Modifications of MC Generator DCM-QGSM-SMM

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Why do we need to improve DCM-QGSM-SMM?

Advatages

- Description of residual nuclei (multi)fragmentation
- Adequate (more or less) description particles yield at NICA energies

Shortcomings (in central collisions)

- Smaller yield of light nuclei coming from coalescence
- Enhanced yield of some species
- Softer momentum spectrum of some species

What do we need to improve DCM-QGSM-SMM?

- Improve the yield of light fragments
- Modification of hadron properties in a dense nuclear matter
- Take into account **nuclear deformation**

Nuclear Deformation: Motivation

Deformation of colliding nuclei leads to increasing fluctuations of many observables

- multiplicities,
- centrality estimation,
- reaction plane estimation
- flows,
- …

For example, Multiplicity Fluctuations

Total multiplicity: $N = \sum_{i=1}^{N_s} m_i$ N_s – number of sources
m_i - multiplicity from a single source

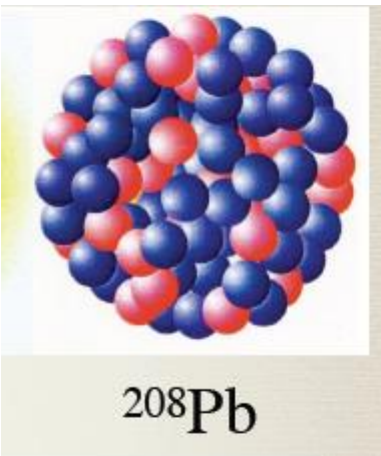
Mean multiplicity: $\langle N \rangle = \langle N_s \rangle \langle m \rangle$

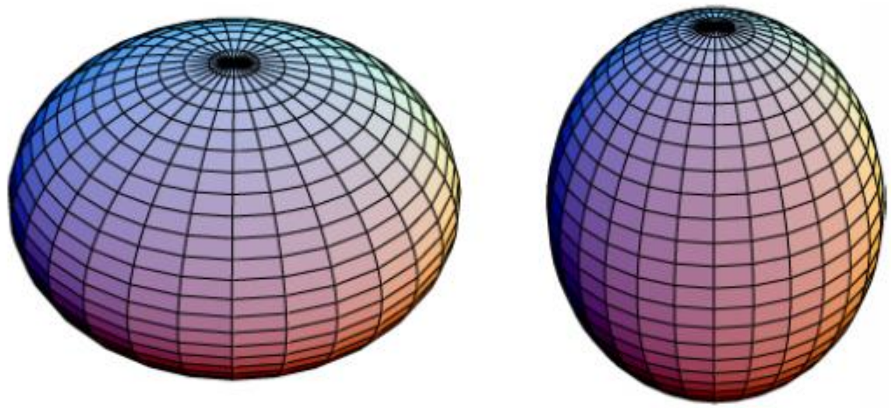
$$\frac{\sigma_N^2}{\langle N \rangle} = \frac{\sigma_m^2}{\langle m \rangle} + \langle m \rangle \frac{\sigma_{N_s}^2}{\langle N_s \rangle}$$

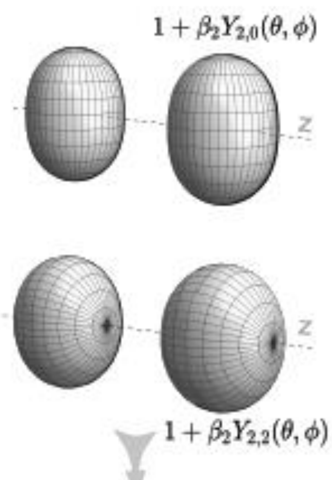
Shapes of nuclei
Geometry of collision

Nuclear Deformation

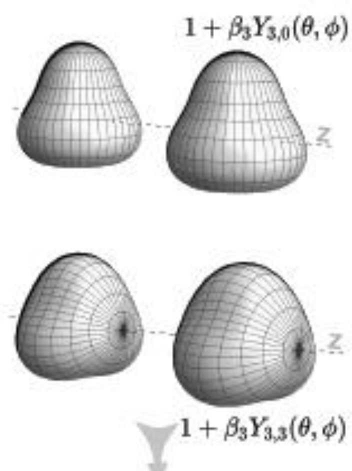
- Nuclei are not spherically symmetric



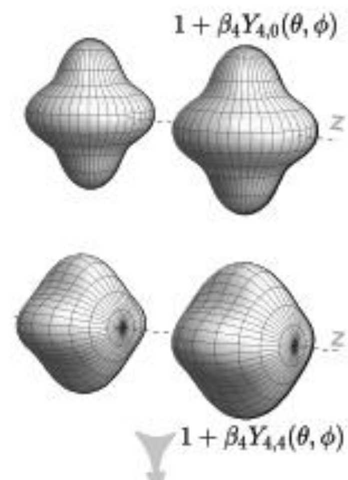




quadrupole



octupole



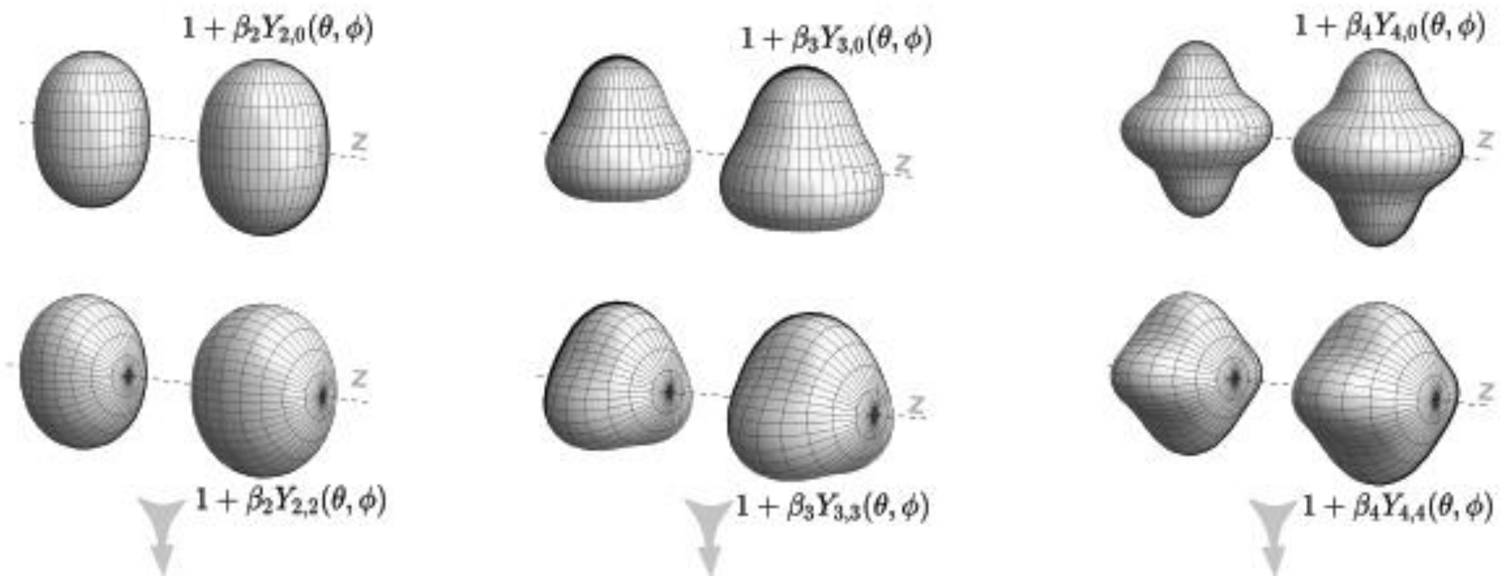
hexadecupole

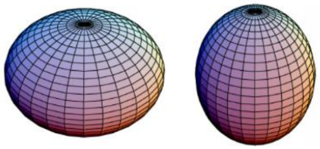
Nuclear Deformation Theory

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{[r-R(\theta,\phi)/a_0]}}$$ - Nuclear density

$$R(\theta,\phi) = C(\alpha_{\lambda\mu})R_0\left[1+\sum_{\lambda=0}^{\infty}\sum_{\mu=-\lambda}^{\lambda}\alpha_{\lambda\mu}Y_{\lambda}^{\mu}(\theta,\phi)\right]$$ - Nuclear radius

$$R(\theta,\phi) = R_0\left(1+\beta_2[\cos\gamma Y_{2,0}+\sin\gamma Y_{2,2}]+\beta_3\sum_{m=-3}^{3}\alpha_{3,m}Y_{3,m}+\beta_4\sum_{m=-4}^{4}\alpha_{4,m}Y_{4,m}\right),$$





