

The Nuclear Force: the First 60 Years

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August 13, 2026

Chadwick's 1932 discovery of the neutron let Heisenberg treat the proton and neutron as isospin partners under an approximate $SU(2)$ symmetry [1]. Three years later Yukawa proposed that the force binding them was carried by a massive boson exchanged between nucleons, with the boson's mass setting the interaction's range through $R \sim \hbar/mc$ [2]. The pion, discovered in 1947, had the correct properties. By the late 1930s it was already clear the force was not purely central: the deuteron's quadrupole moment [3] demanded a tensor piece, which a single pion exchanged between two nucleons naturally supplies through its pseudoscalar coupling.

The general operator structure

Before getting into specifics about the nuclear force, it is worthwhile to understand the most general operator structure any force model has to follow. Eisenbud and Wigner [4] first classified the interaction forms allowed by rotational invariance, parity, time-reversal invariance, and nucleon exchange symmetry, linear in the relative momentum; Okubo and Marshak [5] later completed this symmetry analysis to show the most general two-nucleon potential reduces to a sum of a small set of independent operators built from relative position $\mathbf{r}$, relative momentum $\mathbf{p}$, and the spin ($\boldsymbol{\sigma}_1$, $\boldsymbol{\sigma}_2$) and isospin ($\boldsymbol{\tau}_1$, $\boldsymbol{\tau}_2$) operators:

- **Central:** 1 (spin-independent)
- **Spin-spin:** $\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$
- **Tensor:** $S_{12} = 3(\boldsymbol{\sigma}_1 \cdot \hat{r})(\boldsymbol{\sigma}_2 \cdot \hat{r}) - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$ — mixes states of different orbital angular momentum (e.g. 3S_1 – 3D_1), directly probed by the deuteron quadrupole moment
- **Spin-orbit:** $\mathbf{L} \cdot \mathbf{S}$, where $\mathbf{S} = \frac{1}{2}(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)$ — splits spin-triplet partial waves of different J
- **Quadratic spin-orbit** ($(\mathbf{L} \cdot \mathbf{S})^2$ or L^2): enters once quadratic momentum dependence is allowed, needed once data extend high enough in energy that P- and D-wave splittings can't be fit by linear spin-orbit alone

Each spin-space operator appears twice — once as an isospin scalar and once multiplied by $\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$ — giving the ten-operator charge-independent basis used by early potentials defined in

coordinate space, and which in addition had a hard core. Modern high-precision potentials extend this further: Argonne v14 [6] uses fourteen operators, and Argonne v18 [7] keeps that fourteen-operator charge-independent core and adds charge-dependent and charge-asymmetric terms. The radial coefficient functions multiplying each operator — not the operator basis itself, which is fixed by symmetry — is what constitutes the differences from potential to potential and encodes the underlying physical picture.

First quantitative fits

Gammel and Thaler produced the first semi-quantitative potential built on this operator structure, fitting central, tensor, and spin-orbit terms plus a hard core at $r \approx 0.4$ fm to the nucleon-nucleon scattering data available below ~ 310 MeV [8]. It was, for its time, a strikingly successful fit, good enough that Brueckner and Gammel used it the following year in some of the first realistic nuclear-matter binding-energy calculations [9], and it remained a working reference potential — including in early shell-model Hartree-Fock studies — until the more systematic hard-core fits of the following decade superseded it.

One-pion exchange and its limits

Through the 1940s–50s, one-pion exchange (OPE) became the accepted description of the long-range tail ($r \gtrsim 1.5$ fm), with a coupling constant $g_{\pi NN}^2/4\pi \approx 14$ fixed by pion-nucleon scattering. OPE generates a fixed ratio between the central, spin-spin, and tensor terms, all multiplied by $\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$ since the pion is an isovector. But OPE alone diverges at short distance and cannot produce the strong short-range repulsion needed for nuclear saturation. Taketani, Machida, and Ohnuma [10] formalized this gap by splitting the potential into an outer region (OPE), a middle region (later identified with two-pion exchange), and an inner region requiring a phenomenological cutoff or hard core [11] — the same inner-region problem Gammel and Thaler had already tackled empirically.

