The Heavy Proton

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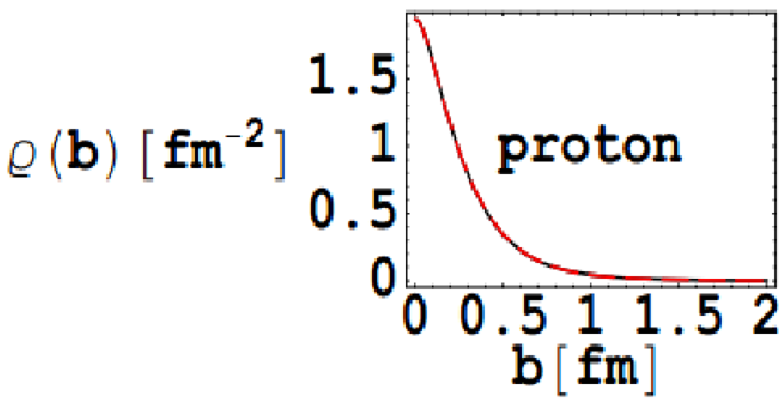
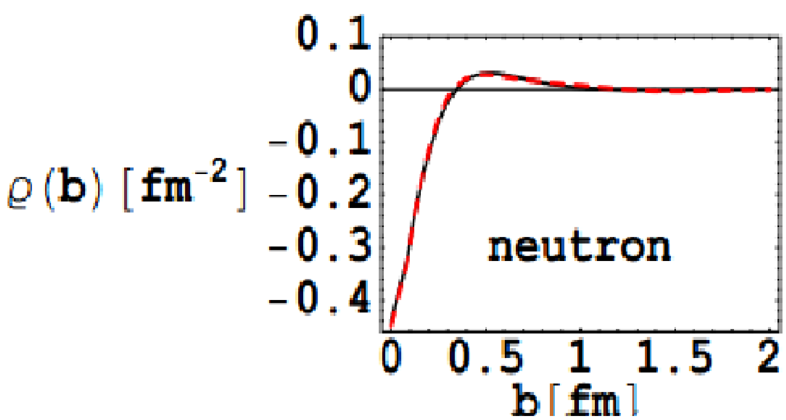
Introduction

The proton is the nucleus of the hydrogen atom, which has one orbiting electron. The proton is the least massive of the baryons. Its mass is 938.272046 $\pm$ 0.000021 MeV, compared to the electron mass of 0.510998928 $\pm$ 0.000000011 MeV, with the ratio 1.83615266 $\pm$ 0.000021.

The "heavy hydrogen" or deuterium atom is a hydrogen atom with a neutron in the nucleus along with the proton. The neutron mass is 939.565379l $\pm$ 0.000021 MeV. The proton and neutron, collectively called nucleons, have spin ½, isospin ½, positive parity and baron number 1, which define nucleons. The proton electric charge is the same as the electron charge with opposite sign. The electron charge is e = (-1.602176565 $\pm$ 0 .000000035) x 10^{-19} coulombs. The neutron has no total electric charge, but it does have a charge distribution, as described below. The charge radius of the proton is ~0.85 x 10^{-15} meters = ~0.85 fm. (Ref. 11):





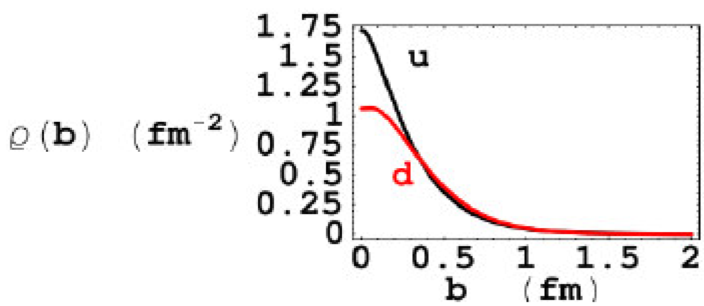
The proton charge radius is slightly positive at large distances and the neutron charge radius is slightly negative at large distances. The area under the proton curve is the charge; the area between the neutron curve and the 0 b-axis is 0 (above is + and below is --)

These charge distributions cause the nucleons to have magnetic moments in nuclear-magneton units (Refs. 16 & 21):

- Proton: 2.792847356 $\pm$ 0.000000023
- Neutron: (1.9130427 $\pm$ 0.0000005

The antiproton has negative electric charge; the antineutron has no electric charge. They both have baryon number -1 (Ref. 12).