Nuclear Deformation

Quadrupole Deformation

Intrinsic deformation of spheroid

$$Q_0 = \int (3z^2 - r^2) d^3 r$$

Electric Quadrupole Deformation

$$Q_0 = \frac{2}{5} Ze \left(a^2 - b^2\right)$$

$$\Delta R = a - b$$

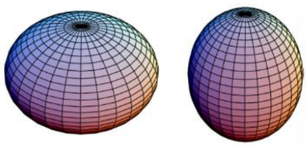
$$\delta = \frac{\Delta R}{\langle R \rangle}$$

$$Q_0 = \frac{4}{5} Ze \langle R \rangle^2 \delta$$

Nuclear Deformation

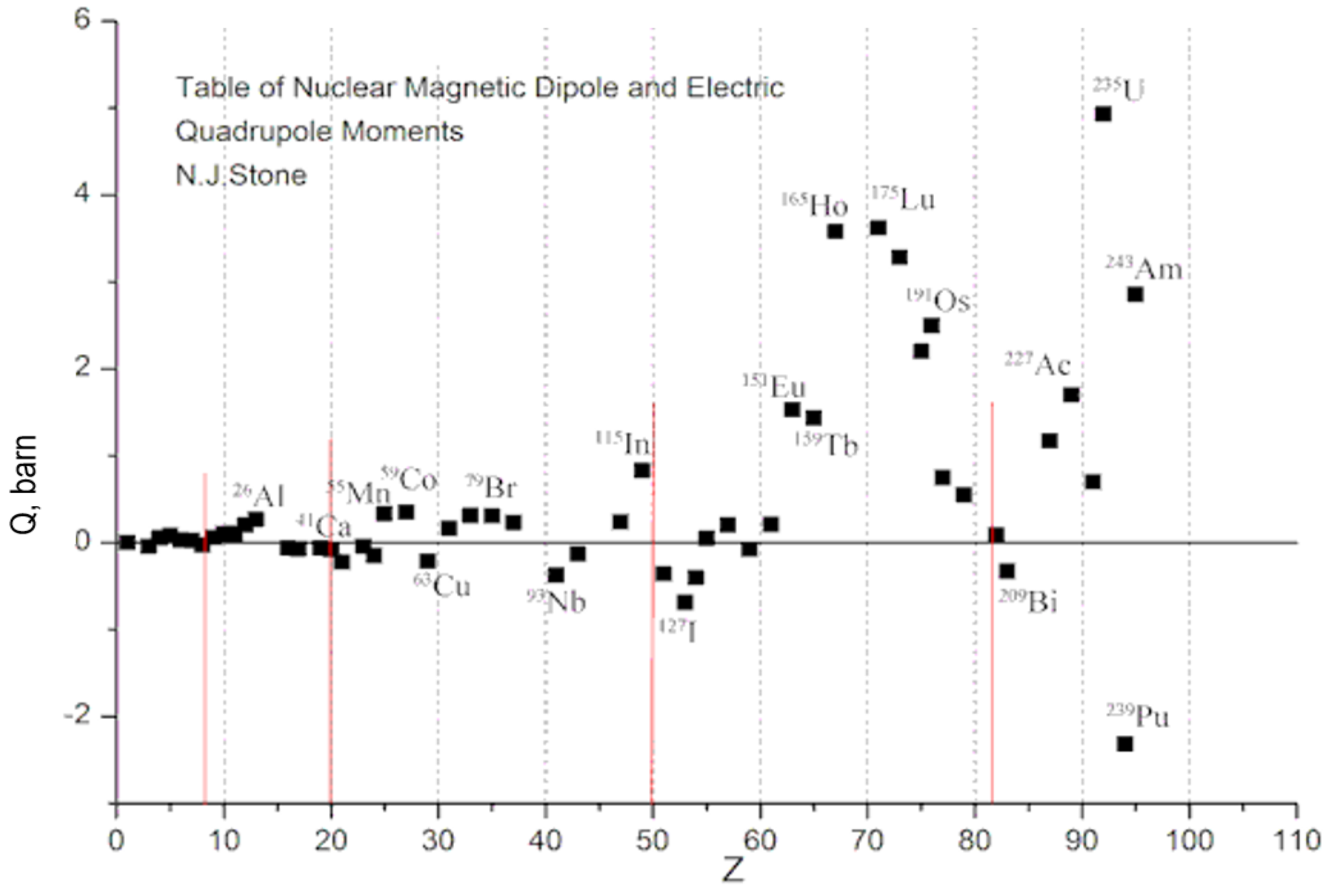
Experiment

EM Quadrupole Moment



For nuclei with spin J ≥ 1

$$Q = \frac{J(2J-1)}{(J+1)(2J+3)} Q_0$$



How to implement deformation into a nuclear model?

Problem

- EM Q << Q_0, for exp. For J = 3/2 Q_0 = 10 Q
- We know nothing about the shape of neutron distributions!

Solution

The Model: **SCQM + FCC** (*N.Cook, G.Musulmanbekov PAN,2008*)

(Strongly Correlated Quark Model + Face-Centered-Cubic lattice)

1. allows to construct the nuclear structure that unifies the features of liquid drop, cluster and shell models
2. demonstrate that all nuclei are intrinsically deformed
3. allows calculate the shapes of proton and neutron distributions inside nuclei

Quark Arrangement inside Nuclei

Strongly Correlated Quark Model

G.Musulmanbekov 1995

↓

Face-Centered-Cubic (FCC) Lattice - like arrangement of Nuclear Structure

N. Cook, G. Musulmanbekov 2008

Quark-Antiquark System
Constituent Quarks – Solitons

Quark-antiQuark $\equiv$ **Breather Solution** of Sine- Gordon equation

$$\partial_{\mu}\partial^{\mu}\phi(x,t)+\sin\phi(x,t)=0$$

Breather – oscillating soliton-antisoliton pair:

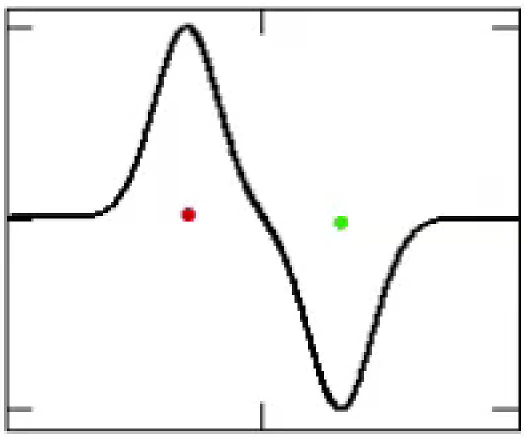
$$\phi(x,t)_{s-as}=4\tan^{-1}\left[\frac{\sinh\left(ut/\sqrt{1-u^{2}}\right)}{u\cosh\left(x/\sqrt{1-u^{2}}\right)}\right]$$

$$\varphi(x,t)_{s-as}=\frac{\partial\phi(x,t)_{s-as}}{\partial x}$$

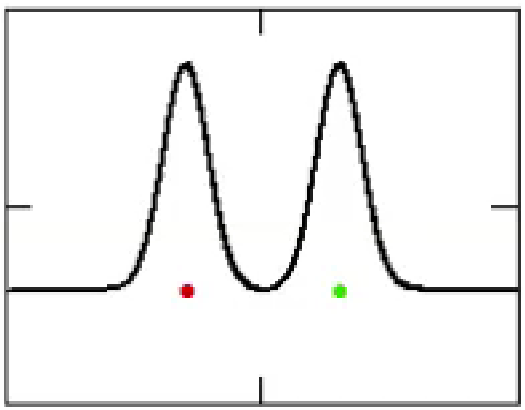
is identical to our quark-antiquark system;

