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A Yukawa-Like Neutron Short-Range Force Profile via Classical Methods.

Vijay T. Ingole[1], Anant S. Wadatkar[2]

[1]Independent Researcher, Former Professor, Professor Ram Meghe Institute of Technology & Research, Amravati 444701, Maharashtra, India
[2]Assistant Professor, Department of Physics, Vinayak Vidnyan Mahavidyalaya, Nandgaon Khandeshwar, Amravati, Maharashtra, India

Abstract:
A classical, phenomenological description of a **short-range radial force associated with an isolated neutron** is presented. The force is defined exclusively in the region external to the neutron core surface radius and is treated as a function of radial distance within the diffuse outer region. Empirically observed features—negligible force beyond a finite range, rapid variation over a narrow radial interval, and absence of long-range behavior—are captured using an exponential radial force profile. The characteristic transition length is motivated by known structural length scales of the neutron's outer region and is not introduced as a fitting parameter. Although the mathematical form is Yukawa-like, the present formulation does not invoke mediator exchange, and is intended solely as a minimal, force-based classical representation of short-range behavior.

Keywords: Short-range force; neutron radial force; exponential force profile; phenomenological model; nuclear length scale; Yukawa-like behavior.

1. Introduction:

The nature of short-range forces associated with nuclear matter has long been recognized as fundamentally distinct from familiar long-range interactions such as electromagnetism and gravitation. Empirical studies show that nuclear effects become appreciable only over distances of order a femtometer and decay extremely rapidly beyond this scale, without exhibiting inverse-power behavior or long-range tails [1–3]. This sharply limited spatial extent remains one of the defining features of nuclear-scale phenomena.

Historically, an influential phenomenological description of this behavior was introduced by Hideki Yukawa, who proposed an exponentially attenuated form to represent the observed short range of nuclear forces [1]. In Yukawa's formulation, the characteristic decay length was introduced phenomenologically to reproduce experimental observations, rather than derived from internal structural considerations. Despite later developments involving quantum field–theoretic interpretations and mediator exchange, the exponential form itself remains a compact and effective representation of short-range behavior.

Modern theoretical approaches particularly, Chiral effective field theory, ab initio many-body calculations, and studies of short-range correlations—have provided increasingly detailed microscopic descriptions of nuclear systems [4–7]. These works emphasize the role of high-momentum components, correlation effects, and multi-nucleon dynamics in shaping nuclear structure and neutron-rich matter. While highly successful, such approaches are often mathematically intricate and do not always yield a simple physical picture of how force magnitude varies with radial distance over the narrow interaction region.

From a complementary standpoint, phenomenological and classical descriptions remain useful when the objective is to clarify the radial force behavior itself, independent of detailed microscopic mechanisms. In particular, the observed abrupt onset and rapid attenuation of short-range nuclear effects suggest that a minimal description based directly on force variation with distance can provide valuable physical insight [2,3,6].

In this work, we adopt such a classical, phenomenological perspective, focusing on a short-range radial force associated with an isolated neutron. The formulation does not introduce a new fundamental interaction, nor does it rely on a specific microscopic model. Instead, it seeks to represent the empirically established short-range behavior using a simple force profile defined in the region external to the neutron core.

The short-range force is described as emerging from the radial density variation and diffuse surface structure of the neutron, extending outward from the effective core radius. Within this external region, the force is negligible at larger radial distances, rises rapidly over a narrow interval, and approaches a limiting value near the core surface. Such behavior naturally motivates the use of an exponential dependence on radial distance as a concise representation of rapid attenuation over a finite spatial scale.

Although the mathematical form employed here is formally similar to Yukawa's exponential description, the present framework differs in interpretation. The exponential dependence is used not as evidence of mediator exchange, but as a phenomenological representation of short-range radial force behavior, motivated by structural variation in the neutron's outer region. In this sense, the approach complements both historical phenomenology and modern microscopic theories by providing a transparent, force-based description of short-range nuclear-scale behavior.

2. Main Framework: Neutron Radial Force Response:

2.1 Motivation and scope

The purpose of this framework is to provide a classical, phenomenological description of a short-range radial force relevant to neutron–neutron proximity, expressed explicitly as a function of separation. The intent is neither to introduce a new fundamental interaction nor to rely on a specific microscopic theory, but to represent the empirically observed short-range behavior using minimal and physically transparent assumptions.

Empirically, neutron–neutron interaction is characterized by the following well-established features:

- It is negligible beyond a finite separation.
- It becomes significant only within a narrow radial interval.
- It varies rapidly over a distance of order a fraction of a femtometer.
- It does not display inverse-power or long-range behavior.