One-boson-exchange (OBE) models

The discovery of the $\rho(770)$, $\omega(782)$, and $\eta(548)$ mesons through the late 1950s and early 1960s gave theorists the ingredients for a systematic multi-meson picture, where each exchanged meson populates the operator basis above according to its spin and parity:

- π (**pseudoscalar, isovector**): tensor and spin-spin operators ($\propto \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$), dominant beyond ~ 2 fm
- η (**pseudoscalar, isoscalar**): same spin structure as the pion, no isospin factor; weakly coupled
- ρ (**vector, isovector**): short-range tensor of opposite sign to the pion’s, partially cancelling it at intermediate range, plus spin-orbit
- ω (**vector, isoscalar**): central operator, short-range repulsion — the field-theoretic origin of the hard core Gammel-Thaler had fit phenomenologically — plus spin-orbit, same sign as the ρ ’s
- σ (**scalar, isoscalar**): central operator only, supplying intermediate-range attraction, standing in for correlated/uncorrelated two-pion exchange

- δ/a_0 (**scalar, isovector**): central operator $\times \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$, a smaller contribution in some models

Each meson’s contribution is a Yukawa function of r regularized by a form factor at the vertex. The Yale group, Hamada and Johnston [12], and Reid [13] all built on the Gammel-Thaler approach, adding quadratic spin-orbit terms and fitting the ten-operator basis, partial wave by partial wave, to increasingly precise phase shifts; Reid’s soft-core version replaced the hard core with a finite, soft Yukawa-squared repulsion.

Field-theoretic refinements in the 1980s and 1990s: Paris and Bonn

The 1970s saw two divergent strategies for the middle-range central and tensor coefficients. The Paris group’s approach [14], culminating in the Paris potential itself [15], treated the two-pion-exchange contribution as an on-shell NN scattering amplitude, reconstructed via dispersion relations from empirical πN and $\pi\pi$ scattering data rather than modeled diagram by diagram. Concretely, the $N\bar{N} \rightarrow \pi\pi$ amplitude was built by analytic continuation and crossing from measured $\pi N \rightarrow \pi N$ and $\pi N \rightarrow \pi\pi N$ amplitudes, then “squared” and related back to NN scattering by unitarity and crossing symmetry — so the intermediate-range attraction came out of measured hadronic data run through dispersion integrals, populating the central and tensor operators with a genuinely calculated radial form. Single π and ρ exchange were added on top of this dispersion-derived middle range, with only a constant phenomenological core below $r \approx 0.8$ fm left as a fitted piece to complete the potential.

The Bonn group’s program, culminating in the “Full Bonn” model [16], took a more explicitly diagrammatic field-theoretic route and was built on the principle to use mesons up to an exchange mass of about 1 GeV. Rather than fitting a phenomenological σ to stand in for the middle-range attraction, the Full Bonn model calculated the two-pion-exchange contribution explicitly as a sum of time-ordered diagrams: uncorrelated box and crossed-box diagrams with two nucleons in flight, plus diagrams where one or both intermediate nucleon lines are replaced by a $\Delta(1232)$ isobar ($N\Delta$ and $\Delta\Delta$ box diagrams), since virtual Δ excitation is a large part of the physical two-pion-exchange process at these energies. On top of this, genuine correlated $\pi\pi$ -exchange effects were effectively included by a scalar ‘ σ meson’ with parameters adjusted to empirical πN and $\pi\pi$ scattering amplitudes, so that the middle-range attraction was tied to independently measured hadronic data rather than adjusted freely. A separate, smaller class of diagrams combining π exchange with ρ exchange was also included, since this $\pi\pi$ - ρ combination is repulsive and acts to counterbalance the otherwise overly strong two-pion attraction at short distance — the diagrammatic analogue of the role the σ plays in simpler OBE models. Single π and ω exchange were added on top as the long- and short-range pieces, respectively, completing the interaction below pion-production threshold.

Because this was formulated as genuine relativistic time-ordered perturbation theory rather than a static potential fit, the Full Bonn model is energy-dependent and nonlocal: the interaction includes meson retardation (the exchanged meson’s energy, not just its momentum, enters the propagator) and depends on the total energy of the two-nucleon system, not just the momentum transfer. This made it awkward to use directly in configuration-space few- and many-body calculations, so simplified, energy-independent versions — Bonn A, B, and C, distinguished mainly by the strength of the tensor force and the resulting deuteron D-state probability — were derived by removing the explicit energy dependence and re-expressing the dynamics in the more conventional local-operator language, at the cost of some of the model’s underlying microscopic content. The full nonlocal, energy-dependent version was later extended above pion-production threshold by explicitly incorporating nucleon and Δ self-energy dressing to maintain unitarity [17, 18]. This

same diagrammatic machinery, simplified and refit, was carried forward into the charge-dependent Bonn potential (CD-Bonn) in the 1990s.

