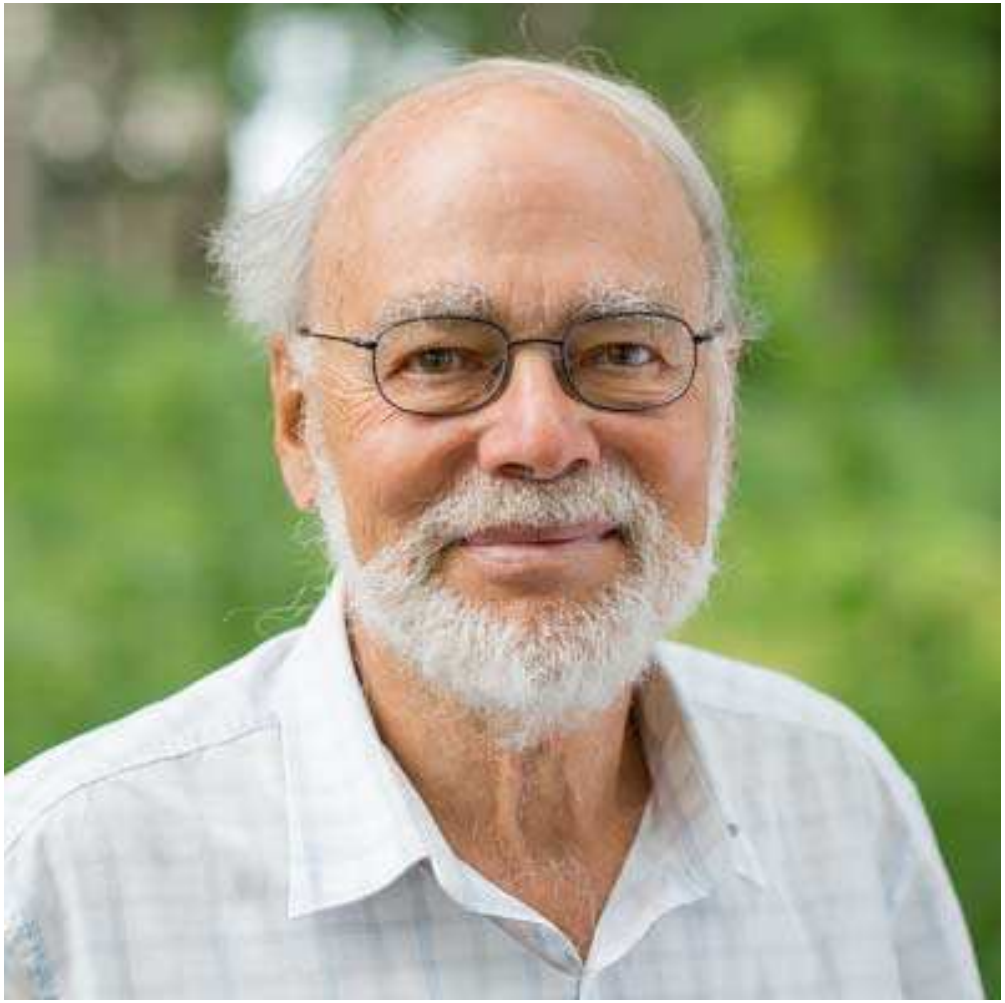
Steven C. Pieper
Nuclear Physicist at the Computational Frontier



Robert Wiringa, Physics Division, Argonne National Laboratory

Work supported by U.S. Department of Energy, Office of Nuclear Physics

Steve's Vita

- Steven Charles Pieper born April 25, 1943, in Oceanside, New York
- Attended primary and secondary schools in Oceanside
- 1965 B.S. with Honors in Physics, University of Rochester
- 1970 Ph.D. in Physics, University of Illinois
- 1970-1972 Research Associate, Case Western Reserve University
- 1972-1974 Research Associate, Argonne National Laboratory
- 1974-1978 Assistant Physicist, Argonne National Laboratory
- 1978-1995 Physicist, Argonne National Laboratory
- 1987-1990 Chief, Physics Division Theory Group,
- 1996-2011 Senior Physicist, Argonne National Laboratory
- 2011-2015 Senior Physicist - Special Term Appointee, Argonne National Laboratory
- 2016-2018 Senior Physicist Emeritus, Argonne National Laboratory
- Passed away October 8, 2018

Honors

- 1996 Fellow, American Physical Society
- 2000 University of Chicago Medal for Distinguished Performance at Argonne
- 2010 American Physical Society Tom W. Bonner Prize in Nuclear Physics

STEVE'S WORK

Steve authored or co-authored $\sim$ 100 papers in refereed scientific journals from 1965-2019.

Those papers have garnered more than 7,000 citations to date.

He contributed significantly to the development of the Speakeasy computer language

He was co-author of the widely used PTOLEMY code for direct heavy-ion reactions.

He contributed to multiple Argonne technical manuals dealing with computation issues.

He supervised $\sim$ 12 postdocs and helped with many other students and postdocs.

He also advised and helped colleagues at Argonne and around the world in many crucial ways.

How do I submit a job on this new machine?

Why doesn’t my code run?

How do I find this bug?

What is the Speakeasy word for ...?

STEVE'S PUBLICATIONS

Steve's publications can be divided (arbitrarily) into six categories.

1. First Works (1965-1969)
   1 undergraduate paper from Rochester and 2 early papers at Illinois

2. Doctoral and Postdoctoral Work (1970-1974)
   12 papers on three-body scattering from Illinois, Case Western Reserve, and Argonne

3. Direct Reaction Studies (1976-1983)
   Development of PTOLEMY code and manual; 11 papers including applications to reactions of carbon, oxygen. calcium, and lead isotopes; 4 additional papers thereafter

4. Ab initio Many-Body Theory with Quantum Monte Carlo (1983-2019)
   - Variational Monte Carlo for liquid ^{3,4}He droplets (1983-1989)
     6 papers using realistic atom-atom potentials for drops with 728 bosons or 240 fermions
   - Nuclear correlations, transparency and response (1987-2002)
     9 papers on structure functions, $(e, e'p)$, nucleon propagation, isovector spin response
   - Cluster variational Monte Carlo for ^{16}O, ^{40}Ca (1990-2017)
     6 papers using realistic two- and three-nucleon potentials, plus ^{15}N and $^{17}_{\Lambda}$O

- Neutron drops and matter (1996-2013)
  5 papers including destruction of the tetraneutron
- Green's function Monte Carlo for structure in $A \leq 12$ nuclei (1997-2015)
  18 papers on energies, excitation spectra, densities, $n - \alpha$ scattering, etc.
  using Argonne v18 two-nucleon and Urbana/Illinois three-nucleon forces
- Momentum distributions and spectroscopic overlaps (2005-2014)
  4 theoretical papers + 4 experimental applications to light rare-isotope reactions
- Nuclear electroweak transitions (2007-2018)
  5 theory + 2 experimental papers on $M1$, $E2$, F, GT transitions, including MEC
- Electroweak response of ^{4}He and ^{12}C (2013-2018)
  5 papers on (e, e') and (ν, ν') cross sections
- Nuclear structure with chiral potentials (2016-2019)
  4 papers evaluating modern Norfolk chiral potentials (instead of that old AV18)

5. Computation (1976-2017)
   3 papers on parallel computation + 6 manuals for MORTRAN, Speakeasy III
   (at various levels), and the IBM SP1 User's Guide

6. Always helping experimentalists (1972-2019)
   2 atomic physics papers and 1 (last) paper on $^{16}\mathrm{O}(\gamma, \alpha)^{12}\mathrm{C}$ + running shifts

First Works & Graduate Work

Steve's first paper came from his undergraduate days at Rochester:

Bandpass Filters for the Ultraviolet

P. W. Baumeister, V. R. Coslich, and S. C. Pieper, Applied Optics **4**, 911 (1965)

That first paper is always special!!

At Urbana from 1965-1970, he first co-authored a couple of papers on Polynomial Bases (heavy on group theory and formulas) before he found a thesis advisor, Jon Wright, and a thesis topic:

CALCULATIONS OF THREE-BODY SCATTERING AMPLITUDES

STEVEN CHARLES PIEPER (1970)

This was coincident with three papers completed at Illinois, all published in Physical Review D (perhaps because Jon Wright was more a particle physicist than a nuclear physicist) starting with:

Variational Principle for Three-Particle Scattering

S. C. Pieper, L. Schlessinger, and Jon Wright, Phys. Rev. D **1**, 1674 (1970)

Steve moved to Case Western Reserve in Cleveland, Ohio, for his first postdoctoral appointment, to work with Ken Kowalski. He continued with three-body scattering problems, with seven papers making ever more sophisticated models and specializing to N-d scattering:

Multiple-Scattering Expansions for Moderate-Energy Particle-Deuteron Scattering

K. L. Kowalski and S. C. Pieper, Phys. Rev. C **4**, 74 (1971)

Calculation of N-d scattering with S-, P-, and D-Wave Forces

S. C. Pieper, Phys. Rev. Lett. **27**, 1738 (1971) First single-author paper and first PRL!

⋮

Perturbative Calculation of Spin Observables in Nucleon-Deuteron Elastic Scattering.

II. Inclusion of a Tensor Force

S. C. Pieper, Phys. Rev. C **6**, 1157 (1972)

In 1972 Steve came to Argonne for his second postdoc, where he finished up his N-d work with two more papers under the Argonne byline:

Perturbative Calculation of Spin Observables in Nucleon-Deuteron Elastic Scattering.