Breather – quark-antiquark pair
Meson

$\varphi(x,t)$



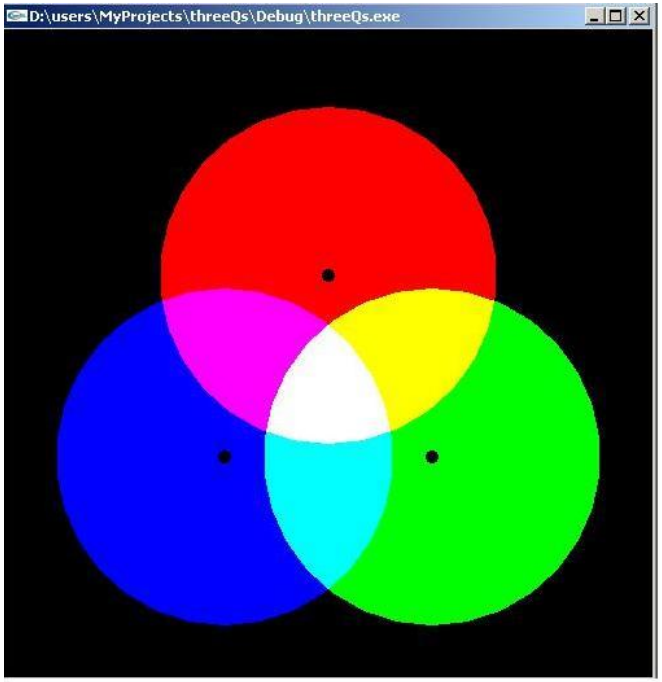
$\varepsilon(x,t)$



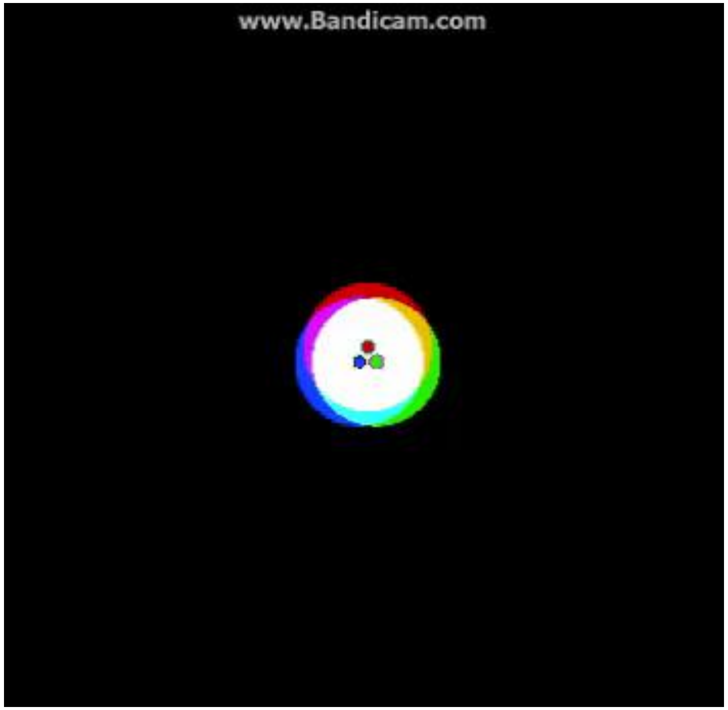
SCQM

Nucleon – 3-color quark system

$SU(3)_{color} \Longleftrightarrow RGB$



Nucleon



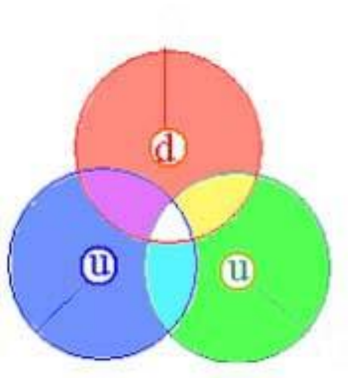
SU(3)$_{color}$ - singlet

Interplay between constituent and current quark states

Chiral Symmetry Breaking ⟺ Restoration

t = 0

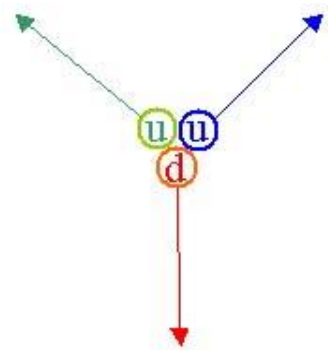
$x = x_{max}$



Constituent quaks

$t = T/4$

$x = 0$

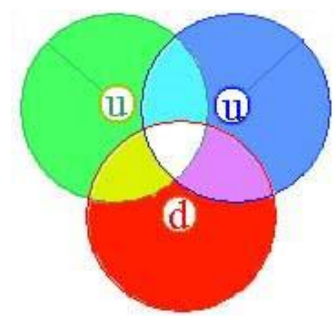


current quarks

Asymptotic freedom

$t = T/2$

$x = -x_{max}$

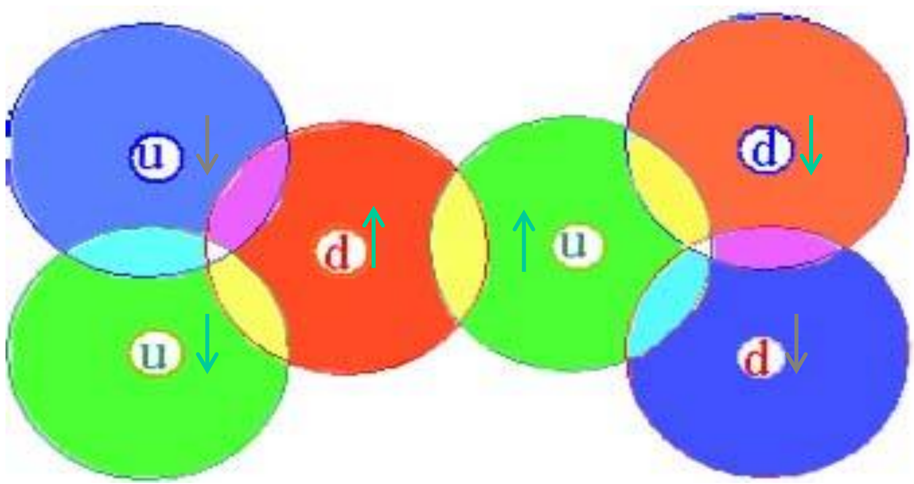


Constituent quarks

During the valence quarks oscillations:

$$\left|B\right\rangle = a_1\left|q_1q_2q_3\right\rangle + a_2\left|q_1q_2q_3\bar{q}q\right\rangle + a_3\left|q_1q_2q_3g\right\rangle + \ldots$$

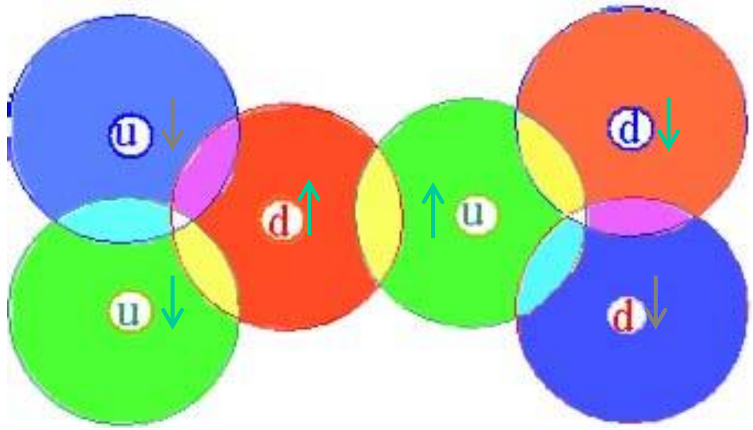
Two Nucleon System in SCQM



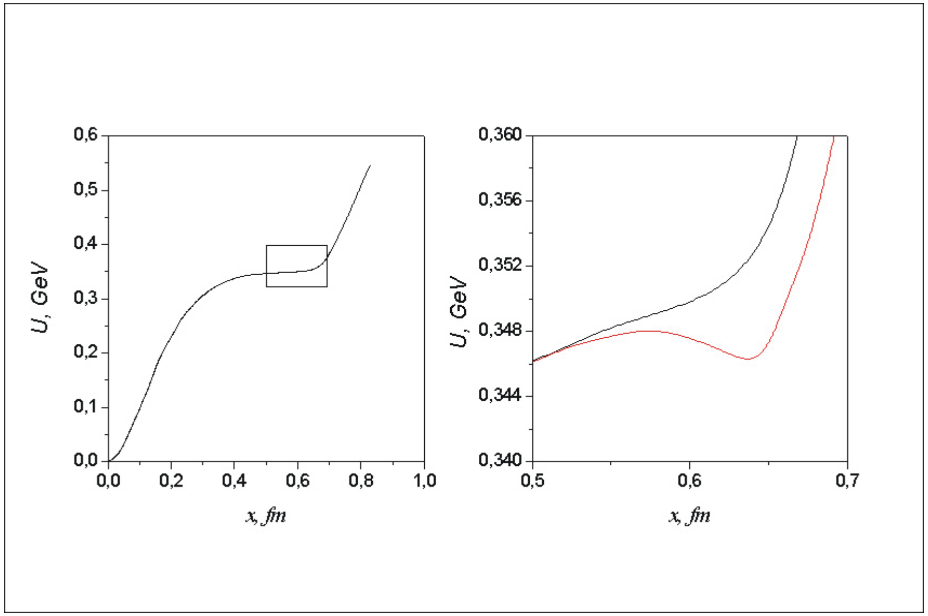
Selection rules for binding two quarks of neighboring nucleons at a junction:

- $SU(3)_{Color}$ – of different colors
- $SU(2)_{Flavor}$ – of different flavors
- $SU(3)_{Spin}$ – of parallel spins

