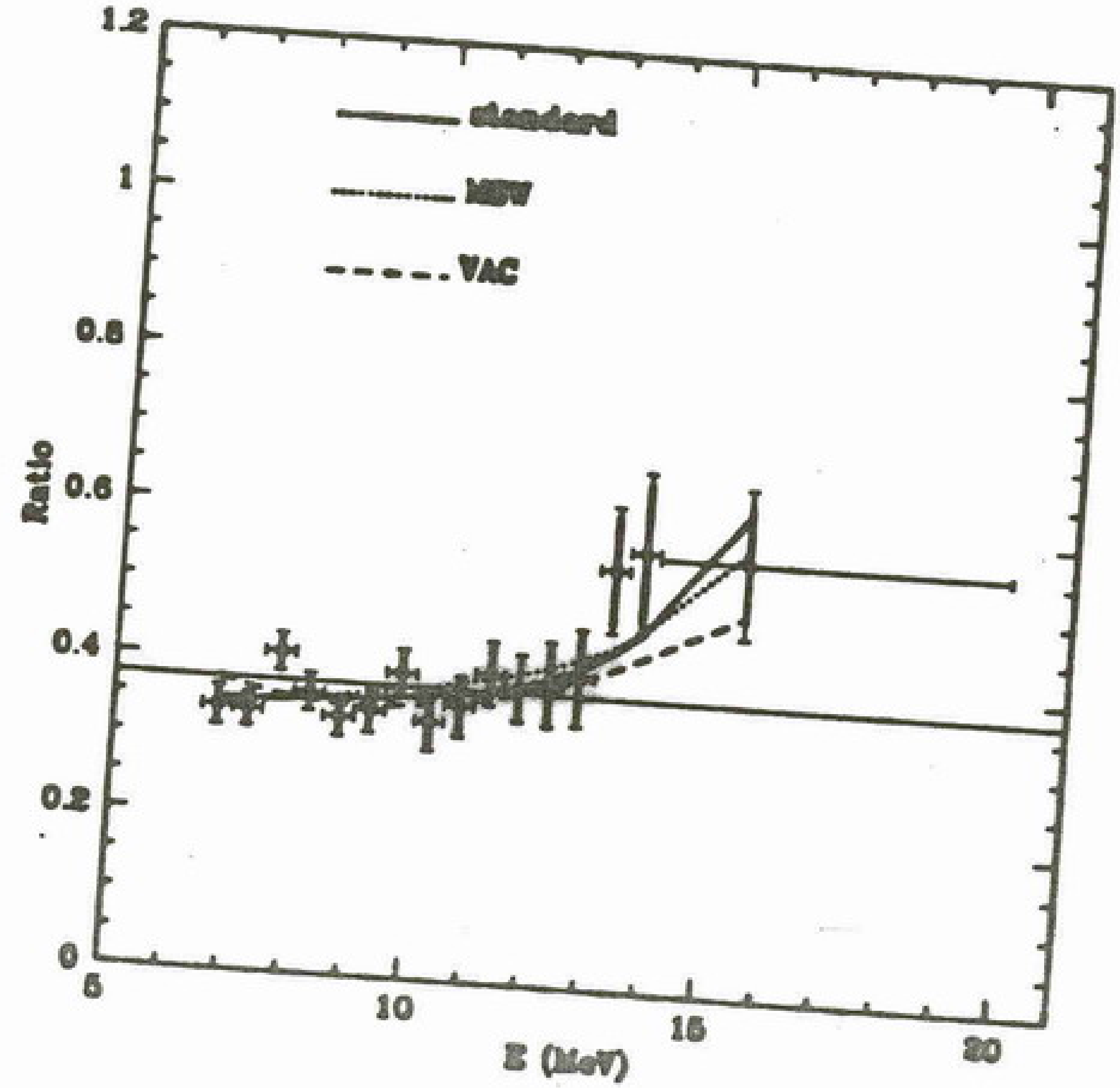


Figure 2: Solar neutrino spectrum ϕ_ν vs the neutrino energy E_ν. The neutrino fluxes from continuum sources are given in units of $cm^{-2}s^{-1}MeV^{-1}$, and the line fluxes in units of $cm^{-2}s^{-1}$. The arrows at the top indicate the ranges of E_ν covered by the experiments mentioned in the text.