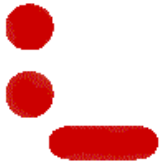
III. Comparison with an Exact Calculation

S. C. Pieper, Phys. Rev. C **8**, 1702 (1973)

Separable potentials for the nucleon-nucleon $^3S_1 - ^3D_1$ *channel*

Steven C. Pieper, Phys. Rev. C **9**, 883 (1974) Steven C. hereafter (not just S.C.)

SPEAKEASY

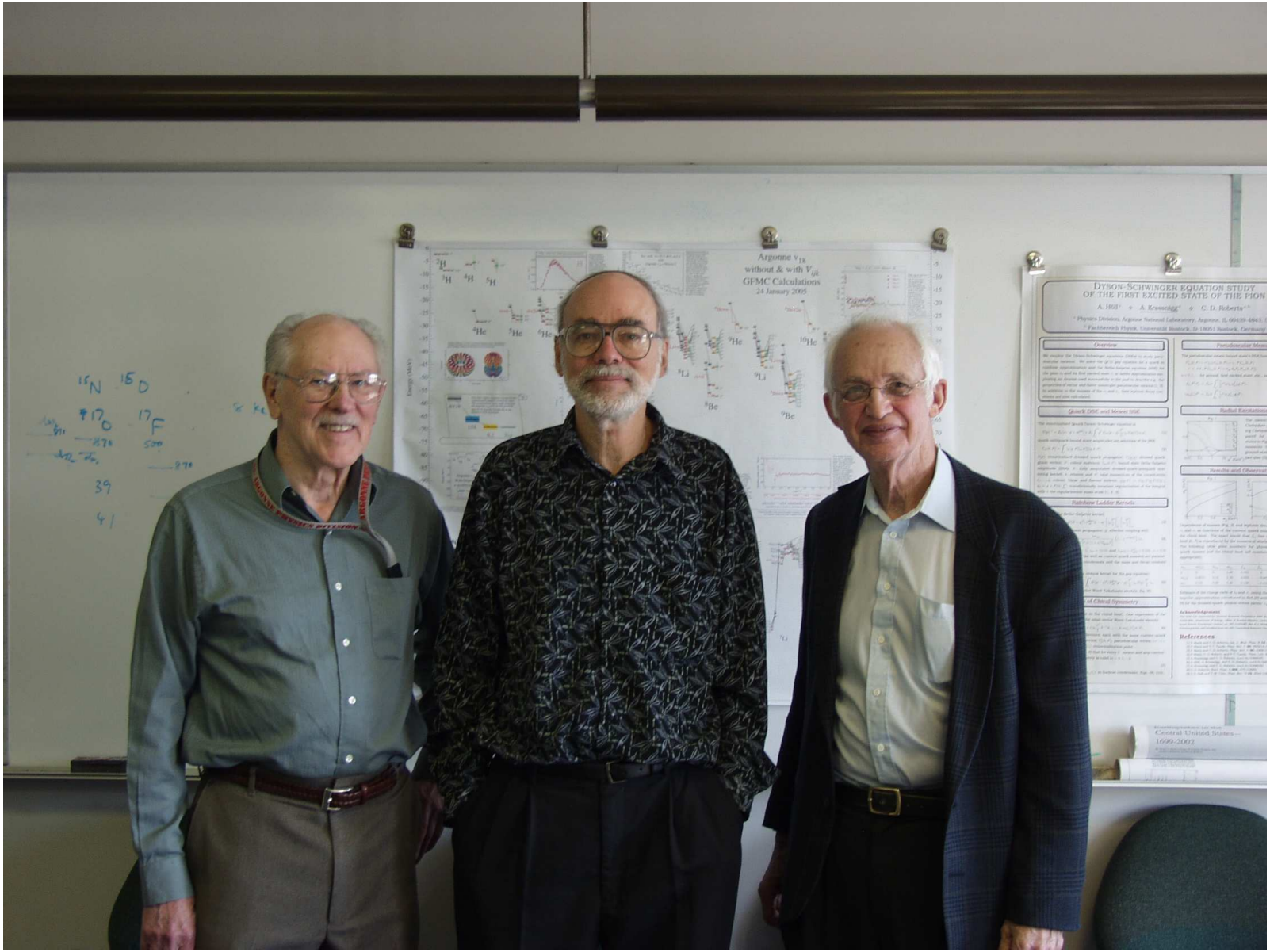


At Argonne, Steve quickly became involved with the Speakeasy computer language project .

To quote from Wikipedia:

“Speakeasy is a numerical computing interactive environment also featuring an interpreted programming language. It was initially developed for internal use at the Physics Division of Argonne National Laboratory by the theoretical physicist Stanley Cohen. He eventually (1978) founded Speakeasy Computing Corporation to make the program available commercially.

“It was initially conceived to work on mainframes, and was subsequently ported to new platforms (minicomputers, personal computers) as they became available. The porting of the same code on different platforms was made easier by using Mortran metalanguage macros to face systems dependencies and compilers deficiencies and differences.”



Dieter Kurath – Steve Pieper – Stan Cohen

11 November 2005

Speakeasy features many built-in functions invoked by keywords, such as CLEBSCH, COULOMB, GEIGEN, INTEGRAL, INTERPOLATE, NINEJ, etc., useful to physicists. It also has many built-in functions that economists (among others) find useful. Physics Division financial accounting was managed under Speakeasy well into the 2000s.

Speakeasy has the facility for users to add their own subroutines to the language as ”linkules.”. Steve helped me link a neutron star program (integrating the Tolman-Oppenheimer-Volkov equations for neutron star structue) written in Fortran, creating my own keyword NEUTSTAR.

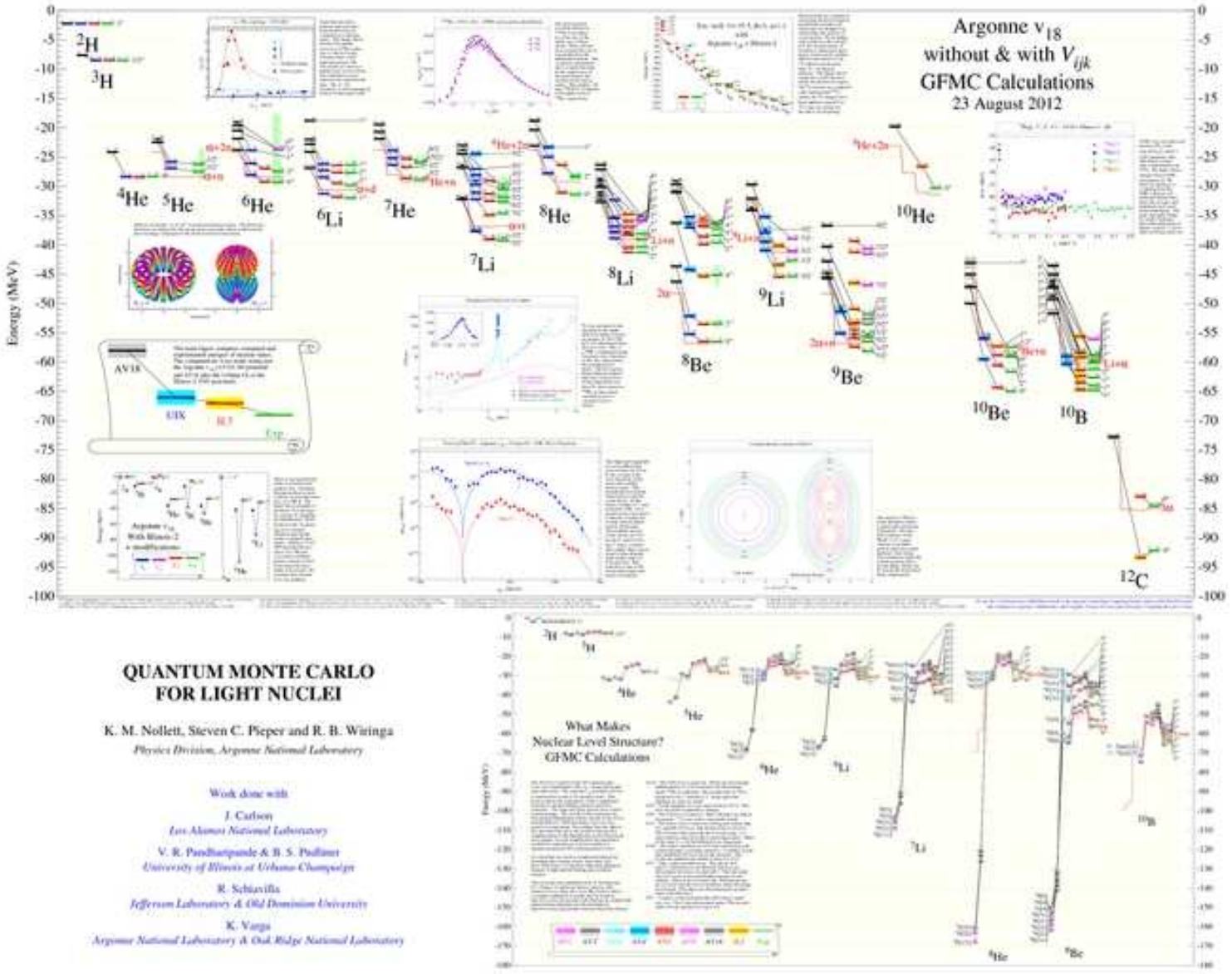
I was invited to present it at the 17th Annual Speakeasy Conference in 1989 along with speakers from IBM and Banca d’Italia, to an audience from the Federal Reserve Board, the First National Bank of Chicago, Amdahl, DEC, Sun, COMSAT, Educational Testing Service, etc. – a lot of fun!