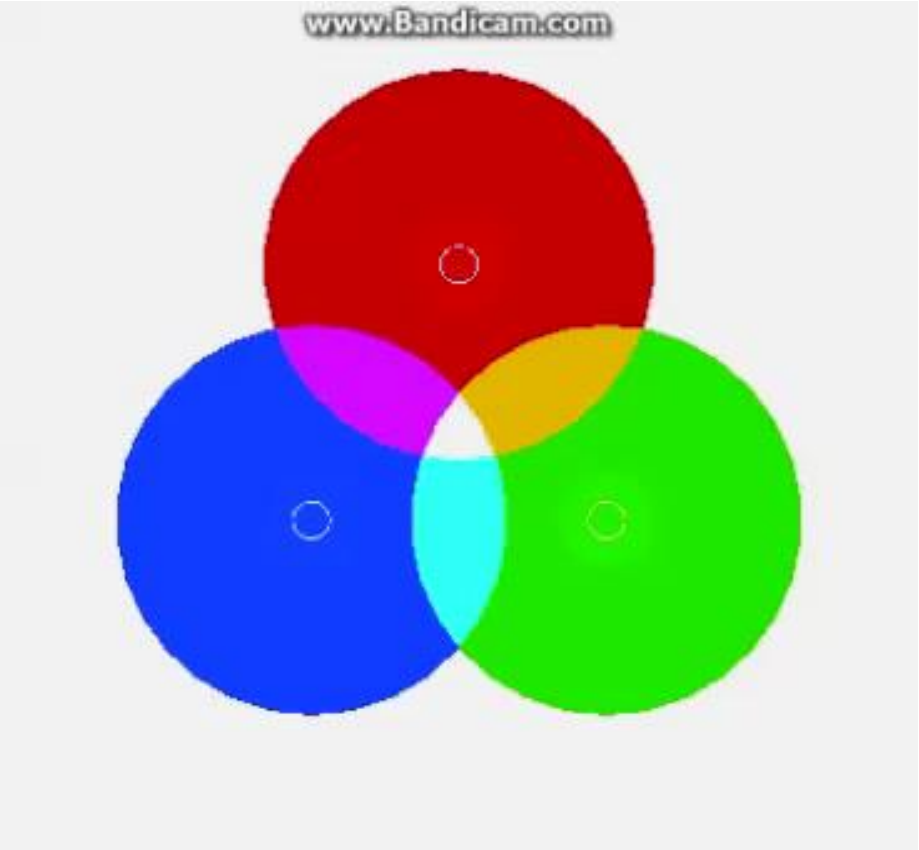
Two Nucleon System in SCQM



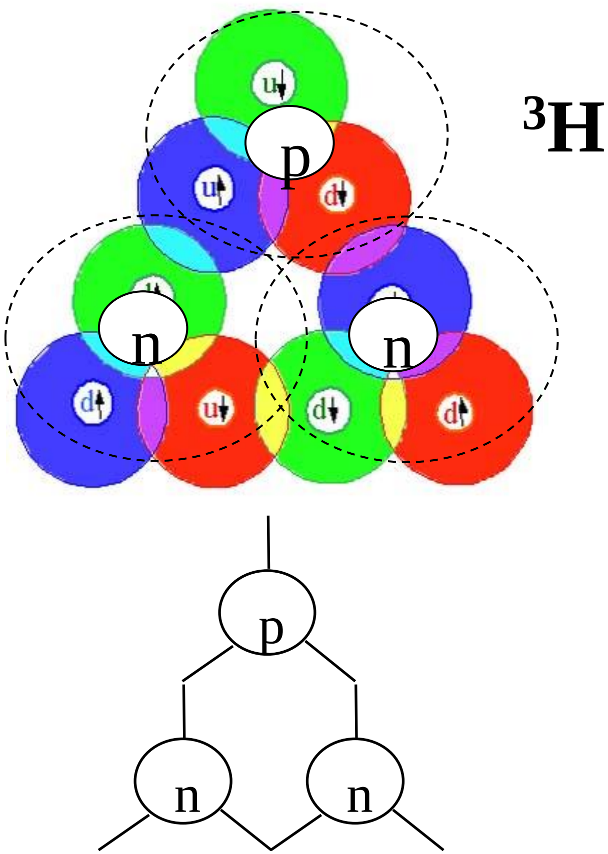
Quark Potential Inside Nuclei

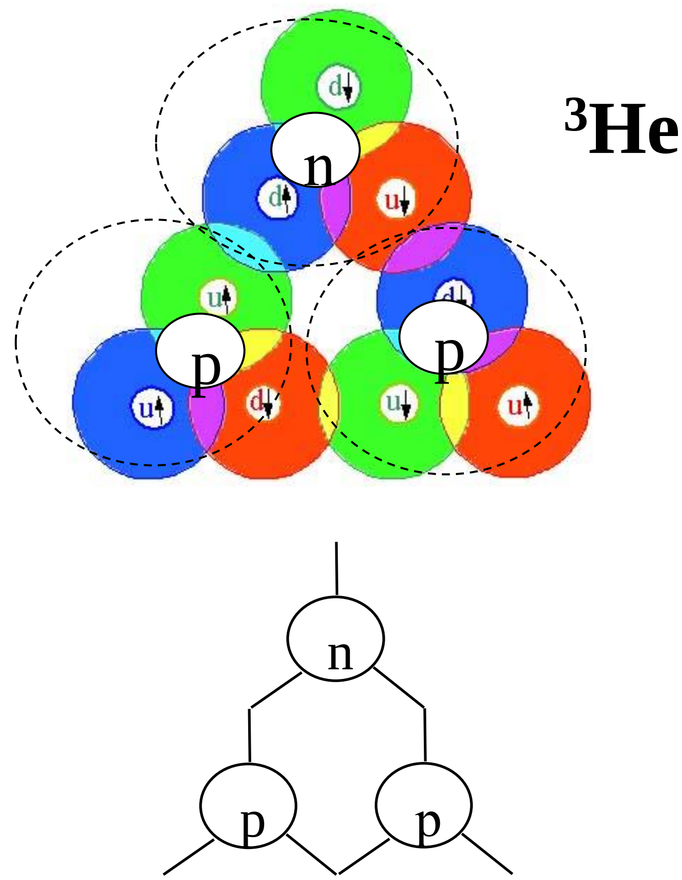


Quarks inside nucleus



Three Nucleon Systems in SCQM

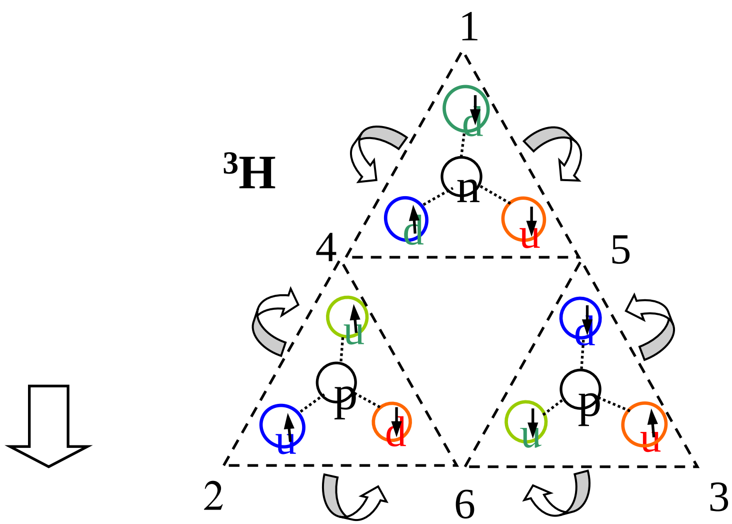




Quark loop → 3 – body force

The closed shell n = 0,   nucleus ^{4}He

^{3}He + neutron or ^{3}H + proton

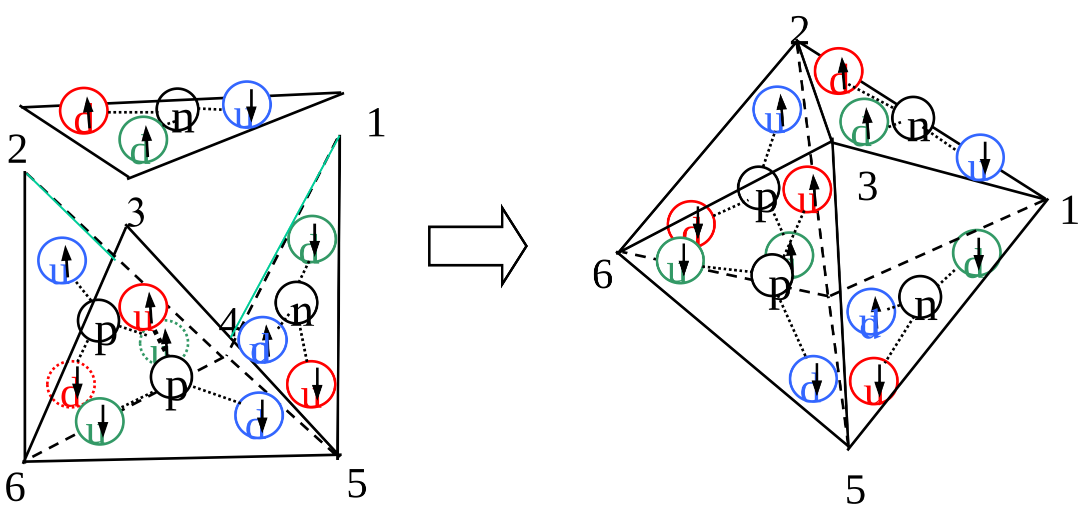


Junctures

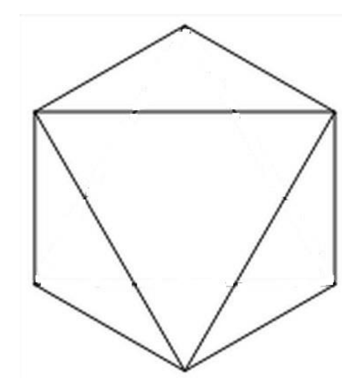
1 ←→ 1

2 ←→ 2

3 ←→ 3



Shell Closure

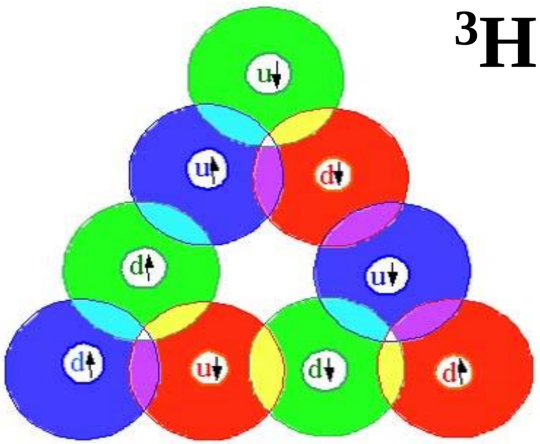


Binding Energy of Stable Nuclei Experiment

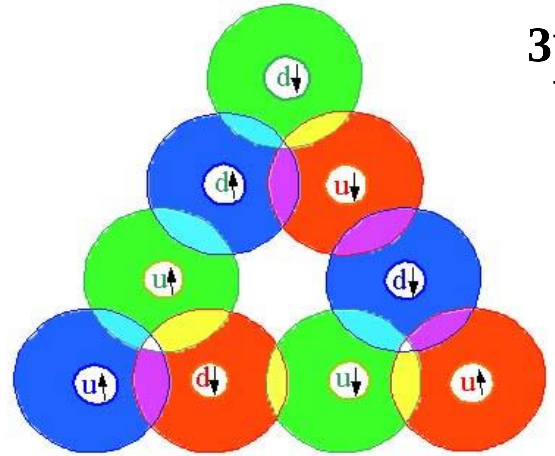
Nucleus	E_B, MeV per junction	Number of quark loops	Free quark ends	Nuclear forces
d	1.1	no	4	2-body (attr. + repul.)
^3H	2.83	1	3	2-body + 3-body (attr.)
^3He	2.57	1	3	2-body + 3-body (attr.)
^4He	7.07	4	0	2-body + 4-body (attr.)