The proton is composed of 2 up quarks (u) and 1 down quark (d). The u quark has electric charge +2e/3 and the d quark has electric charge -1e/3. They both have baryon number ½. The neutron is composed of 2 d quarks and 1 u quark. The quark masses are u = 2.3 $\pm$ 0.6 MeV and d = 4.8 $\pm$ 0.4 MeV (Refs. 13 & 16). It is posited that the force (gluon interactions with the quarks, Ref. 14) binding the quarks in the nucleon increases without limit as the separation between the quarks increases. So, the quarks cannot escape the nucleon (Rev. 15). A simple model of such a confining force is the 3-dimensional harmonic oscillator (Ref. 17). The quark density for both nucleons is (Ref. 11):



Heavy Nucleons

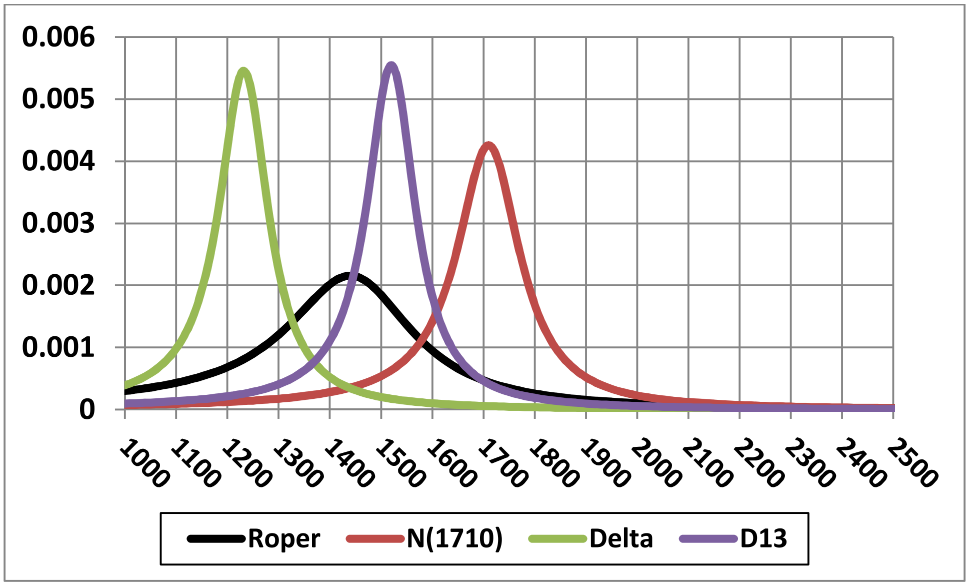
There are known two more massive versions of nucleons, which are called resonances because, when created, they quickly decay to a proton or a neutron and other final particles (Ref. 16):

- N(1440): mass of 1440 $\pm$ ~25 MeV with a resonance width of 300 $\pm$ ~125 MeV
- N(1710): mass of 1710 $\pm$ ~30 MeV with a resonance width of 150 $\pm$ ~100 MeV

These are Breit-Wigner resonance positions and widths (Ref. 18).

The first of these was discovered by the author in 1963, so it is informally called the Roper Resonance (Refs. 2-6). The title of this document, The Heavy Proton, refers to this massive nucleon. These resonances can be regarded as excited states of the nucleon.

Resonances can be represented mathematically by the relativistic Breit-Wigner distribution (Ref. 17). The following is a plot of the Roper and the N(1710) heavy protons along with two other well-established nucleon resonances, the Delta and the D13:



These resonance curves are normalized to 1 for the area under the curve.

Note that the Roper is much broader than the other resonances shown. It was hard to find in pion-nucleon scattering data because it caused a small shoulder on the side of the D13 resonance.