Speakeasy also has a very flexible graphics package, and Steve was the consummate master. Virtually all the graphs in our later papers were done from Speakeasy.

Steve was a co-author with Stan of multiple manuals up to 1980:

Speakez Manual *The Speakeasy III Reference Manual* *VM/CMS version*

Stanley Cohen and Steven C. Pieper Ab homine caveat computator



A Speakeasy graphic by Steve

PTOLEMY

PTOLEMY *A Program for Heavy-Ion Direct-reaction Calculations*

M. H. Macfarlane and Steven C. Pieper ANL-76-11 (1976)

(in collaboration with D. H. Gloeckner)

Abstract

PTOLEMY is a program for the computation of nuclear elastic and direct-reaction cross sections. It carries out optical-model fits to elastic-scattering data at one or more energies and for one or more combinations of projectile and target, collective model DWBA calculations of excitation processes, and finite-range DWBA calculations of nucleon-transfer reactions. It is fast and does not require large amounts of memory. The input is exceptionally flexible and easy to use. This report outlines the types of calculations that PTOLEMY can carry out, summarizes the formulas used, and gives a detailed description of its input.

PTOLEMY has many things in common with Speakeasy, including keywords and that flexible, syntax-tolerant method of input, with extensive error-checking.

Testimonials

John Schiffer says Steve wrote PTOLEMY (with Macfarlane) early in his career. It was originally intended and used for heavy-ion reactions, (many more partial waves) to supplement the plethora of light-ion codes at the time time (JULIE, DWUCK, etc.), It made highly efficient use of the computing power of the day. Steve was well aware of the dangers of others "improving" the code, and introducing mistakes, so he controlled it strictly. PTOLEMY was highly user friendly and self explanatory program and it quickly became the reaction code of choice by many of us. I think it is still the best around, and has many hidden features that can be extremely useful. I hope that PTOLEMY remains around in the FRIB age.

Ben Kay recommends PTOLEMY for all your reaction-code needs! From light-ion transfer to heavy ion multi-nucleon transfer, from pair transfer to inelastic scattering, from ANCs to fully-integrated GFMC and AV18 overlaps, PTOLEMY has it all .... except a useful manual!

It also comes in German! (The result of several visits by Steve to the Technical University of Munich, aka Argonne East, ca. 1980).

```
reset
PRINT 0
REACTION: 40Ca(d,p)41Ca(7/2- 0.0) ELAB=20
parameterset dpsb r0target LABANGLES LSTEP=1
lmin=0 lmax=30 maxlextrap=0 asymptopia=60
PROJECTILE wavefunction av18 r0=1 a=0.5 l=0
;
TARGET
NODES=0 l=3 jp=7/2 r0=1.28 a=.65 vso=6 rso0=1.1
aso=.65 rc0=1.3
;
INCOMING
v = 90.671 r0 = 1.15 a = 0.762
vi = 2.348 ri0 = 1.334 ai = 0.513
vsi = 10.218 rsi0 = 1.378 asi = 0.743
vso = 3.557 rso0 = 0.972 aso = 1.011
vsoi = 0 rsoi0 = 0 asoi = 0 rc0 = 1.303
;
OUTGOING
v = 47.758 r0 = 1.185 a = 0.69
vi = 2.028 ri0 = 1.208 ai = 0.69
vsi = 6.447 rsi0 = 1.208 asi = 0.69
vso = 5.9 rso0 = 0.992 aso = 0.63
vsoi = 0 rsoi0 = 0 asoi = 0 rc0 = 1.275
;
ANGLEMIN=0 ANGLEMAX=50 ANGLESTEP=1
;
WRITENS crosssec
END
```

```
reset
DRUCKEN 0
REAKTION: 40Ca(d,p)41Ca(7/2- 0.0) ELAB=20
parameterset dpsb r0target LABWINKES LSCHRITT=1
lmin=0 lmax=30 maxlextrap=0 asymptopia=60
WURFGESCHOSS wavefunction av18 r0=1 a=0.5 l=0
;
ZIELSCHEIBE
KNOTEN=0 l=3 jp=7/2 RR0=1.28 a=.65 vso=6 rso0=1.1
aso=.65 rc0=1.3
;
EINGANG
v = 90.671 RR0 = 1.15 a = 0.762
vi = 2.348 ri0 = 1.334 ai = 0.513
vsi = 10.218 rsi0 = 1.378 asi = 0.743
vso = 3.557 rso0 = 0.972 aso = 1.011
vsoi = 0 rsoi0 = 0 asoi = 0 rc0 = 1.303
;
AUSGANG
v = 47.758 RR0 = 1.185 a = 0.69
vi = 2.028 ri0 = 1.208 ai = 0.69
vsi = 6.447 rsi0 = 1.208 asi = 0.69
vso = 5.9 rso0 = 0.992 aso = 0.63
vsoi = 0 rsoi0 = 0 asoi = 0 rc0 = 1.275
;
WINKELMINIMUM=0 WINKELMAXIMUM=50
WINKELSCHRITT=1
;
SCHREIBE crosssec
VERLASSE
```

Ab Initio Many-Body Theory

Goals

Understand many-body systems at the level of elementary interactions between individual particles, including

- Binding energies, excitation spectra, relative stability, matter properties
- Densities, electromagnetic moments, response to external probes
- Clustering, paricle-cluster and cluster-cluster reactions

Requirements

- Two-body potentials that accurately describe bound-state and elastic scattering data
- Consistent multi-body potentials and current operators (where required)
- Accurate methods for solving the many-nucleon Schrödinger equation

Hamiltonian

$$H = \sum_i -\frac{\hbar^2}{2m}\nabla_i^2 + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

The Nuclear Many-Body Schrödinger Equation

Realistic nuclear Hamiltonians have spatial, spin, and isospin dependence so the many-body Schrödinger equation (MBSE) for bound states is:

$$H\Psi(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_A; s_1, s_2, ..., s_A; t_1, t_2, ..., t_A)$$

$$= E\Psi(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_A; s_1, s_2, ..., s_A; t_1, t_2, ..., t_A)$$

This corresponds to

$2^A \times \binom{A}{Z}$ coupled second-order differential equations in 3A dimensions!

which is

96 for ^{4}He

17,920 for ^{8}Be

3,784,704 for ^{12}C

843,448,320 for ^{16}O

This is a challenging many-body problem!

Quantum Monte Carlo

Quantum Monte Carlo (QMC) methods are an efficient way to solve the MBSE.

Some of the QMC methods used are:

- Variational Monte Carlo (VMC)
  Construct a parametrized trial function Ψ_V for the system and minimize the energy expectation value
  $$E_V = \frac{\langle \Psi_V | H | \Psi_V \rangle}{\langle \Psi_V | \Psi_V \rangle} \geq E_0$$
  using Metropolis Monte Carlo algorithm to evaluate the many-body integral. For $A \leq 12$ nuclei, a complete sum over spin and isospin can be made. This gives an upper bound to the ground state or low-lying excited states of given $(J^\pi; T)$ quantum numbers. The better the trial function and minimization method, the closer to true E_0.

- Cluster VMC (CVMC)
  For larger nuclei, like ^{16}O or ^{40}Ca, a complete spin-isospin sum is impractical, so a cluster expansion is made in the number of nucleons n connected by spin-isospin dependent correlations and smaller spin-isospin sums are made (although for many clusters):
  $$E_V = \frac{N}{D} = C = \sum_i c_i + \sum_{i<j} c_{ij} + \sum_{i \neq j<k} c_{i,jk} + \sum_{i<j<k} c_{ijk} + \ldots$$
  where the c terms are A-body spatial integrals with limited spin-isospin dependence.

- Green's function Monte Carlo (GFMC)

  Project out lowest energy state from trial function by propagation in imaginary time:

$$\Psi(\tau) = \exp[-(H - E_0)\tau]\Psi_V \qquad \Psi(\tau \to \infty) = \Psi_0$$

  Accurate evaluation of $\Psi(\tau)$ can be done stochastically in small time steps $\Delta\tau$

$$\Psi(\mathbf{R}_n, \tau) = \int G(\mathbf{R}_n, \mathbf{R}_{n-1}) \cdots G(\mathbf{R}_1, \mathbf{R}_0)\Psi_V(\mathbf{R}_0) d\mathbf{R}_{n-1} \cdots d\mathbf{R}_0$$

  Complete spin-isospin sums currenly possible for $A \leq 12$; perhaps a little beyond in future.

- Auxiliary field diffusion Monte Carlo (AFDMC)

  Alternate approach is to use a basis given by the outer product of nucleon positions and the outer product of the single-nucleon (iso)spinor states. This requires a modified propagator that is at most linear in the operators O that appear in H, obtained by a Hubbard-Stratonovich transformation with auxiliary field variables x:

$$e^{-O^2/2} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx\, e^{-x^2/2} e^{xO}$$

  AFDMC effectively samples spin-isospin rather than summing, so much larger nuclei or infinite matter (by particles in a box) can be evaluated.