3-10



Bahcall and Krastev ('98)

A new analysis of SNO data in progress (E. Beier)

3-11

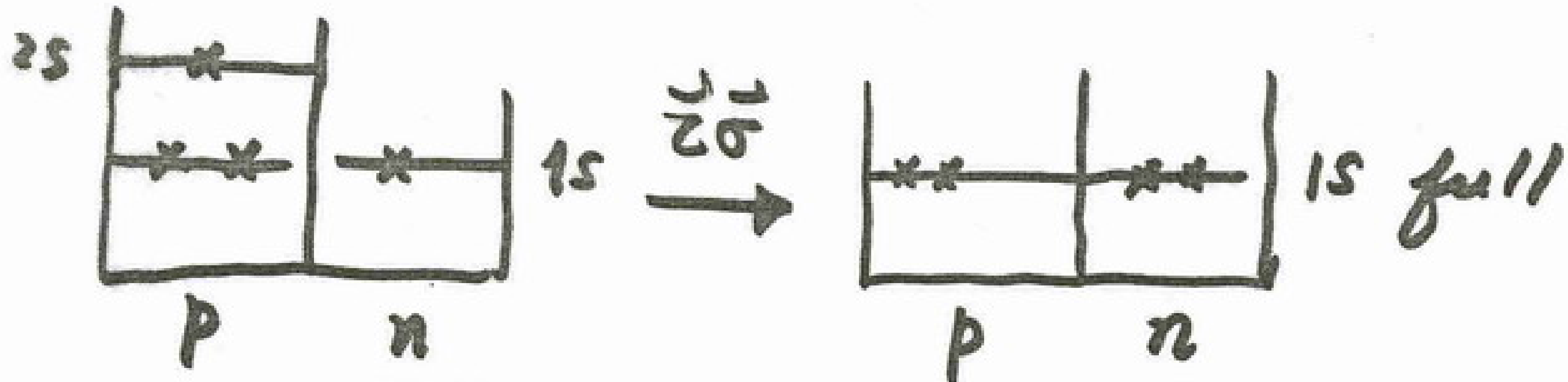
Table 1
Calculated values of S_0(hep). The table lists all the published values with which we are familiar of the low energy cross section factor for the hep reaction shown in Eq. 1.

S_0(hep) (10^{-20} kev b)	Physics	Year	Reference
630	single particle	1952	[10] Salpeter
3.7	forbidden; $M_\beta \propto M_\gamma$	1967	[11] Werntz-Brennan
8.1	better wave function	1973	[12]
4-25	D-states + meson exchange	1983	[13] Tegner-Bargholtz
15.3 ± 4.7	measured ${}^3He(n,\gamma){}^4He$	1989	[14] Wolfs et al.
57	measured ${}^3He(n,\gamma){}^4He$	1991	[15] Wervelman et al.
	shell model		
1.3	destructive interference, detailed wavefunctions	1991	[16] Carlson
1.4-3.1	Δ-isobar current	1992	[17] Schiavilla et al

Why so unstable ?