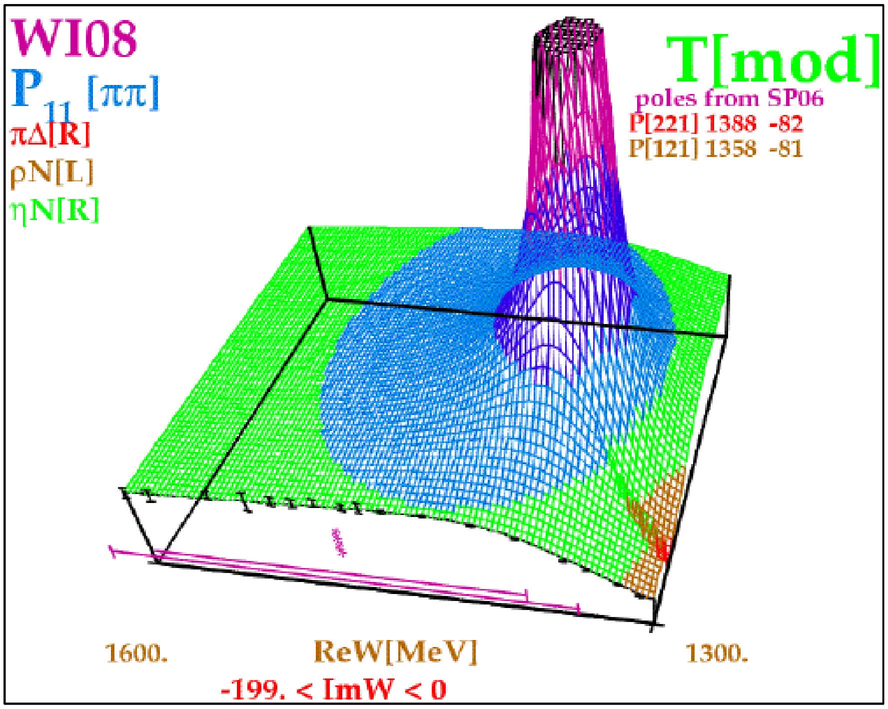
Structure of the Roper Resonance

The internal structure of the Roper Resonance has been a long-term mystery. Here is a summary of some of the possibilities:

- Radial excitation of the 3 quarks in the nucleon (Ref. 26). In the simple 3-dimensional harmonic oscillator model the nucleon is the lowest energy level and the excited states are higher energy levels (Ref. 17)
- Quark-Diquark state: The interaction is different for the two quarks in the Diquark than it is between the quark and the Diquark. (Ref. 27)
- Pentaquark structure: 3 quarks and a quark-antiquark pair (sea quarks). The quarks pair can convert into a gluon (Ref. 19)
- Hybrid structure: 3 quarks and 1 gluon. Appears to be similar to the pentaquark structure. (Ref. 28)
- 3D harmonic oscillator representation for the Roper and other nucleon resonances assuming the 3-quark model for all nucleon resonances (Ref. 33)

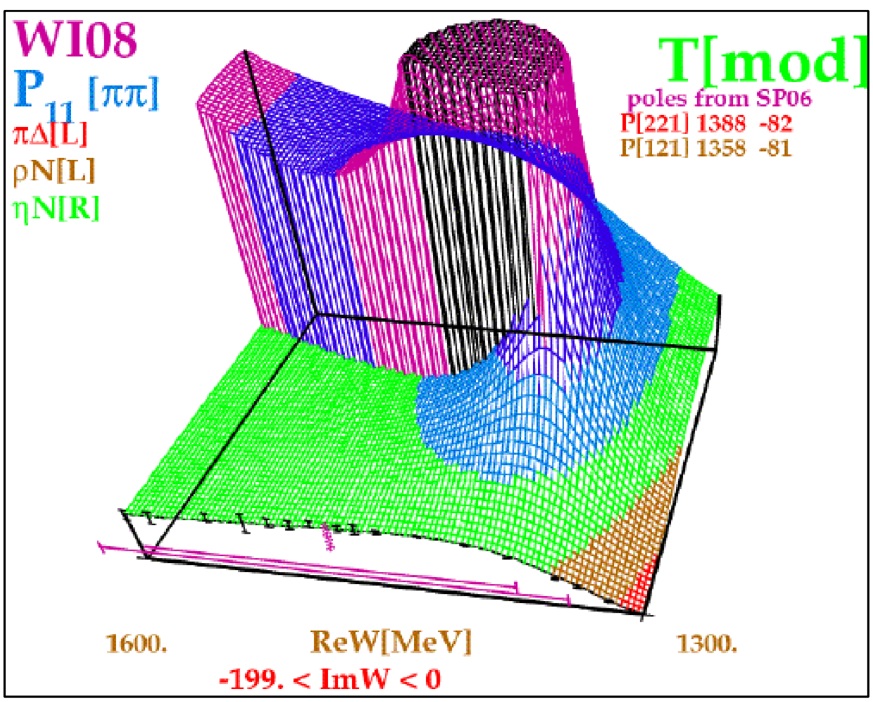
I think it is fair to say that the internal structure of the Roper resonance has not been settled yet.

The Roper pole position (Ref. 20) in the complex energy plane as determined by fitting scattering and production data is



Note that the pole position and width differ considerably from the Breit-Wigner resonance position and width: N(1440): mass of 1440 ± ~25 MeV with a resonance width of 300 ± ~125 MeV

There is another nearby pole in the unphysical complex plane behind the first pole.



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