The Nuclear Quantum Monte Carlo Collaboration

In 1981 I arrived at Argonne after completing my Ph.D. at Illinois in 1978 under Vijay Pandharipande, and a first postdoc at Los Alamos. I quickly learned that Steve Pieper was THE computational expert in the Physics Division, and introduced him and Vijay, who I was continuing to collaborate with. This was the start of a beautiful collaboration, futhered as additional students, postdocs, and visitors from Illinois and elsewhere joined in.

In total, Steve and Vijay shared 22 papers before Vijay passed away in early 2006. I joined on 12 of those, plus another 30 with Steve over the years, many of these with Joe Carlson and/or Rocco Schiavilla, as well as many others in our grand nuclear QMC collaboration.

QUANTUM LIQUID DROPS

Vijay and his group, including Jorge Lomnitz-Adler and Joe Carlson, began using VMC to study 3- and 4-body nuclei with the realistic Reid soft-core potential in the early 1980s. Thinking about how to do larger nuclei, he suggested a sort of "warm-up" problem: computing the properties of self-bound drops of helium atoms. Steve was looking for something new to do, and jumped right in, performing VMC calculations for drops of up to 728 atoms of bosonic ^{4}He (interacting by the modern HFDHE2 potential of Aziz). Our friend John Zabolitzky was doing GFMC calculations for up to 112-atom drops, so we made a joint publication:

Calculations of Ground-State Properties of Liquid ^{4}He Droplets

V. R. Pandharipande, J. G. Zabolitzky, Steven C. Pieper, R. B. Wiringa, U. Helmbrecht, Phys. Rev. Lett. **50**, 1676 (1983)

This was followed by several more Argonne/Urbana papers, including

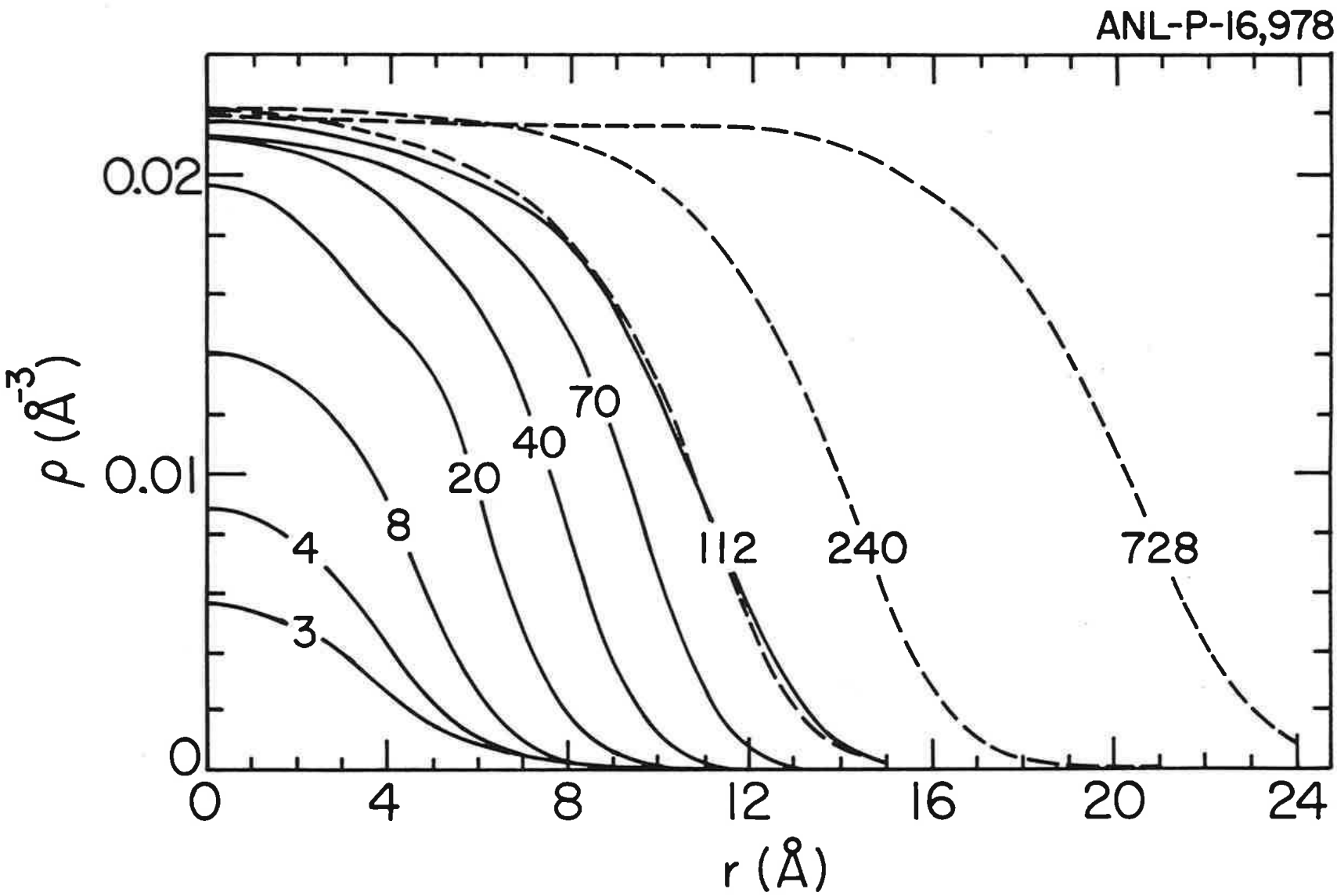
Variational Monte Carlo calculations of ground states of liquid ^{4}He and ^{3}He drops

V. R. Pandharipande, Steven C. Pieper, R. B. Wiringa, Phys. Rev. B **34**, 4571 (1986)

Up to 240-atom drops for fermionic ^{3}He, but $\sim$20-40 needed to form bound state.

Single-particle orbitals in liquid-helium drops

D. S. Lewart, V. R. Pandharipande, Steven C. Pieper, Phys. Rev. B **37**, 4950 (1988)



Density distributions computed by GFMC (solid lines) and VMC (dashed lines).

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John Zabolitzky - Steve Pieper - Roger Smith - Ray Bishop

Altenberg, Germany, August 1983

CVMC FOR ^{16}O AND ^{40}CA

By the late 1980s we were ready to try real nuclei with a realistic two- and three-nucleon potential – Argonne v14 + Urbana VII – using the cluster VMC method:

Ground State of ^{16}O

Steven C. Pieper, R. B. Wiringa, V. R. Pandharipande, Phys. Rev. Lett. **64**, 364 (1990)

Initial results at the four-body cluster level (with some spin-orbit terms only at two-body level) were very encouraging, with a claimed binding energy per particle of -7.0 MeV, not so far from the experimental -8.0 MeV.

More detailed work followed, including a very interesting study:

Origins of Spin-Orbit Splitting in ^{15}N

Steven C. Pieper, V. R. Pandharipande, Phys. Rev. Lett. **70**, 2541 (1993)

which obtained ∼85% of the observed splitting between $p_{1/2}$ and $p_{3/2}$ hole states, with half from two-nucleon $\mathbf{L} \cdot \mathbf{S}$ terms and half from pion-exchange between three or more nucleons.,

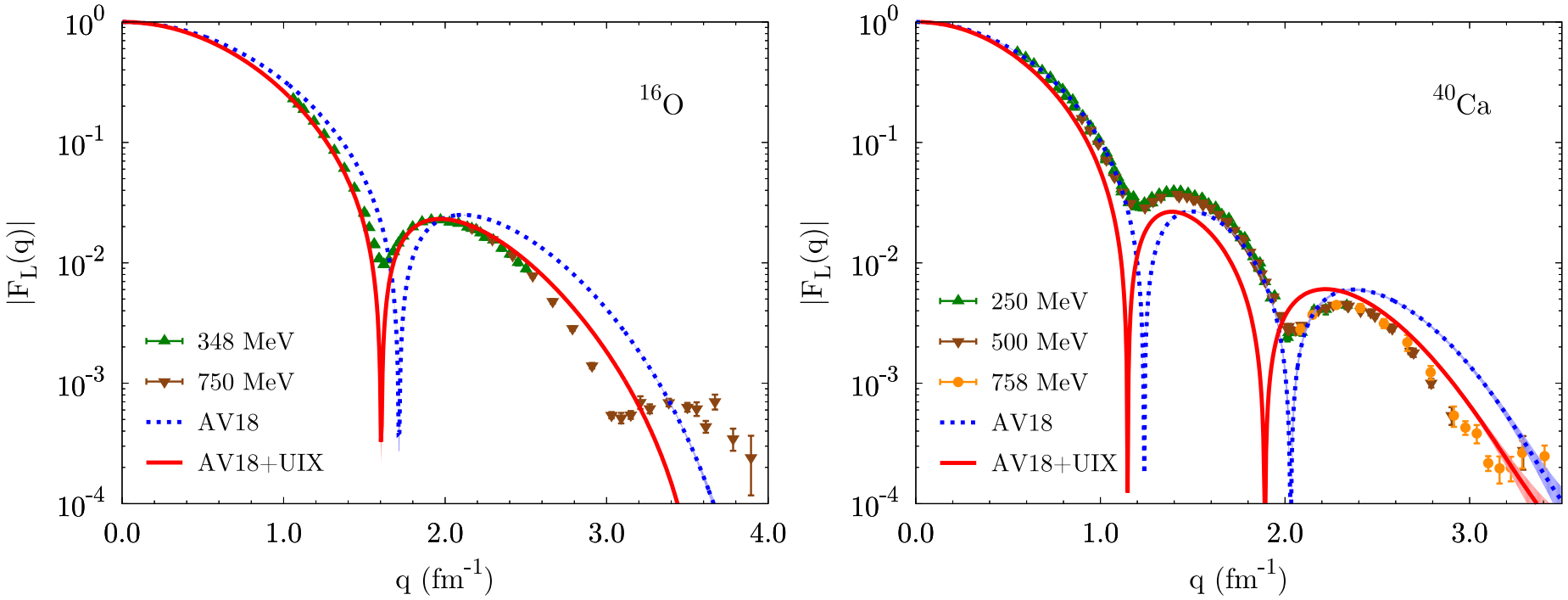
Steve continued to improve on the calculations, going to five-body clusters and removing approximations, resulting in a discouraging loss of binding. Attention turned to GFMC for light p-shell nuclei (discussed below) in the mid-1990s. In the late 1990s, Steve and postdoc Renato Roncaglia tried to make a cluster GFMC, but systematic errors were unsatisfactory and the work was never published.