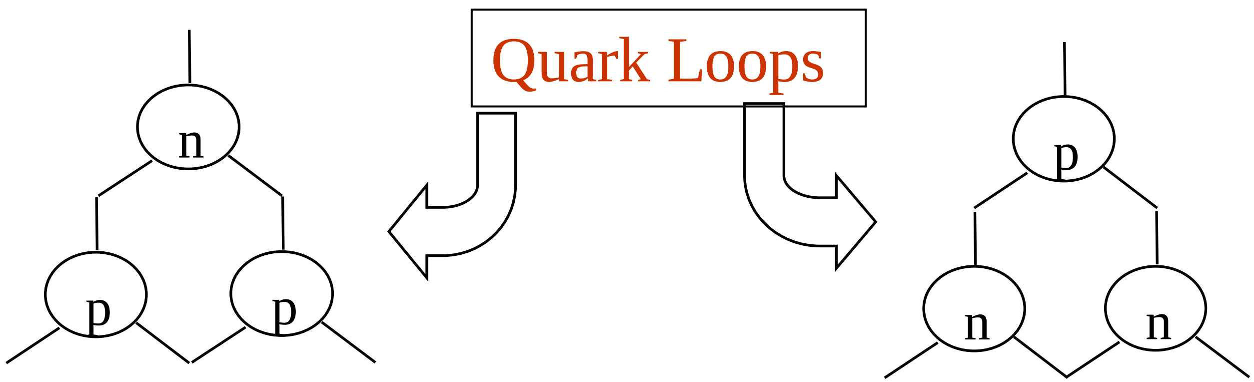
Three Nucleon Systems in SCQM

^3H



^3He





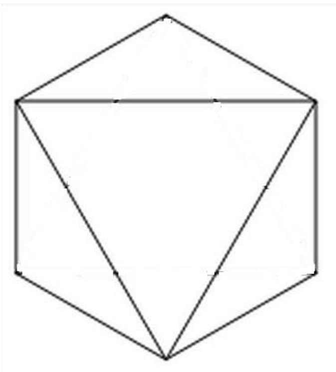
^3He – block

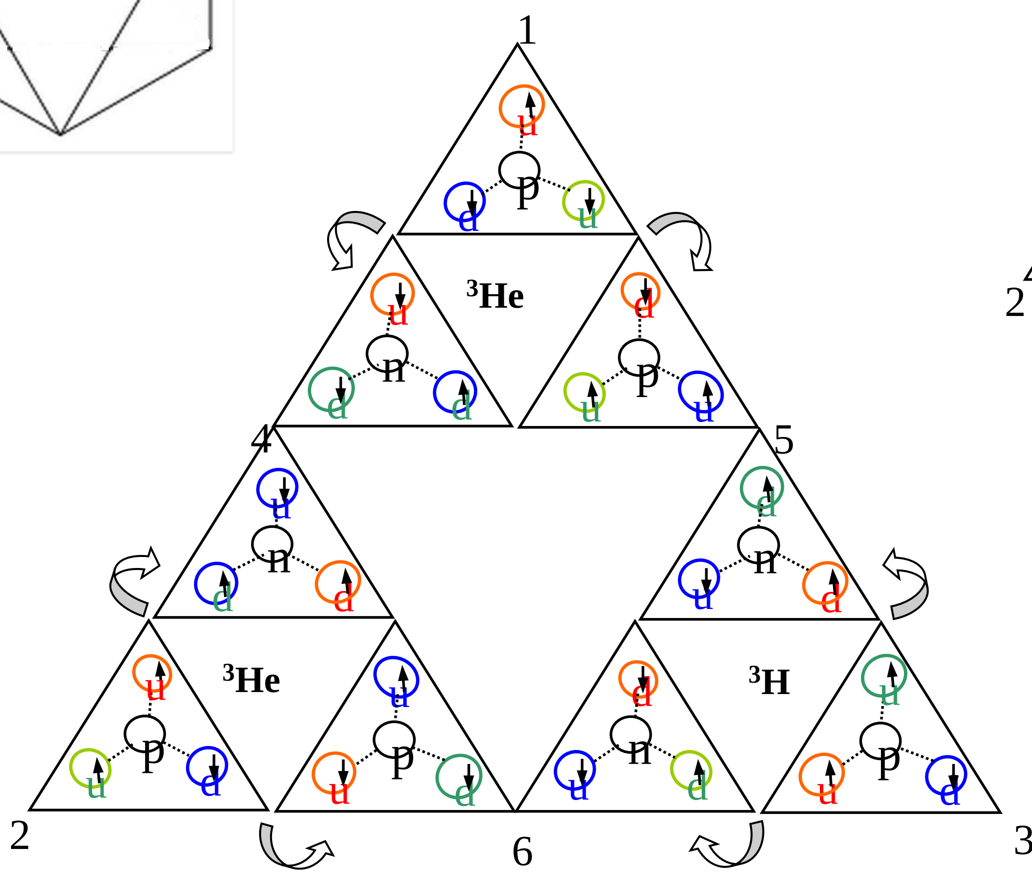
^3H – block

Basic building blocks of Nuclear Structure

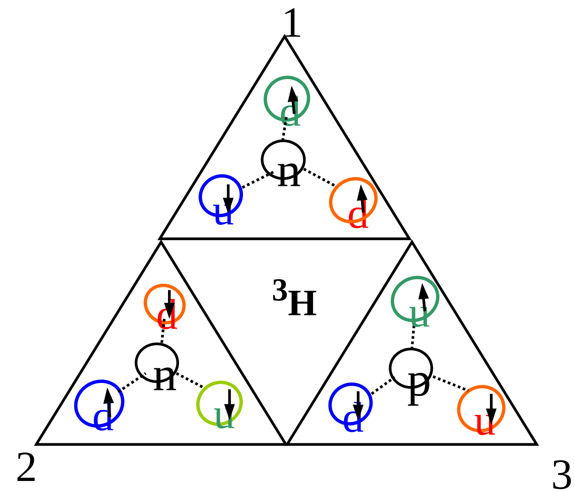
The closed shell n = 1, ^{16}O

Shell Closure



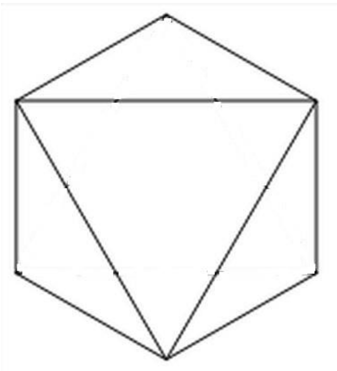


Face of ^{16}O octahedron

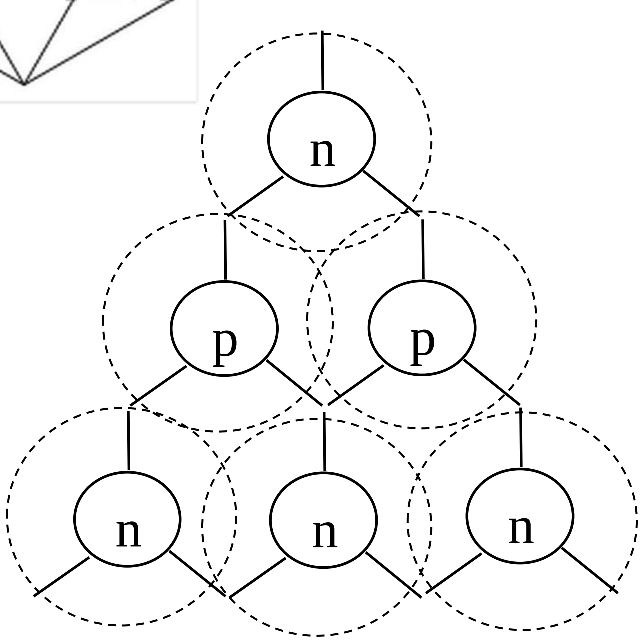


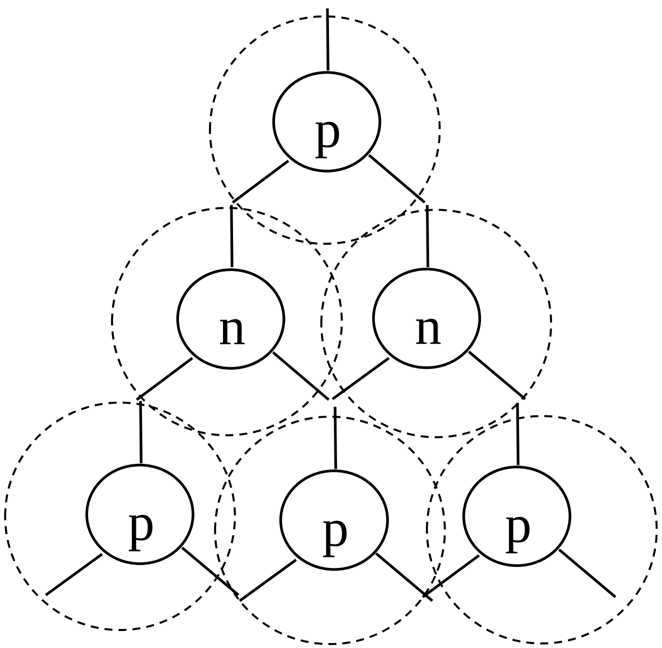
The closed shell n = 2, ^{40}Ca

Shell Closure

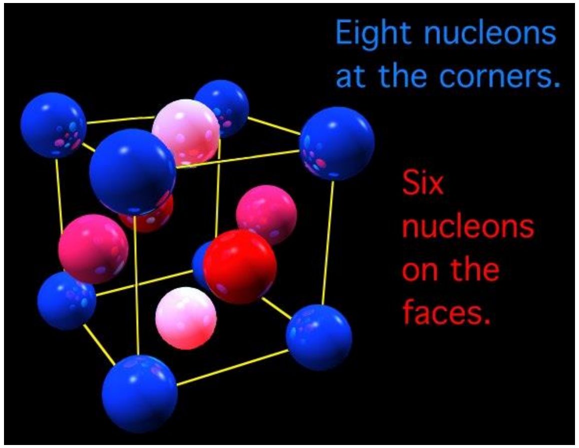


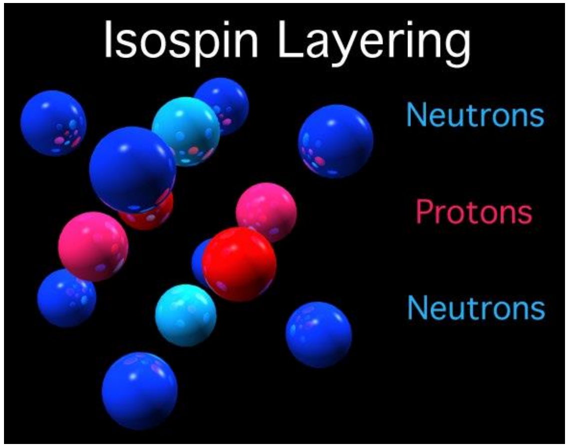
Faces of ^{40}Ca octahedron

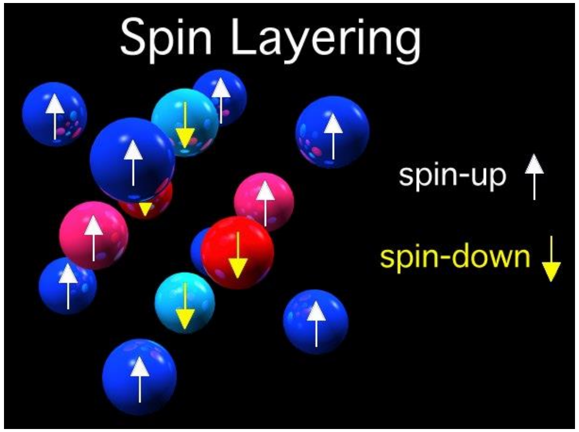


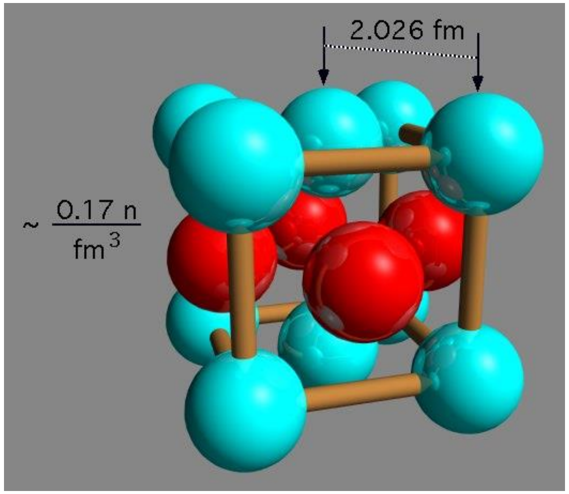


SCQM →FCC Lattice





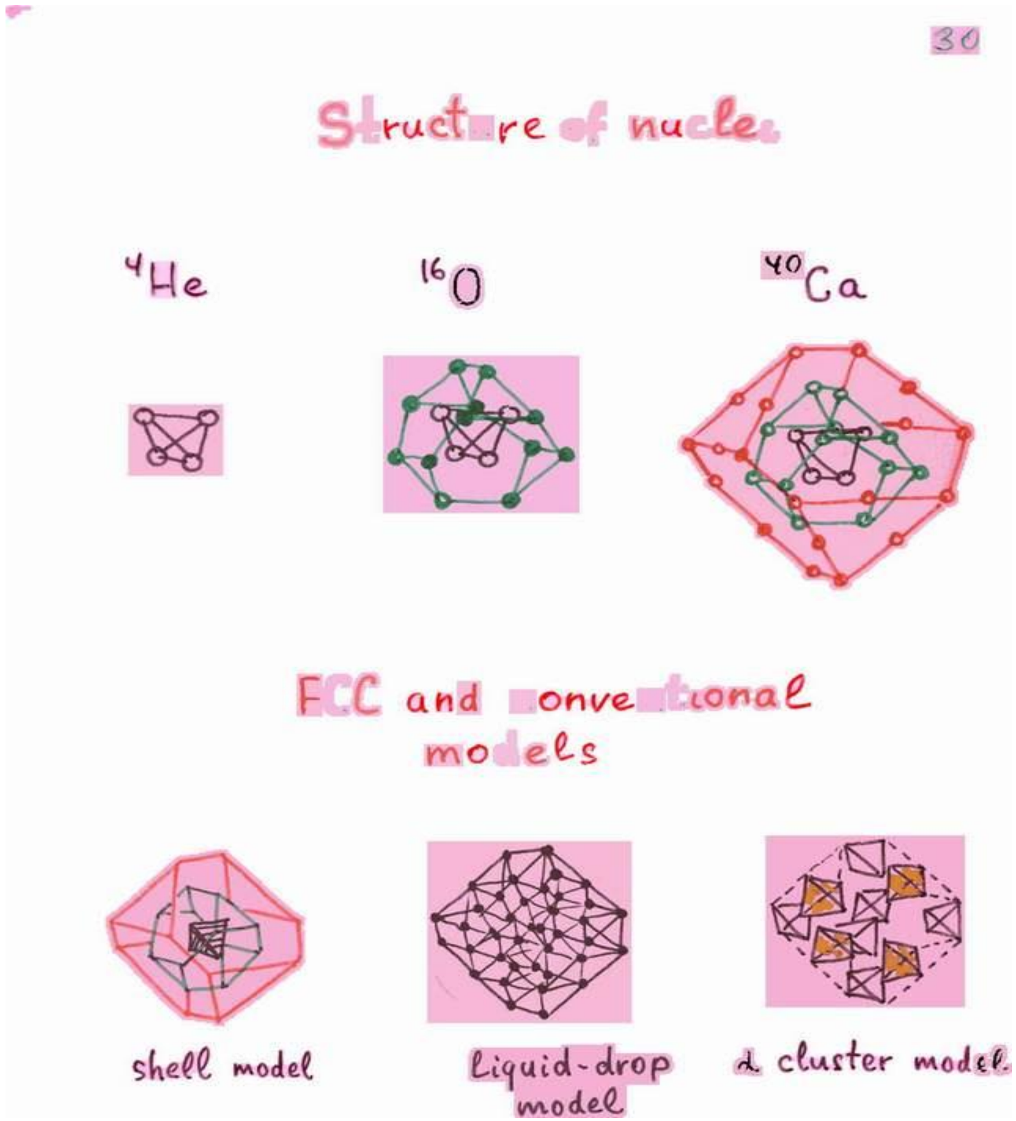




SCQM → Nuclear Structure

- Nucleon are located on the sites of face-centered cubic lattice.
- Protons and neutrons are **strongly correlated**
- Nuclei with a closure shells has a shape of tetrahedron (s-shell) and truncated tetrahadron/octahadron (p, d, f, …-shells).