1) Pauli principle

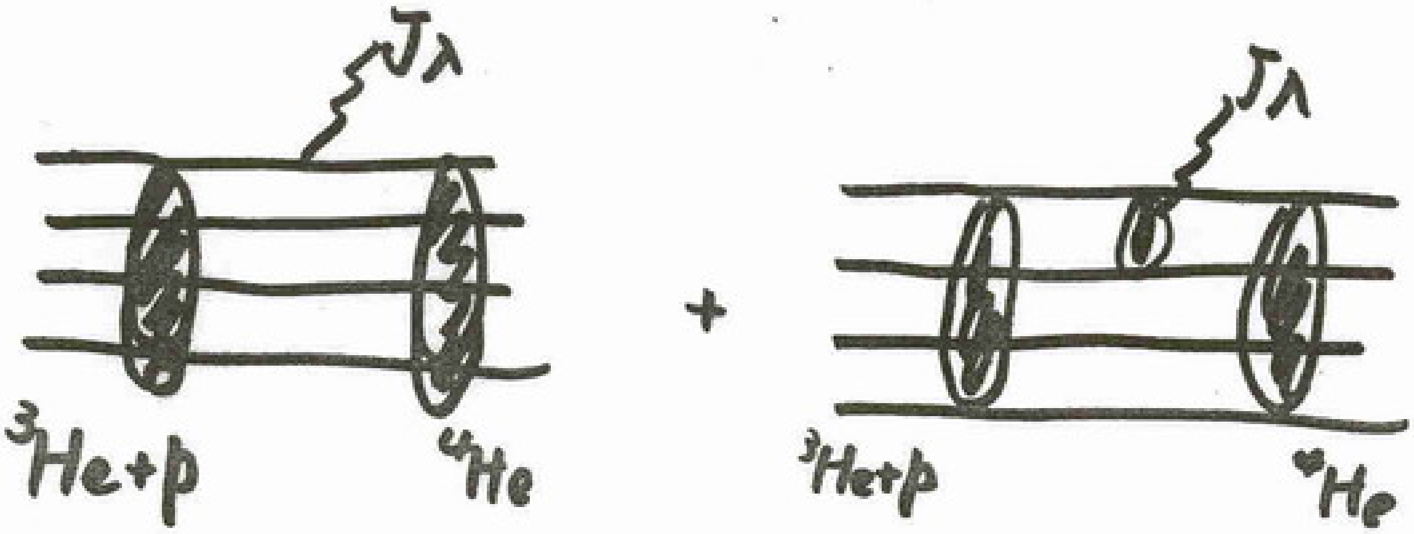
$$^{3}_{2}He_1 + p \longrightarrow {}^{4}_{2}He_2 + e^- + \nu_e$$



[31] $\longrightarrow$ [4]

p (2s) $\longrightarrow$ n(1s) highly suppressed

2)



1-body + 2-body (Exchange currents)

cancel each other

⇒ 2-body contributions need to be calculated with very high precisin

⇒ EFT*

3-13

T.-S. Park et al.,

Phys. Rev. C 67, 055206 (2003)

4-body w.f. provided by

Schiavilla and the Pisa group

$$S_{hep}(0) = (8.6 \pm 1.3) \times 10^{-2} \text{ keV-b}$$

~15% error

⇒

Φ_ν(hep) can now be predicted with a finite (~15%) error.

cf. Bahcall's challenge

3-14 20

Possibility to check the reliability
of the whole argument
using data ?

"hen"

$^3He + n \longrightarrow {}^4He + \gamma$

Same type of suppression of 1-body
contribution

→ dominance of EXC currents

→ stringent test of MEEFT

Y.-H. Song & T.-S. Park, nucl-th/0311055

$\sigma = (60.1 \pm 3.2 \pm 1.0)\ \mu b$

$\sigma^{exp} = (54 \pm 6)\ \mu b$ or $\sigma^{exp} = (55 \pm 3)\ \mu b$

4. Further Examination of MEEFT-EFT*

$$\mathcal{T}^{EFT^*} \sim \langle \Psi^{SNPA} | \mathcal{O}^{EFT} | \Psi_i^{SNPA} \rangle$$

possible mismatch ?

◉ Constuction of V_{ij}^{EFT} realistic enough, and its application to electroweak transitions yet to be done.

cf. e.g., Epelbaum, Glöckle, U-G. Meißner et al.

- V_{ij}^{EFT} derived by Epelbaum et al., uses a cut-off parameter Λ, which is consistent with the value used by Park et al.

→ We concentrate here on discussing issues within MEEFT.

Big help from Stony Brook

cf. Bogner, Kuo & Schwenk,

Phys. Rep. 386 ('03) 1.

V^{phenom} is <u>not</u> unique for short distance

$\longleftrightarrow$ off-shell ambiguity

model dependence

$$V^{phenom} \xrightarrow{\text{eliminate } k \gtrsim 2.1\,\mathrm{fm}^{-1}} V_{low\text{-}k}$$

<u>$V_{low\text{-}k}$ is unique !!</u>

In EFT*, there is a cut-off attached to Γ.