In 2015, new postdoc Diego Lonardoni was looking for a problem, and Steve suggested dusting off the CVMC code and, with the tremendous improvements in computing power from intervening years, going up in size:

Variational calculation of the ground state of closed-shell nuclei up to A=40

D. Lonardoni, A. Lovato, Steven C. Pieper, R. B. Wiringa, Phys. Rev. C **96**, 024326 (2017)

Binding energy results were disappointing, but correlations in the wave function were qualitatively good for many applications, such as charge form factors:



Correlations in Nuclei

The collaboration worked on many aspects of correlations induced in nuclear wave functions by the interactions and their consequences for reactions. Some of the more notable works:

Nuclear transparency to intermediate-energy nucleons from $(e, e'p)$ reactions

V. R. Pandharipande, Steven C. Pieper, Phys. Rev. C **45**, 791 (1992) Roy Holt recommends!

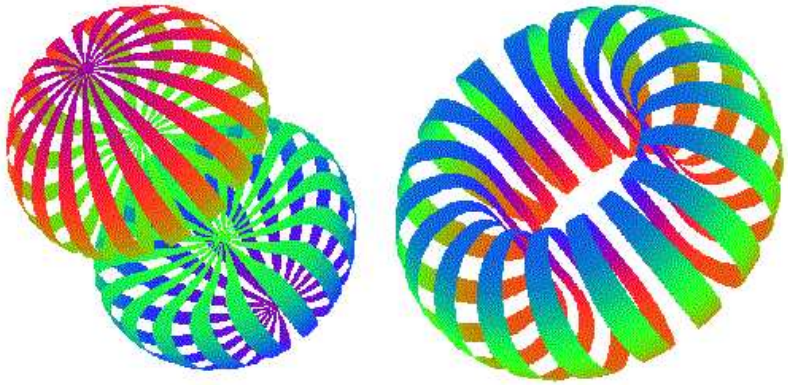
Isovector spin-longitudianl and -transverse response of nuclei

V. R. Pandharipande, J. Carlson, Steven C. Pieper, R. B. Wiringa, R. Schiavilla, Phys. Rev. C **49**, 789 (1994)

Femtometer toroidal structures in nuclei

J. L. Forest, V. R. Pandharipande, Steven C. Pieper, R. B. Wiringa, R. Schiavilla, A. Arriaga, Phys. Rev. C **54**, 646 (1996)

The latter led to our most enduring piece of graphics, made by Steve with Speakeasy (of course):

$M_d = \pm 1$  $M_d = 0$

Constant density surfaces of deuteron in different spin projections

GFMC FOR $A \leq 12$ NUCLEI

In 1988 Joe Carlson published the first GFMC solution for ^{4}He with fully realistic interactions.
In 1991 I published improved A=3,4 VMC calculations with some initial results for ^{6}Li.
In 1993 Argonne's MCS Division dedicated a brand new 128-Node IBM SP1 computer;
Steve helped write the manual with MCS collaborators Bill Gropp and Rusty Lusk:

Users Guide for the ANL IBM SP1

William Gropp, Ewing Lusk, and Steven C. Pieper, ANL/MCS-TM-198 (1994)

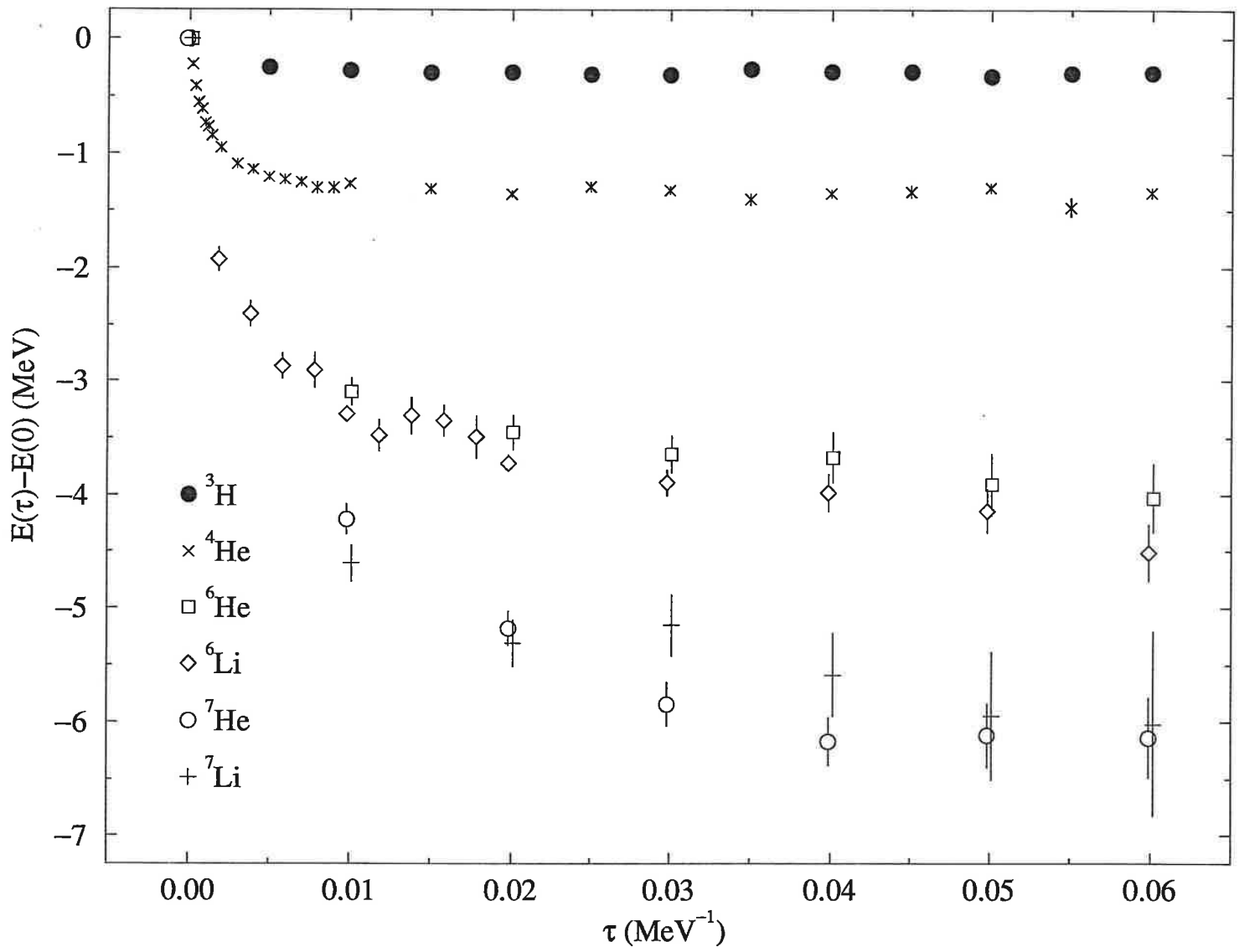
The SP1 supported multiple parallel environments, including MPI (Message Passing Interface), and MCS was at the forefront of parallel computing.

Vijay saw we now had the techniques and power to solve p-shell nuclei with realistic interactions in GFMC. New grad student Brian Pudliner got the assignment for his thesis project.

After a first PRL on $A \leq 6$, (with a thank you to Steve and MCS), the details were all brought out in a major 31-page article:

Quantum Monte Carlo calculations of nuclei with $A \leq 7$

B. S. Pudliner, V. R. Pandharipande, J. Carlson, Steven C. Pieper, R. B. Wiringa, Phys. Rev. C **56**, 1720 (1997)



$E(\tau) - E(\tau = 0)$ for the ground states of A=3-7 nuclei

In 2017 the Departement of Energy's Office of Science selected this paper as one of its "40 Years of Research Milestones."