- Nucleons are arranged in alternating (antiferromagnetic) spin, isospin layers.
- SCQM leads to Face-Centered-Cubic (FCC) Lattice symmetry of nuclear structure!

Face – Centered – Cubic Lattice Model (FCC) (N. Cook, 1987)



FCC Lattice Model

Particle in 3D box

$$-(h^2/2m)(d^2\Psi/dr^2) + V(r)\,\Psi(r) = E\,\Psi(r)$$

For harmonic oscillator potential cartesian coordinate system

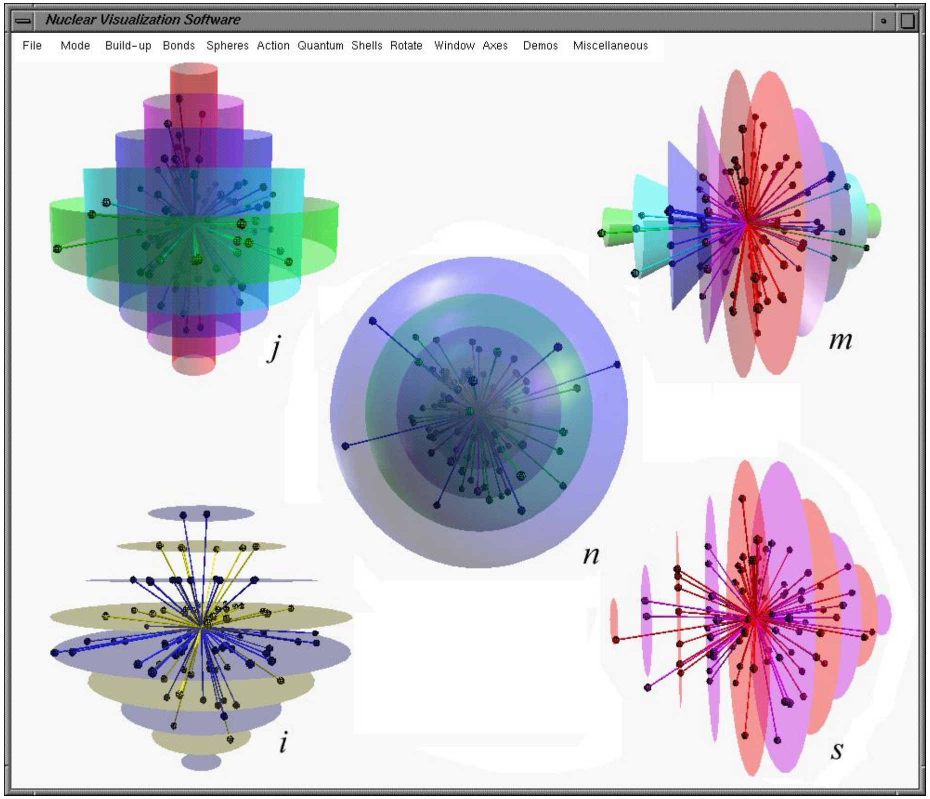
$$E_N = h\omega_0(n_x + n_y + n_z + 3/2) = h\omega_0(N + 3/2)$$

$$N = 0, 1, 2, 3, \ldots$$

Different combinations of $\mathbf{n_x}$, $\mathbf{n_y}$ and $\mathbf{n_z}$ that give the same total **N** – value denote spatially distinct " degenerate" states, with the same energy.

If the origin of the coordinate system is taken as the center of the central tetrahedron, then the closure of each consecutive, symmetrical (x=y=z) geometrical shell in the lattice composes precisely the numbers of nucleons in the shells derived from the three-dimensional Schrodinger equation.