$\rightarrow$ similar to the use of $V_{low\text{-}k}$

off-shell ambiguity expected to be reduced

"The uniqueness" of $V_{low\text{-}k}$

$\Leftrightarrow$ Λ-independence of HOT

half-off-shell T-matrix

$\Omega = V^{-1}T$: wave operator

$|\Psi^{distorted}\rangle = \Omega|\Psi_0\rangle$

Criticism of "$V_{low\text{-}k}$" à la Bogner et al.

- ~~of~~ HOT : unphysical

  Why do we have to impose Λ-independence on HOT ?

- Related problem

  Are wave functions a physical observable ?

"Integrating out" high-energy physics in nuclear physics

$$H = H_0 + V$$

$$H|\Psi\rangle = E|\Psi\rangle$$

$$\begin{cases} P = \sum_{i=1}^{d} |i\rangle\langle i| & : \text{"model" space : low-energy regime} \\ Q = \sum_{i=d+1}^{\infty} |i\rangle\langle i| \end{cases}$$

$$\begin{pmatrix} PHP & PHQ \\ QHP & QHQ \end{pmatrix} \begin{pmatrix} P|\Psi\rangle \\ Q|\Psi\rangle \end{pmatrix} = E \begin{pmatrix} P|\Psi\rangle \\ Q|\Psi\rangle \end{pmatrix}$$

Solve for $Q|\Psi\rangle$ and insert it in the equation controlling $P|\Psi\rangle$

Bloch-Horowitz eq

$$H_{\text{eff}}^{B\text{-}H}(E) = H + H \frac{1}{E - QHQ} H$$

Energy-dependent !!!

Avoid energy dependence

Lee-Suzuki method
Phys. Lett. B91('80) 173

Similarity transformation Θ

$$\Theta^{-1} H \Theta \equiv \mathcal{H}^{LS}_{low\,k} = \begin{pmatrix} PHP & PHQ \\ 0 & QHQ \end{pmatrix}$$

block-triangular matrix

$$\Theta = 1 + \omega = \begin{pmatrix} 1 & 0 \\ \omega & 1 \end{pmatrix}$$

$$\omega \equiv Q\omega P$$

Bogner et al's $V_{low\text{-}k}$ corresponds to $\mathcal{H}^{LS}_{low\,k}$

→ No E-dependence

but

Non-hermitian

Unitary transformation method

S. Okubo, Prog. Theor. Phys. 12 (1954) 603.

Epelbaum et al.,
a recent reference
S. Fujii et al., PRC 70, 024003 (2004)

$$H\Psi = E\Psi$$

$$H' = U^{\dagger} H U, \quad \Psi' = U^{\dagger}\Psi$$

choose U in such a manner that

$$QH'P = 0$$

Energy-independent and Hermitian H'

$$U = \begin{pmatrix} P(1+\omega^{\dagger}\omega)^{-1/2}P & -P\omega^{\dagger}(1+\omega\omega^{\dagger})^{-1/2}Q \\ Q\omega(1+\omega^{\dagger}\omega)^{-1}P & Q(1+\omega\omega^{\dagger})^{-1/2}Q \end{pmatrix}$$

$$V^{low\text{-}k} = P V'_{bare} P$$

This corresponds to imposing the Λ-independence condition only on on-shell T-matrix (phase shifts, d-binding energy).

Bogner et al. report

$V_{low\text{-}k}^{BLS} \cong V_{low\text{-}k}^{Hermitian}$ numerically

Fujii et al report,
with $\Lambda \cong 2\,fm^{-1}$ (used by the Stony Brook group),
$V_{low\text{-}k}^{LS}$ overbinds ^3H and ^4He
significantly. (by ~3MeV)

($\Lambda \cong 5\,fm^{-1}$ needed to avoid this difficulty.)

Effects for J to be seen.

Is the Λ appearing in the derivation of $V_{low\text{-}k}$ something extraneous to Λ of EFT ?

- In MEEFT, Λ is practically identified with ~~Λ_{eff}~~ Λ_{EFT}.