The precision era in the 1990s

The Nijmegen group’s partial-wave analyses [19] turned the pp and np database into a precision benchmark — χ^2/datum near 1 — against which the radial coefficients of any operator-basis potential would now be judged, while Argonne v14 [6] fixed the fourteen-operator basis as the new working standard.

By the early 1990s the field had converged on a small set of potentials fit essentially exactly to the world scattering database, and it’s worth being specific about what “exactly” meant in each case. The Nijmegen group’s 1994 paper [20] presented four related models built from their own definitive 1993 partial-wave analysis [21] of the 1992 world database (1787 pp and 2514 np data points below 350 MeV): an updated meson-theoretical Nijm93 potential ($\chi^2/\text{datum} = 1.87$, since its functional form is tied to a fixed set of meson couplings rather than adjusted freely in each partial wave); and three purely phenomenological potentials — Nijm I (nonlocal, retaining an explicit p^2 term in the central force), Nijm II (the same fit with that nonlocal term set to zero), and Reid93 (an update of the 1968 Reid potential regularized with dipole form factors instead of Reid’s original singular Yukawas) — each with its own coefficients fit separately in every partial wave up to $J = 4$ or 5, and all three achieving $\chi^2/\text{datum} = 1.03$, a quality the authors described as rivaling the partial-wave analysis itself.

Argonne v18 [7] fit the same Nijmegen 1992 database plus additional low-energy nn scattering parameters and the deuteron binding energy, using 40 adjustable parameters across its 18-operator basis (the 14 charge-independent AV14-type operators plus 3 charge-dependent and 1 charge-asymmetric operator, plus a complete electromagnetic interaction — Coulomb, vacuum polarization, and magnetic-moment terms) to reach $\chi^2/\text{datum} = 1.09$ for 4301 pp and np data points between 0 and 350 MeV.

CD-Bonn [22], building on [23], pushed the database further still, fitting the expanded “world” database available by 2000 — 2932 pp data ($\chi^2/\text{datum} = 1.01$) and 3058 np data ($\chi^2/\text{datum} = 1.02$), a substantially larger sample than the 1992 Nijmegen database thanks to new-generation experiments using internally polarized gas targets and stored, cooled beams. This was, at the time, a more accurate reproduction of the data than any existing phase-shift analysis. The fit was achieved partly by introducing two effective σ mesons whose couplings were allowed to vary partial wave by partial wave — a phenomenological flourish layered on top of the Full Bonn model’s diagrammatic TPE — and its charge-dependence was not simply fit freely but constrained by the Full Bonn model’s own predictions for charge-symmetry and charge-independence breaking in every partial wave up to $J = 4$. As with its parent model, CD-Bonn’s potential was represented directly in terms of nonlocal, covariant one-boson-exchange Feynman amplitudes, so — unlike the local AV18 and Nijmegen forms — its off-shell behavior differed in a characteristic, physically motivated way, a difference that shows up concretely as larger binding energies in few- and many-body systems where local potentials tend to underbind [24].

It was against this backdrop — an operator basis established by Eisenbud, Wigner, and Okubo-Marshak, first quantitatively populated by Gammel and Thaler, and refined for three decades through OBE fitting into potentials now indistinguishable from data at the $\chi^2/\text{datum} \approx 1$ level — that Weinberg’s 1990–91 papers [25, 26] proposed a different organizing principle: a chiral effective field theory expansion, replacing the ad hoc σ , fitted cutoffs, and meson zoo with contact terms and pion exchanges ordered by systematic power counting from QCD’s symmetries. The same

operator basis still describes the resulting potential, but the physics generating each coefficient — and the ability to estimate theoretical uncertainty order by order — would be fundamentally different, setting the field’s direction for the following decade.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

The conceptual layout of the manuscript was envisioned by the author. During the preparation of the work, the author used Claude Pro in order to fill subsections with content and references. After using the tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the article.

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