Face – Centered – Cubic Lattice



$$\boldsymbol{n} = (x + y + z - 3)/2 = (r \sin\theta \cos\phi + r \sin\theta \sin\phi + r \cos\theta - 3) / 2$$

$$\boldsymbol{j} = l + s = (x + y - 1) / 2 = (r \sin\theta \cos\phi + r \sin\theta \sin\phi - 1) / 2$$

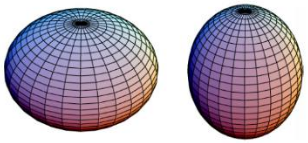
$$\boldsymbol{m} = x / 2 = (r \sin\theta \cos\phi) / 2$$

Resume on Nucleus structure

1. Close **link between the nodes of a lattice** with **quantum numbers** of **Shell Model**.
2. **Nuclei possess crystal-like structure**
3. Nucleon locations are arranged according to FCC lattice
4. All nuclei are deformed, even with shell closure!
5. Nuclear deformations are **multipolar**

Model vs Experiment

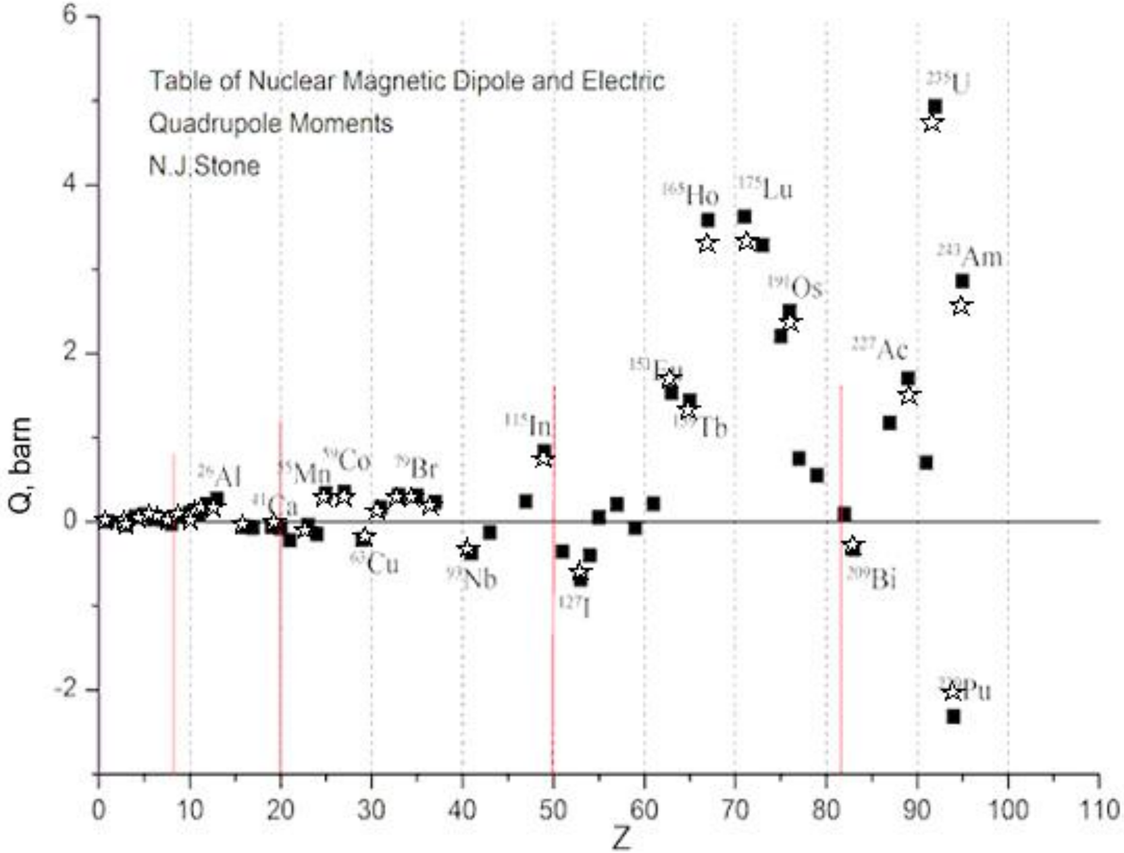
Electric Quadrupole Moment

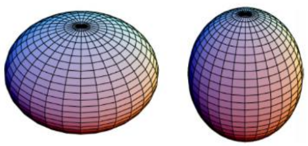


Model

$$Q = \frac{J(2J-1)}{(J+1)(2J+3)}Q_0$$

■ - Exp , ☆ - Model





Nuclear Deformation

Model vs Experiment

Charged(proton) Quadrupole Moments

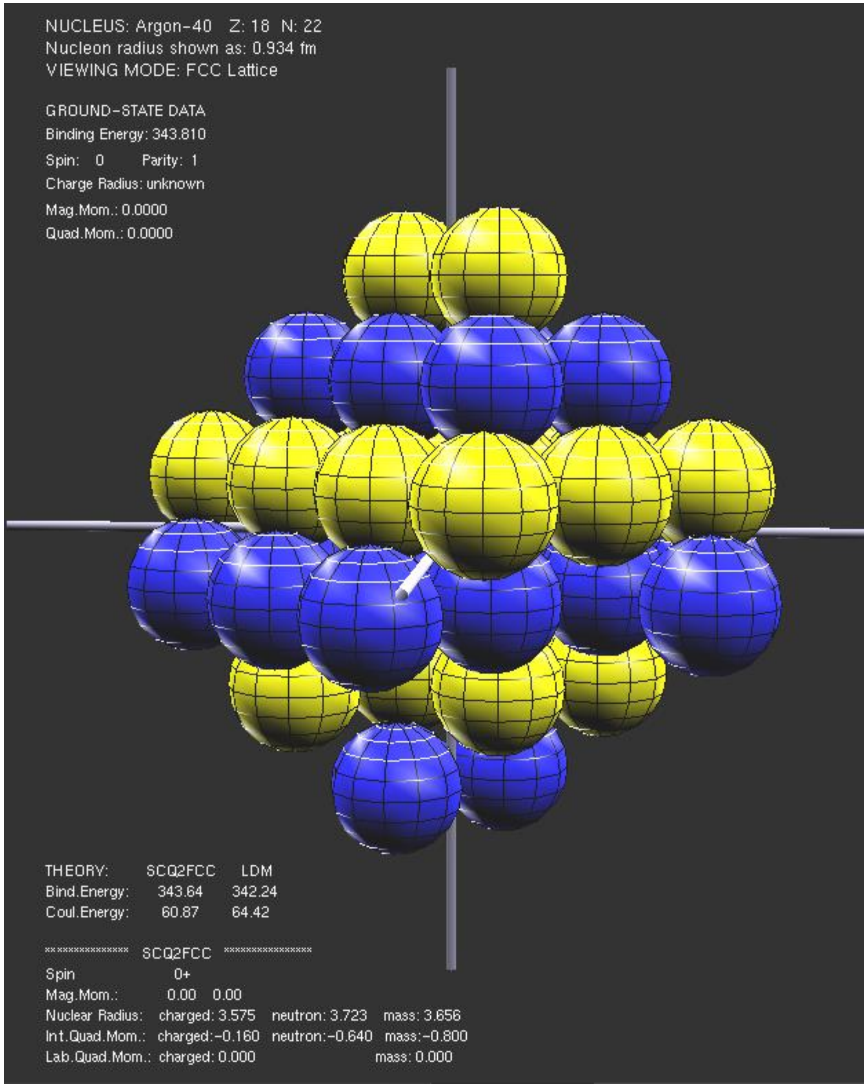
Neutron Quadrupole Moments

Nuclear Matter Quadrupole Moments

$$Q_0 = \sum_{k=1}^{Z} \left(2\, z_k^2 - x_k^2 - y_k^2\right)$$

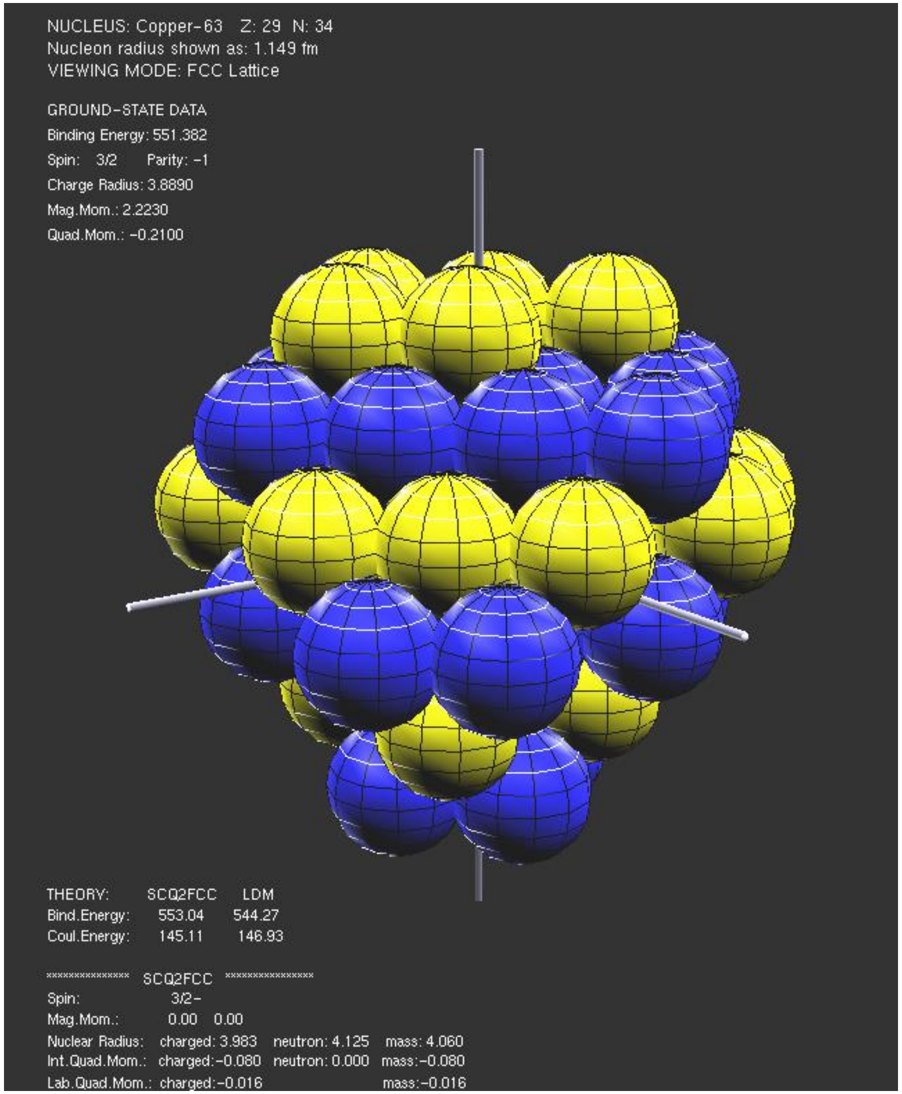
Nucleus		**C**	**Al**	**Ar**	**Cu**	^{115}**In**	^{118}**Sn**	^{131}**Xe**	^{197}**Au**	^{208}**Pb**	^{209}**Bi**	^{235}**U**
Charged Q	**Exp.**	0	0.15	0	**-0.21**	0.8	**0**	**-0.12**	**0.54**	0	-0.37	4.9
	Model		0.18	0	**-0.02**	0.7	**0**	**-0.6**	**0.58**	0	-0.26	4.7
Model												
Charged Qo,		-0.08	0.49	0.16	**-0.1**	1.28	**0.32**	**-1.92**	**2.96**	-0.34	-0.49	10.1
Neutron Qo		-0.08	0.	0.64	**0**	-2.56	**-0,32**	**0.72**	**-1.28**	-5.42	-3.96	2.3
Matter Qo		-0.16	0.49	0.80	**-0,1**	-1.28	**0**	**-1.2**	**1.68**	-5.76	-4.45	12.4

