HEAVY BARYONS USING VARIOUS Q-Q POTENTIALS IN NON-RELATIVISTIC QUARK MODEL (NRQM)

DR SANJEET KUMAR

Senior Assistant Professor

PG Department of Physics

HD Jain College VKSU ,Ara

ABSTRACT

Heavy baryons, containing at least one heavy quark (charm or bottom), are vital systems for exploring the dynamics of the strong interaction and testing Quantum Chromodynamics (QCD) predictions. The Non-Relativistic Quark Model (NRQM) offers a practical approach to study these baryons by modeling the interactions between quarks using effective potentials. This paper investigates the properties of heavy baryons through different quark-quark potentials—such as Coulomb, linear confinement, harmonic oscillator, and Yukawa potentials—within the NRQM framework. Mass spectra, decay characteristics, and internal structures are analyzed, providing insight into quark distributions, binding mechanisms, and comparison with experimental findings.

1. INTRODUCTION

Heavy baryons are three-quark systems in which one or more quarks are heavy (ccc or bbb). Studying these particles enhances our understanding of QCD in the non-perturbative regime, where quark confinement and gluon-mediated interactions dominate. Unlike light baryons, heavy quarks move relatively slowly, which allows for the application of non-relativistic approximations.

The Non-Relativistic Quark Model (NRQM) treats baryons as three-body systems, with quarks interacting via effective potentials that reflect both short-range QCD forces and long-range confinement. NRQM has been successfully applied to:

- Predict masses of singly, doubly, and triply heavy baryons.

- Calculate spin-dependent splittings and hyperfine structures.
- Analyze decay processes, including strong, weak, and electromagnetic channels.
- Investigate internal structures through wave functions, enabling calculations of magnetic moments and form factors.

This paper focuses on the application of various quark-quark potentials within NRQM to describe heavy baryons, providing theoretical predictions aligned with experimental observations.

2. Theoretical Framework

1) 2.1 Non-Relativistic Quark Model

In NRQM, the Hamiltonian of a baryon consisting of three quarks is:

$$H = \sum_{i=1}^{3} \left(\frac{p_i^2}{2m_i}\right) + \sum_{i<j} V_{q-q}(r_{ij}) + H_{\square\square\square\square} + H_{\square\square\square\square\square}$$

Where $V_{q-q}(r_{ij})$ encapsulates the effective interaction between quarks i and j, and spin-color terms include:

- **Spin-spin interactions:** Responsible for hyperfine splittings.

$$V_{\square\square} = \sum_{i<j} \frac{2\alpha_s}{3m_i m_j}(S_i \cdot S_j)\,\delta^3(r_{ij})$$

- **Spin-orbit interactions:** Contribute to fine structure splittings.

$$V_{\square\square} = \sum_{i<j} \frac{1}{r_{ij}}\frac{dV}{dr_{ij}}(L \cdot S)$$

- **Tensor interactions:** Affect angular momentum coupling.

The Schrödinger equation for a baryon is:

$$H\Psi(r_1, r_2, r_3) = E\Psi(r_1, r_2, r_3)$$

Solutions $\square$ yield baryon wave functions, which encode spatial, spin, flavor, and color information.

2) 2.2 Quark-Quark Potentials

1. Coulomb Potential

Represents short-range interactions from one-gluon exchange:

$$V_{\square\square\square\square\square\square\square}(r) = -\frac{4}{3}\frac{\alpha_s}{r}$$

Where $\square_s$ is the strong coupling constant, typically running with scale.

2. Linear Confinement Potential

Models long-range confinement, ensuring quarks cannot escape:

$$V_{\square\square\square\square\square\square}(r) = ar + b$$

Here, a is the string tension ($\approx 0.18\ \square\square\square^2$) and b is an adjustable constant.

3. Harmonic Oscillator Potential

A mathematical simplification:

$$V_{\square\square}(r) = \frac{1}{2}kr^2$$

Where k is the oscillator strength. Often used for analytical calculations of wave functions.

4. Yukawa Potential

Describes meson-mediated interactions:

$$V_{\square\square\square\square\square\square}(r) = -g^2\frac{e^{-mr}}{r}$$

Where g is the coupling and m is the meson mass. Useful for including medium-range effects.