1997 NP - Math Wins the Heart of an Atom

For years, determining the interactions involving individual protons or neutrons required intense calculations based on a series of assumptions about the particles and fields involved. This landmark 1997 paper offered a more sophisticated approach that took advantage of increasing computational power to answer questions about the reactions and structures at the heart of an atom. The new computational approach, quantum Monte Carlo, allows researchers to see the splendor of the nuclear shell structure emanating directly from the interactions between protons and neutrons. This theoretical work and related advanced computer algorithms opened the doors for scientists using computer simulations to examine and predict the energy levels of some atomic nuclei.

This work continued with a series of papers for larger nuclei and more nuclear states:

Quantum Monte Carlo calculations of $A = 8$ nuclei

R. B. Wiringa, Steven C. Pieper, J. Carlson, V. R. Pandharipande, Phys. Rev. C **62**, 014001 (2000)

Joe's constrained path to mitigate fermion sign problem implemented

Realistic models of pion-exchange three-nucleon interactions

Steven C. Pieper, V. R. Pandharipande, R. B. Wiringa, J. Carlson, Phys. Rev. C **64**, 014001 (2001)

Introduction of more sophisticated Illinois $3N$ potentials

(Thought about calling them Kankakee potentials – half way between Argonne & Urbana)

Quantum Monte Carlo calculations of $A = 9, 10$ nuclei

Steven C. Pieper, K. Varga, R. B. Wiringa, Phys. Rev. C **66**, 044310 (2002)

Kalman implemented code for increasingly complicated single-particle states

Quantum Monte Carlo calculations of excited states in $A = 6 - 8$ nuclei

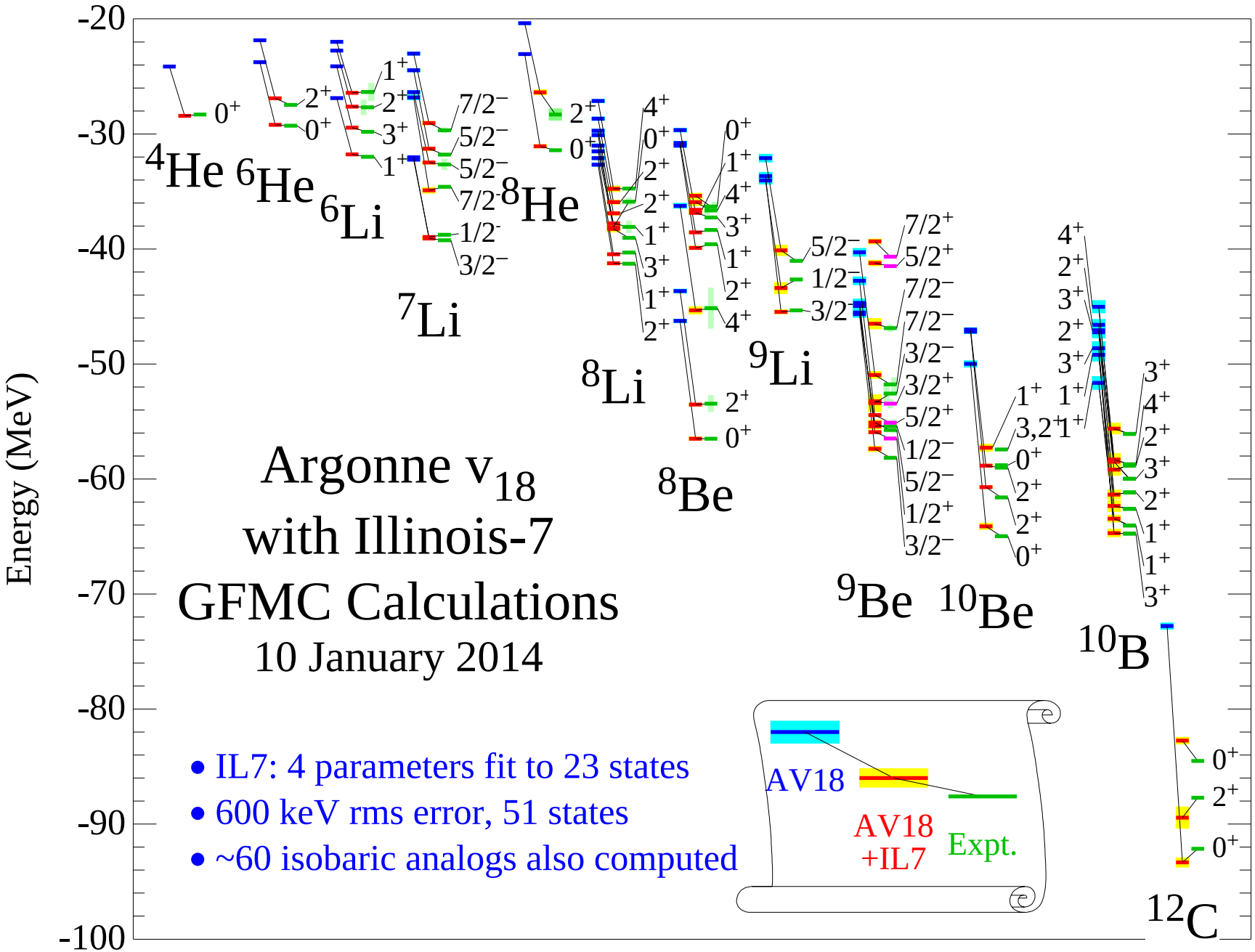
Steven C. Pieper, R. B. Wiringa, J. Carlson, Phys. Rev. C **70**, 054325 (2004)

Second and higher states of given $J^\pi; T$ made orthogonal to ground state in GFMC

Quantum Monte Carlo calculations of Neutron-α Scattering

Kenneth M. Nollett, Steven C. Pieper, R. B. Wiringa, J. Carlson, G. M. Hale, Phys. Rev. Lett. **99**, 022502 (2007) Ken showed a good H could reproduce the observed ^{5}He resonance properties

Eventually we built up this spectrum:


Energy (MeV)
-20
-30
-40
-50
-60
-70
-80
-90
-100
4He
6He
6Li
7Li
8He
8Li
8Be
9Li
9Be
10Be
10B
12C
Argonne v18
with Illinois-7
GFMC Calculations
10 January 2014
• IL7: 4 parameters fit to 23 states
• 600 keV rms error, 51 states
• ~60 isobaric analogs also computed
AV18
AV18
+IL7
Expt.

MISSING NUCLEI: GONE FOR A REASON

Evolution of Nuclear Spectra with Nuclear Forces

R. B. Wiringa, Steven C. Pieper, Phys. Rev. Lett. **89**, 182501 (2002)

$\Longrightarrow$ Featured in Physical Review Focus for 11 October 2002 $\Longleftarrow$

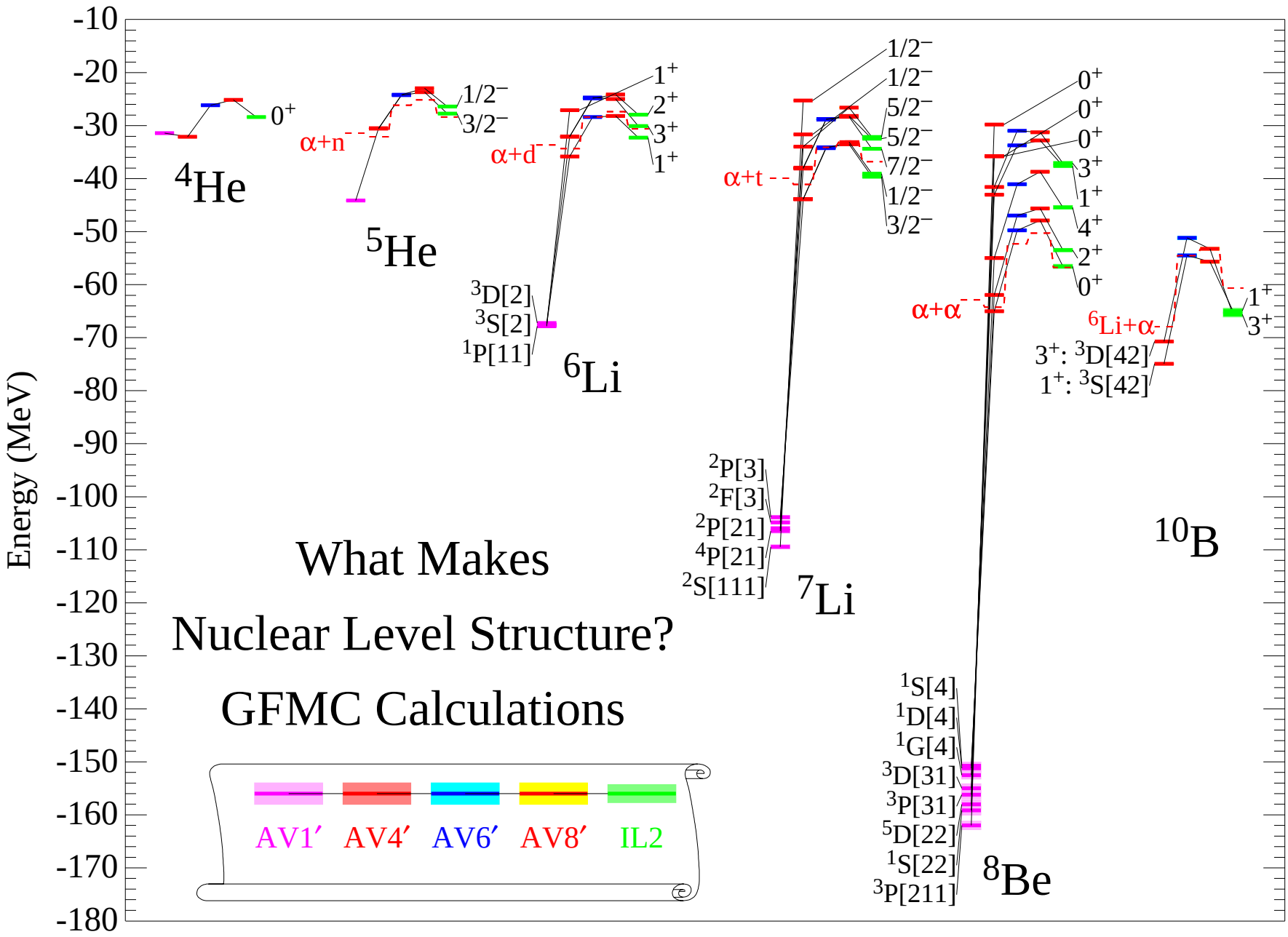
An interesting question is what parts of the nuclear force are necessary to produce the observed spectrum of light nuclei, in particular, no stable 5- or 8-body nuclei – an essential fact for having stars like the sun that live long enough for nuclear physicists to evolve!.