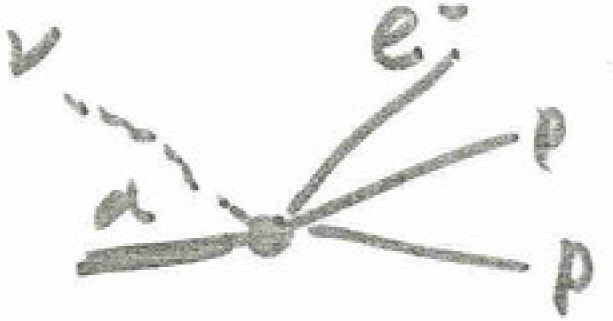
  $\Leftrightarrow$ Introduction of Λ does not ~~[illegible]~~ induce addition transition operators .

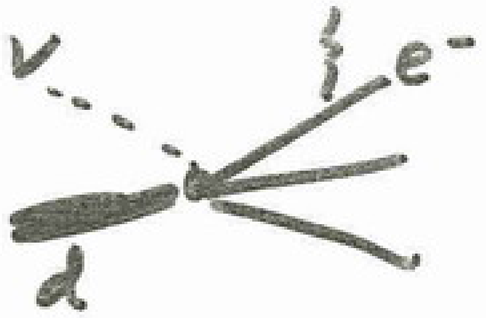
  $$\mathcal{O} \to \mathcal{O}' = U^{\dagger} \mathcal{O} U$$

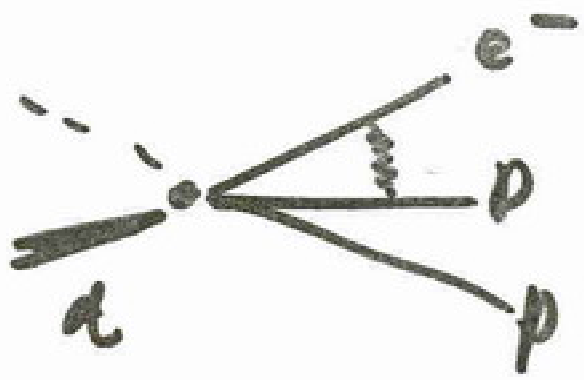
- Epelbaum et al. propose to consider possible differences between $\mathcal{O}$ and $\mathcal{O}'$

It is hoped that the use of "renormalization" by fitting to observables reduces the significance of this controversy.

Radiative corrections





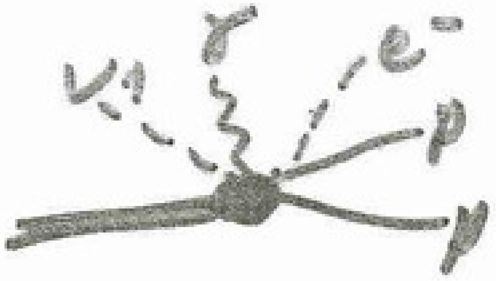


$\sigma(\nu d)$ may be affected up to $2 \sim 3$ %

Similar effects expected for $pp \rightarrow d + e^+ + \nu_e$, etc.

- "Conventional approach"

Hadronic structure effects



$$\bar{u}[f_V(q^2)\gamma_\mu + f_A(q^2)\gamma_\mu\gamma_5 + \cdots]u$$

$$q_\mu \to q_\mu - eA_\mu$$

model dependence
not well controlled

- Quark-lepton approach

At the current quark level

everything is well controlled

$\Rightarrow$

must be embedded in
hadronic states

model dependence !!

Application of EFT

S. Ando et al.,
Phys. Lett. B 595 (2004) 250.

"Warm-up" problem

(In fact, important on its own right.
CKM unitarity check.

SNS experiments)

$$1 \to \left(1+\frac{\alpha}{2\pi}e_V^R\right)$$

$$g_A \to \tilde{g}_A\left[1+\frac{\alpha}{4\pi}(e_A^R-e_V^R)\right]$$

two unknown LEC's,
e_V^R & e_A^R

→ Application to νd, pp. etc.

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H. Fearing	(TRIUMF)
Y. H. Song	(Seoul)

My deep thanks to all of them.

- The Current status of MEEFT-EFT's has been reviewed

- Its strengths and the formal problems involved in it discussed

- The practical utility of MEEFT is hoped to survive these problems.

- Further studies needed