Total Potential in NRQM:

$$V_{q-q}(r) = V_{\square\square\square\square\square\square\square} + V_{\square\square\square\square\square\square} + V_{\square\square} + V_{\square\square} + V_{\square\square\square\square\square\square}$$

3. Mass Spectra of Heavy Baryons

By solving the Schrödinger equation with the above potentials, one can predict baryon masses. Typical examples:

Baryon	Predicted Mass (MeV)	Potential Model
$\square_{bc}$	6979	Coulomb + Linear
$\square_{bc}$	7109	Coulomb + Linear
$\square_{c}$	2286	Harmonic Oscillator
$\square_{c}$	2455	Coulomb + Linear + Spin-Spin

- **Spin-dependent splittings** produce mass differences between states with same quark content but different total spin.
- NRQM predictions are often consistent with LHCb and Belle experimental data.
- Sensitivity to potential parameters allows fine-tuning for better agreement.

4. Decay Properties

Heavy baryon decays are classified as:

1. **Strong Decays:** Emission of light mesons (pions, kaons). Dominant for excited baryons.
2. **Weak Decays:** Semileptonic and non-leptonic processes. Important for CKM matrix studies.
3. **Electromagnetic Decays:** Radiative transitions, e.g., $\square_c^* \to \Lambda_c \gamma$.

Decay rates depend on:

- Wave function overlaps of initial and final states.
- Spin-flavor couplings.
- Kinematic factors.

NRQM provides a straightforward way to calculate matrix elements for these decays.

5. Internal Structure and Wave Functions

Baryon wave functions are decomposed as:

$$\Box_{\Box\Box\Box\Box\Box\Box}(r_1, r_2, r_3) = \psi_{\Box\Box\Box\Box\Box} \otimes \Box_{\Box\Box\Box\Box} \otimes \Box_{\Box\Box\Box\Box\Box\Box} \otimes \Box_{\Box\Box\Box\Box\Box}$$

- **Spatial Wave Function:** Determines quark distributions and baryon sizes.
- **Spin Wave Function:** Affects hyperfine splitting and magnetic moments.
- **Flavor Wave Function:** Encodes quark content and symmetry properties.
- **Color Wave Function:** Ensures baryons are color singlets.

By analyzing $\Box_{\Box\Box\Box\Box\Box}$, one can compute:

- Charge radii
- Magnetic moments
- Electromagnetic form factors

6 Future Prospects

Potential areas for further research include:

- Relativistic extensions of NRQM for heavy-light baryons.
- Incorporation of three-body forces derived from lattice QCD.
- Detailed study of triply heavy or exotic baryons.
- Experimental validation of predictions with next-generation colliders.

7. CONCLUSION

The Non-Relativistic Quark Model, combined with various quark-quark potentials, provides a solid theoretical framework to study heavy baryons. Despite its simplicity, NRQM effectively captures essential features of QCD, including confinement and short-range interactions, allowing reliable predictions of mass spectra, decay properties, and internal structures. Future refinements, including relativistic corrections and improved potential models, will further enhance its predictive power and alignment with experimental results.

REFERENCES

1. S. Noh, "Nonrelativistic quark model analysis of heavy baryons," *Phys. Rev. D*, vol. 108, p. 014004, 2023.
2. M. Pervin, W. Roberts, and S. Capstick, "Semileptonic decays of heavy Λ baryons in a quark model," *Phys. Rev. C*, vol. 72, p. 035201, 2005.
3. Q. F. Song, "Bottom-charmed baryons in a nonrelativistic quark model," *Eur. Phys. J. C*, vol. 84, p. 12426, 2024.
4. Particle Data Group, "Quark Model," *Review of Particle Physics*, 2024.
5. R. K. Bhaduri, *Models of the Nucleon: From Quarks to Soliton*, Addison-Wesley, 1988.
6. S. Capstick and N. Isgur, "Baryons in a relativized quark model with chromodynamics," *Phys. Rev. D*, vol. 34, p. 2809, 1986.
7. D. Ebert, R. Faustov, and V. Galkin, "Masses of heavy baryons in the relativistic quark model," *Phys. Rev. D*, vol. 72, p. 034026, 2005.
8. J. Vijande, F. Fernandez, and A. Valcarce, "Constituent quark model study of heavy baryons," *J. Phys. G*, vol. 31, p. 481, 2005.