We took the (wonderfully accurate) AV18 potential and made successively simpler approximations, called AVX' (X=8,6,4,2,1) potentials, by stripping out velocity dependence, spin-orbit, tensor, and spin-isospin components. We then made GFMC calculations of the nuclear spectrum for these models up to $A = 10$ nuclei.

We found that an AV4' force, with spin-isospin dependence, was necessary for nuclear saturation, i.e., the fact that $A \geq 4$ nuclei are not much more bound than ^{4}He.

However, to get the feature that ^{5}He and ^{8}Be are both unstable against breakup into sub-clusters, we needed an AV6' potential with tensor components.

Finally, to be sure that ^{6}Li and ^{7}Li are stable against breakup, an AV8' potential with spin-orbit terms seemed to be required.


Energy (MeV)
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
-170
-180
^{4}He
0$^+$
^{5}He
α+n
1/2$^-$
3/2$^-$
^{6}Li
α+d
^{3}D[2]
^{3}S[2]
^{1}P[11]
1$^+$
2$^+$
3$^+$
1$^+$
^{7}Li
α+t
^{2}P[3]
^{2}F[3]
^{2}P[21]
^{4}P[21]
^{2}S[111]
1/2$^-$
1/2$^-$
5/2$^-$
5/2$^-$
7/2$^-$
1/2$^-$
3/2$^-$
^{8}Be
α+α
^{1}S[4]
^{1}D[4]
^{1}G[4]
^{3}D[31]
^{3}P[31]
^{5}D[22]
^{1}S[22]
^{3}P[211]
0$^+$
0$^+$
0$^+$
3$^+$
1$^+$
4$^+$
2$^+$
0$^+$
^{10}B
^{6}Li+α
3$^+$: ^{3}D[42]
1$^+$: ^{3}S[42]
1$^+$
3$^+$
What Makes
Nuclear Level Structure?
GFMC Calculations
AV1′
AV4′
AV6′
AV8′
IL2

NEUTRON SYSTEMS, ELECTROWEAK TRANSITIONS, SPECTROSCOPIC OVERLAPS

Many additional papers going beyond binding energies, including work from a series of excellent postdocs, many supported through the DOE SciDAC programs:

Can Modern Nuclear Hamiltonians Tolerate a Bound Tetraneutron?

Steven C. Pieper, Phys. Rev. Lett. **90**, 252501 (2003)

Steve single-handedly shoots down an experimentally claimed particle-stable 4-neutron system

Quantum Monte Carlo calculation of electroweak transition matrix elements in $A = 6 - 7$ nuclei

Muslema Pervin, Steven C. Pieper, R. B. Wiringa, Phys. Rev. C **76**, 064319 (2007)

First GFMC calculations of nuclear transitions

Quantum Monte Carlo calculation of spectroscopic overlaps in $A \leq 7$

I. Brida, Steven C. Pieper, R. B. Wiringa, Phys. Rev. C **84**, 024319 (2011)

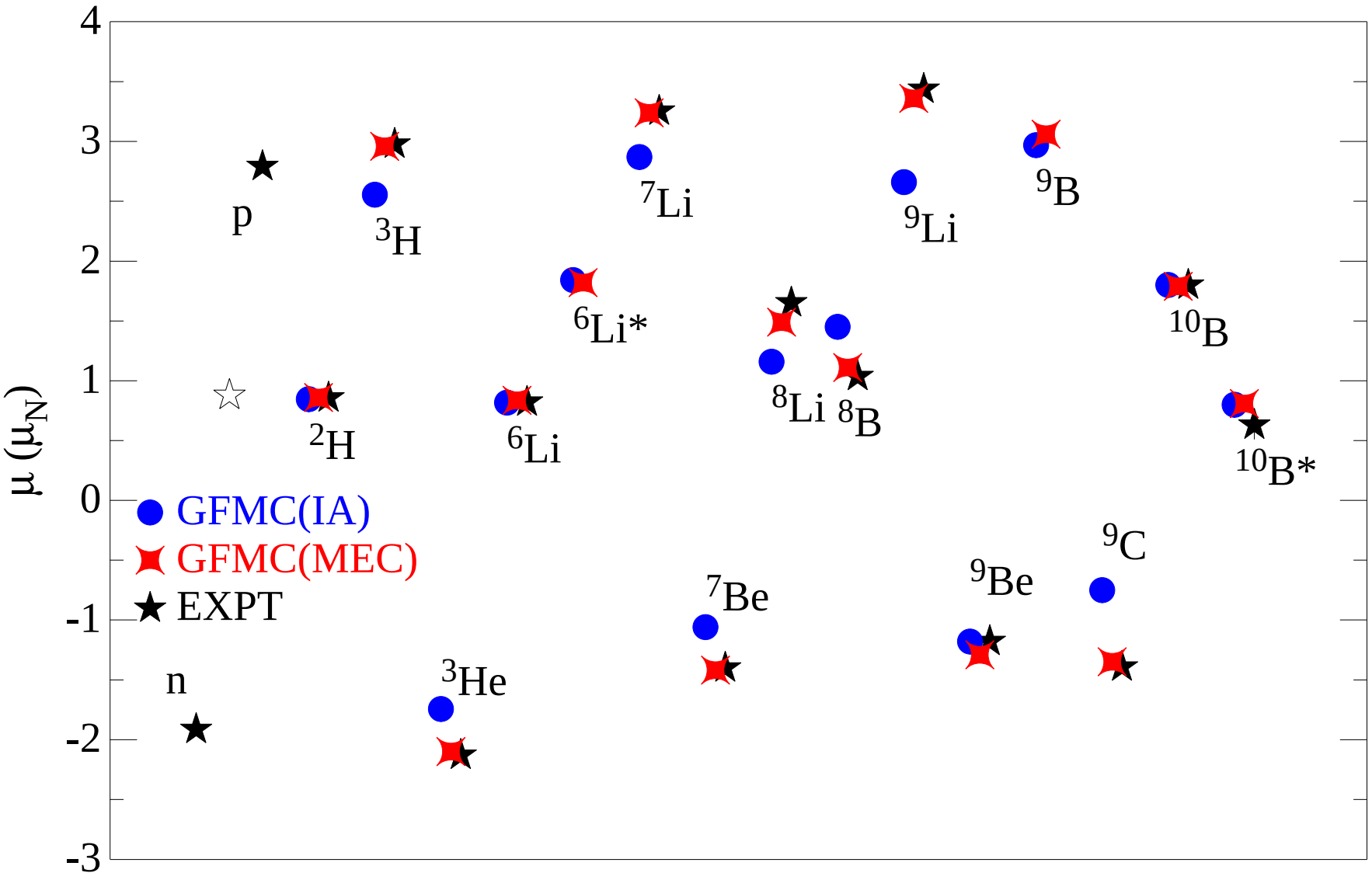
First GFMC calculations of spectroscopic overlaps

Quantum Monte Carlo calculation of electromagnetic moments and transitions in $A \leq 9$ nuclei with meson-exchange currents derived from chiral effective field theory

S. Pastore, Steven C. Pieper, R. Schiavilla, R. B. Wiringa, Phys. Rev. C **87**, 035503 (2013)

Chiral effective field theory invasion starts creeping in through the back door;

MEC shown to be important even for static properties



Magnetic moments: experiment (black), GFMC in impulse approximation (blue), GFMC with meson-exchange currents added (red)

SELF-ENDOWED RESEARCHER

Steve officially retired in 2011, but that did not stop or particularly slow down his output, although he much preferred to calculate than write.