These characteristics suggest that the interaction is more naturally represented as a short-range radial force response associated with proximity and surface structure, rather than as a long-range field.

2.2 Radial separation and characteristic regions:

In the present formulation, the short-range force is defined exclusively for the region beyond the neutron core surface radius (Rn=1.0 fm). Let Rs denote the radial distance measured outward from the neutron core surface into the diffuse outer response region. The internal neutron radius Rn serves only to define the onset of this short-range response and does not enter explicitly into the force expression.

Accordingly, the radial force is treated as a function of Rs alone. Distances corresponding to Rn <1.0 fm are not considered, as the present framework is concerned solely with the **external short-range response** prior to core overlap.

With this definition, three characteristic regimes may be identified:

Non-interacting region: For Rs ≳ Ro (of order 1.2–1.3 fm), the force is negligible. Where Ro is neutron free radius.

Transition region: As Rs decreases below Ro , the force rises rapidly over a narrow interval, reflecting increasing proximity of the diffuse outer regions.

Limiting contact region: As Rs→0, the force approaches its maximum value, corresponding to effective surface contact. Further reduction in separation is not considered within the present model.

2.3 Physical interpretation: contact-like surface response:

The short-range force may be visualized as emerging from the radial density variation of the neutron, with higher effective density toward the core and progressively lower density in the diffuse outer region.

- A diffuse outer region**,** arising from surface irregularity and distributed response, characterized by lower effective density and greater separation, and therefore offering weaker force compared to the confined region near the core radius.
- As the radial distance decreases from the diffuse outer extent Ro toward the neutron core surface radius Rn, the effective density of the neutron's outer region increases and the radial force rises accordingly, reaching its maximum value at Rn , corresponding to the characteristic neutron confinement force and at larger radial distances, the diffuse outer region produces only a weak force response.
- The radial force rises steeply over a narrow interval.
- A strongly limiting regime is reached near core proximity.

In this interpretation, interaction strength is governed by density due to surface-level structural response.

2.4. Radial force formulation:

To represent this behavior mathematically, the radial interaction is expressed directly in terms of a radial confinement force, defined as a function of surface separation:

$$F(Rs) = Fn * exp\left[-\frac{Rs}{\lambda}\right]$$

Here:

- Fn is the characteristic neutron confinement force scale,
- Rs is the separation distance beyond beyond effective neutron core radius Rn
- λ is the characteristic transition length.

This form ensures that the force is maximal as (Rs = 0) and decays rapidly as separation increases.

2.5. Justification of the exponential form:

The exponential dependence is adopted for the following reasons:

- It naturally represents rapid attenuation over a finite spatial interval using a single characteristic length scale.
- The formulation is dimensionally consistent, with λ rendering the exponent dimensionless.
- It avoids inverse-power behavior and any implied long-range interaction.

- Exponential profiles are widely used in classical descriptions of contact compliance, attenuation, and evanescent response.
- The parameter λ is not treated as a fitting constant, but as a physically motivated transition width separating diffuse and confined response regions.

Guided by earlier analyses of neutron confinement scales [8], this transition width may be associated with the difference between the free-response and confined radii of the neutron's internal structure.

Previously estimated values, approximately 0.19 fm for the free-response radius and 0.155 fm for the confined radius, suggest a characteristic scale:

$$\lambda \approx 0.19 - 0.155 \approx 0.035\ fm$$

As the separation decreases, the interaction acts on the neutron as a whole rather than at a sharply defined boundary. The diffuse outer response progressively contracts toward the confined inner structure, and λ represents the finite radial interval over which this internal adjustment occurs.

While the exponential form resembles that used in Yukawa's phenomenological description, the present formulation does not adopt the Yukawa equation itself. Instead, the exponential dependence is employed as a physically grounded representation of short-range radial response, motivated by structural variation rather than mediator-based assumptions.