Colloquium: Laser probing of neutron-rich nuclei in light atoms

Z.-T. Lu, P. Mueller, G. W. F. Drake, W. Nortershauser, Steven C. Pieper, Z.-C. Yan, Rev. Mod. Phys. **85**, 1383 (2013)

Steve predicted charge radii of ^{6,8}He before measurements in innovative atom trap experiments

Charge Form Factor and Sum Rules of Electromagnetic Response Functions in ^{12}C

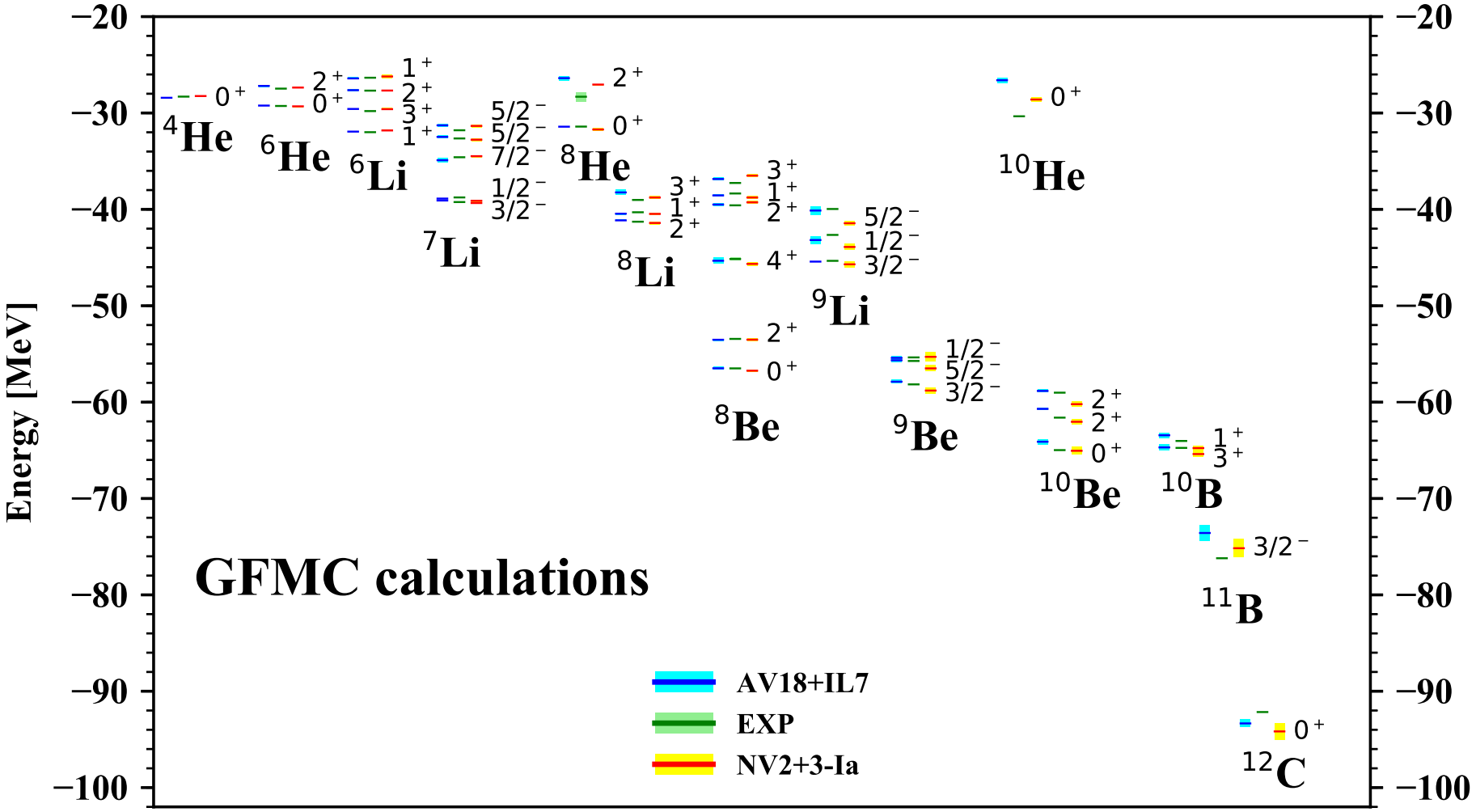
A. Lovato, S. Gandolfi, Ralph Butler, J. Carlson, Ewing Lusk, Steven C. Pieper, R. Schiavilla, Phys. Rev. Lett. **111**, 092501 (2013)

First of (so far) five papers led by Alessandro, with important contributions to the computational algorithms by Ralph Butler and Ewing (Rusty) Lusk

Light-Nuclei Spectra from Chiral Dynamics

M. Piarulli, A. Baroni, L. Girlanda, A. Kievsky, A. Lovato, Ewing Lusk, L. E. Marcucci, Steven C. Pieper, R. Schiavilla, M. Viviani, R. B. Wiringa, Phys. Rev. Lett. **120**, 052503 (2018)

Chiral Effective field theory comes in the front door with the Norfolk potentials!



Energy spectra for Argonne v18 + Illinois-7, experiment, and Norfolk NV2+3 model Ia

SUMMARY AND CODA

Quantum Monte Carlo methods for nuclear physics

J. Carlson, S. Gandolfi, F. Pederiva, Steven C. Pieper, R. Schiavilla, K.E. Schmidt, R.B. Wiringa, Rev. Mod. Phys. **87**, 1067 (2015)

A 52-page summary of (almost) everything we had learned to do with nuclear QMC, including original work by Steve on the second 0^+ (Hoyle) state in ^{12}C that is crucial for the chemical evolution of the universe.

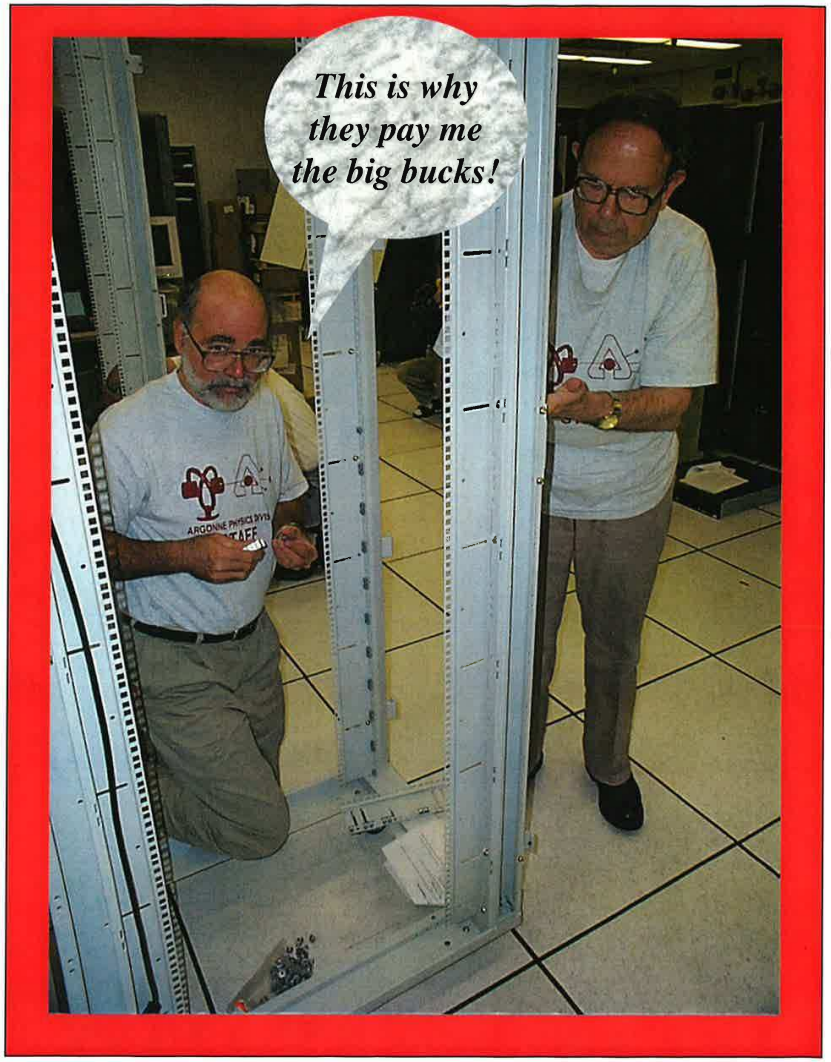
Impact of $^{16}O(\gamma,\alpha)^{12}C$ measurements on the $^{12}C(\alpha,\gamma)^{16}O$ astrophysical reaction rate

R. J. Holt, B. W. Filippone, Steven C. Pieper, Phys. Rev. C **99**, 055802 (2019)

Last (posthumous) paper, from helping with a sophisticated Speakeasy calculation

COMPUTATION

THE PHYSICS OF CHIBA BARNRAISING OCTOBER 1999



Steve's Life Outside of Physics

After graduation in 1965, Steve married his high school sweetheart ♡ Gail Frances Worsnopp ♡.

Gail graduated in 1965 from the University of Connecticut, and continued her studies at Illinois, becoming a Doctor of Philosphy in Classical Philology. in 1969 (ahead of Steve).

Steve and Gail collaborated on three important projects, with fantastic results produced in 1970, 1973, and 1976:

Kara - Kirsten - Shannon

owl

Steve, Gail, and I made numerous trips to Europe, often alternating between Elba and Trento, to attend conferences (and do some sightseeing).

Bob - Steve - Gail

Schiesshorn (2605m) near Arosa, Switzerland, July 1990

Steve & Gail

Gran Paradiso National Park, near Pont, Italy, July 2000

After Steve’s retirement in 2011, Steve & Gail made many true vacation trips all over the world, including Egypt, Japan, Peru, Russia. They let me tag along on two - to East Africa and to the Galapagos Islands

Ngorongoro Crater, Tanzania, January 2015

Would everyone in the audience who co-authored a paper with Steve, please stand up and give him a big round of applause.