2.6. Numerical illustration

Using the structurally motivated estimate (λ =0.035 fm), the force may be written illustratively as:

$F(Rs) \approx\ 10^5 * exp\left[-\frac{Rs}{0.035}\right]$ for $0 \leq Rs\ \leq 0.5\ fm$

Here:

- Fn $\approx\ 10^5$ N is the characteristic neutron confinement force scale,
- Rqco ≈0.19 fm
- Rqc ≈0.155 fm
- $\lambda \approx$ (Rqco - Rqc) is the characteristic transition length
- $\lambda \approx$ 0.19 - 0.155 ≈0.035 fm
- Rs is the separation distance beyond effective neutron core radius Rn,
- 0 ≤ Rs ≤ 0.5 fm

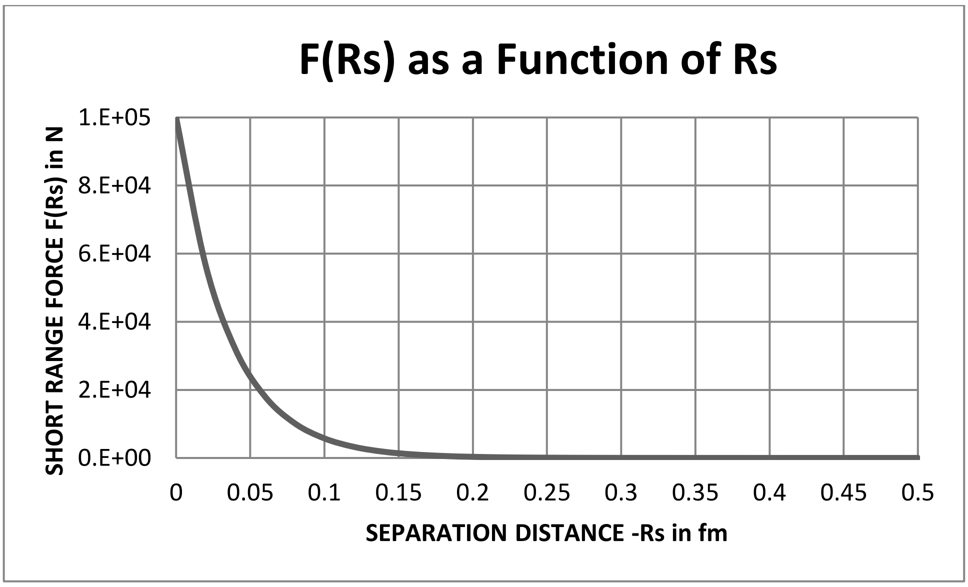

Figure 1: *Illustrative exponential short-range radial force* F(Rs) *(newton) as a function of separation distance* Rs *(fm), measured outward from the neutron core surface radius (*Rn=1.0 fm*). The curve is evaluated using the characteristic transition length* $\lambda=0.035$ fm *and demonstrates rapid attenuation of the force beyond the effective short-range region, with* F(Rs) *approaching the characteristic force scale* $Fn\approx10^5$ newton *as* $Rs\rightarrow0$.

Conclusions:

A classical, phenomenological framework has been presented for describing a short-range radial force associated with the external structure of a neutron, expressed explicitly as a function of radial distance beyond the neutron core surface radius. The formulation deliberately avoids invoking new fundamental interactions or relying on specific microscopic models, and instead focuses on representing the empirically observed short-range behavior using minimal and physically transparent assumptions.

The analysis treats the short-range force as a property of the neutron's diffuse outer region, extending outward from the effective core radius Rn . Within this region, the force is negligible at larger radial distances, rises rapidly over a narrow interval, and reaches a limiting maximum near the core surface. This behavior reflects the underlying radial density variation and surface-level structural response of the neutron, rather than long-range field effects or inverse-power laws.

By defining the radial distance Rs as the sole independent variable, the framework isolates the external short-range response and avoids the need to consider internal core dynamics or center-to-center geometry. The resulting force profile captures the sharp onset and rapid attenuation characteristic of short-range nuclear phenomena while remaining entirely classical in construction.

An exponential dependence on Rs is adopted as a concise and physically reasonable representation of this behavior. The associated transition length λ is not introduced as an adjustable fitting parameter, but is motivated by previously identified structural length scales within the neutron's outer region. This finite length scale sets the width over which the force changes significantly and reproduces the observed abrupt decay of interaction strength.

Although the mathematical form bears a formal resemblance to Yukawa's phenomenological description of nuclear forces, the present formulation does not imply mediator exchange or field-theoretic interpretation. Instead, the exponential profile is employed purely as a phenomenological representation of a short-range radial force, arising from structural variation in the neutron's external region.

Overall, the framework demonstrates that the essential features of short-range force behavior—namely its limited range, rapid variation over a fraction of a femtometer, and absence of long-range influence—can be coherently described within a simple, force-based classical model. This perspective provides a transparent and physically intuitive complement to more detailed microscopic approaches and offers a useful reference framework for further phenomenological or comparative studies.

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