^{40}Ar



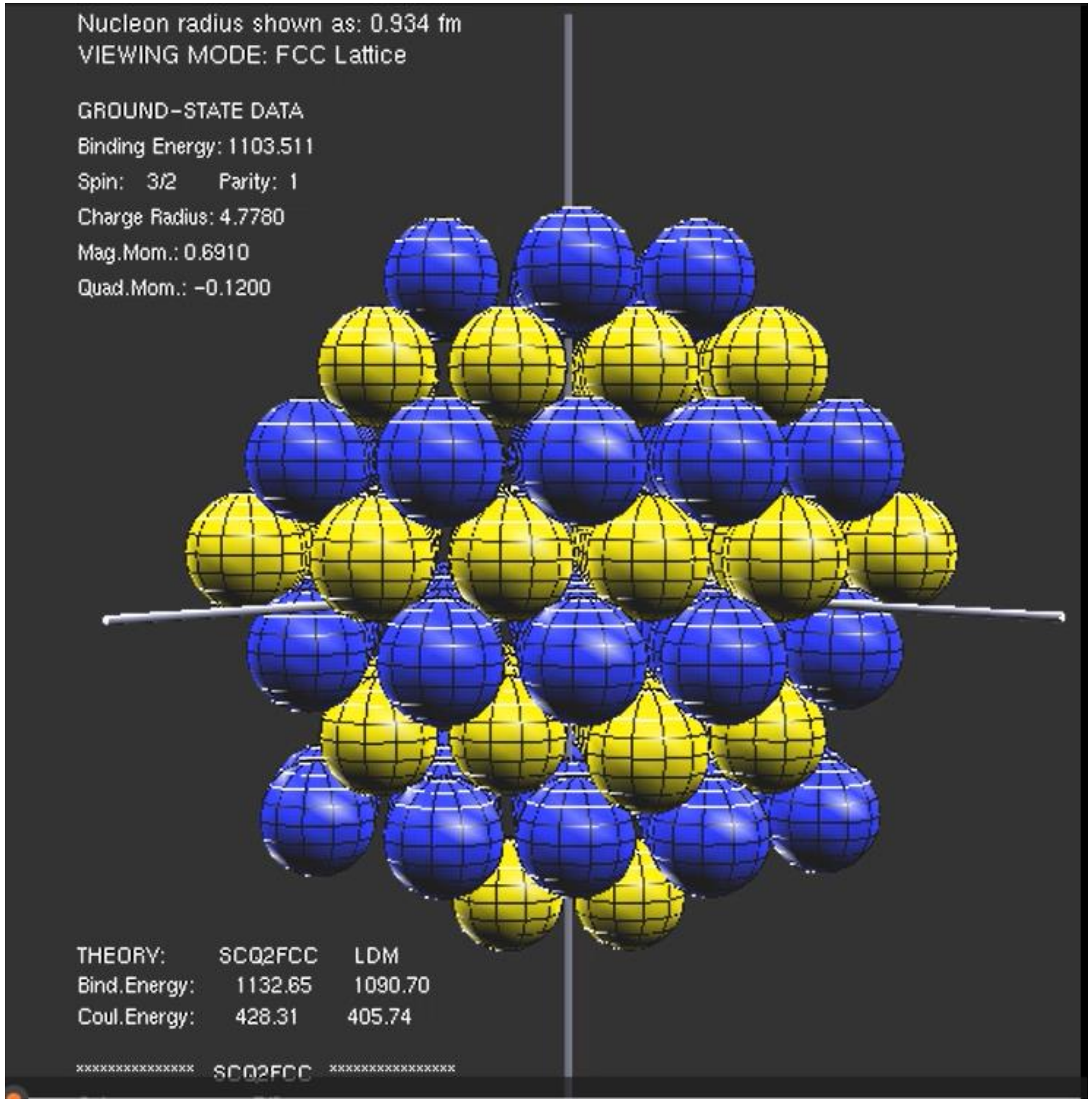
NUCLEUS: Argon-40 Z: 18 N: 22
Nucleon radius shown as: 0.934 fm
VIEWING MODE: FCC Lattice
GROUND-STATE DATA
Binding Energy: 343.810
Spin: 0 Parity: 1
Charge Radius: unknown
Mag.Mom.: 0.0000
Quad.Mom.: 0.0000
THEORY: SCQ2FCC LDM
Bind.Energy: 343.64 342.24
Coul.Energy: 60.87 64.42
SCQ2FCC
Spin 0+
Mag.Mom.: 0.00 0.00
Nuclear Radius: charged: 3.575 neutron: 3.723 mass: 3.656
Int.Quad.Mom.: charged: -0.160 neutron: -0.640 mass: -0.800
Lab.Quad.Mom.: charged: 0.000 mass: 0.000

^{63}Cu



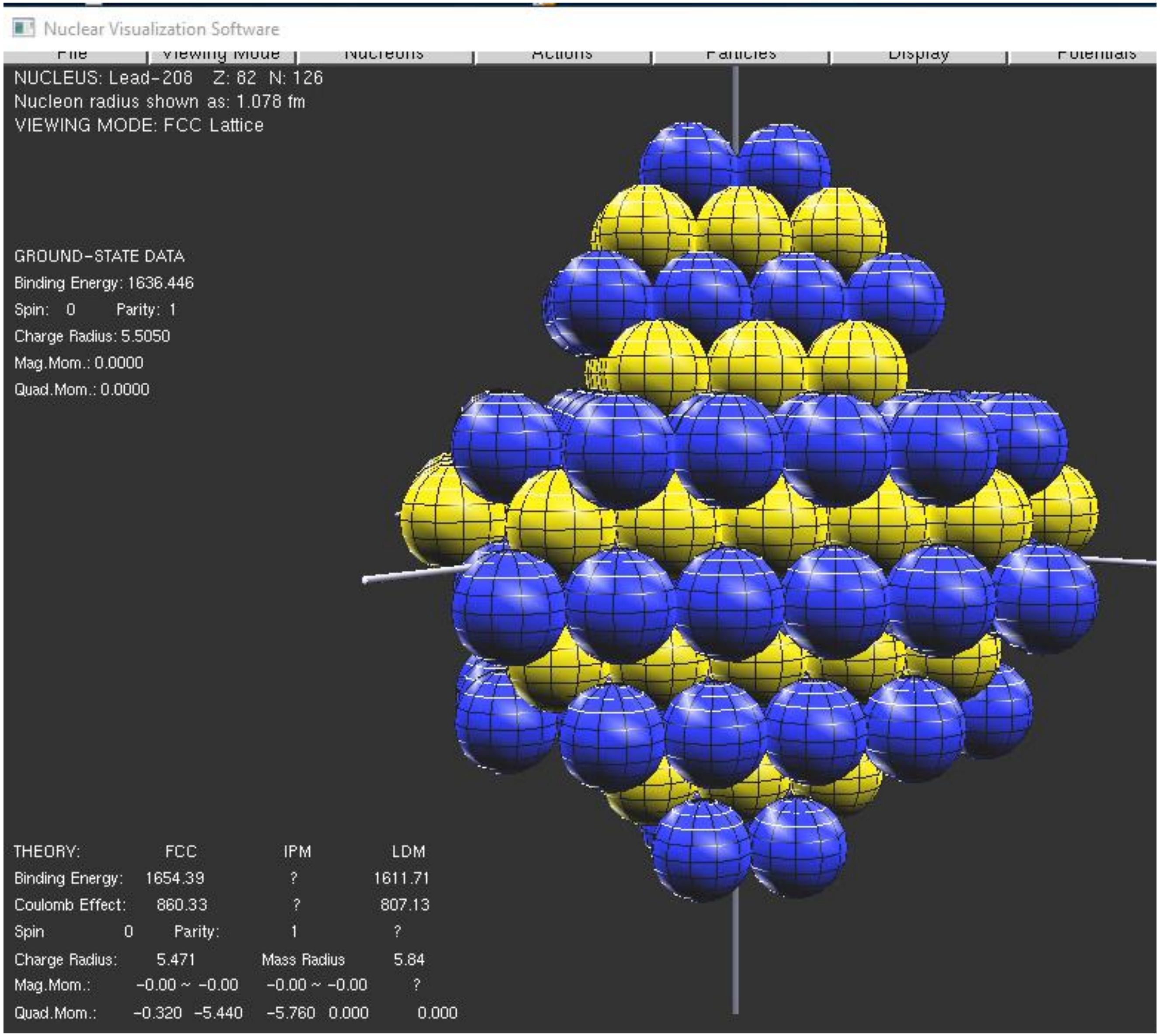
NUCLEUS: Copper-63 Z: 29 N: 34
Nucleon radius shown as: 1.149 fm
VIEWING MODE: FCC Lattice
GROUND-STATE DATA
Binding Energy: 551.382
Spin: 3/2 Parity: -1
Charge Radius: 3.8890
Mag.Mom.: 2.2230
Quad.Mom.: -0.2100
THEORY: SCQ2FCC LDM
Bind.Energy: 553.04 544.27
Coul.Energy: 145.11 146.93
SCQ2FCC
Spin: 3/2-
Mag.Mom.: 0.00 0.00
Nuclear Radius: charged: 3.983 neutron: 4.125 mass: 4.060
Int.Quad.Mom.: charged: -0.080 neutron: 0.000 mass: -0.080
Lab.Quad.Mom.: charged: -0.016 mass: -0.016

^{131}Xe



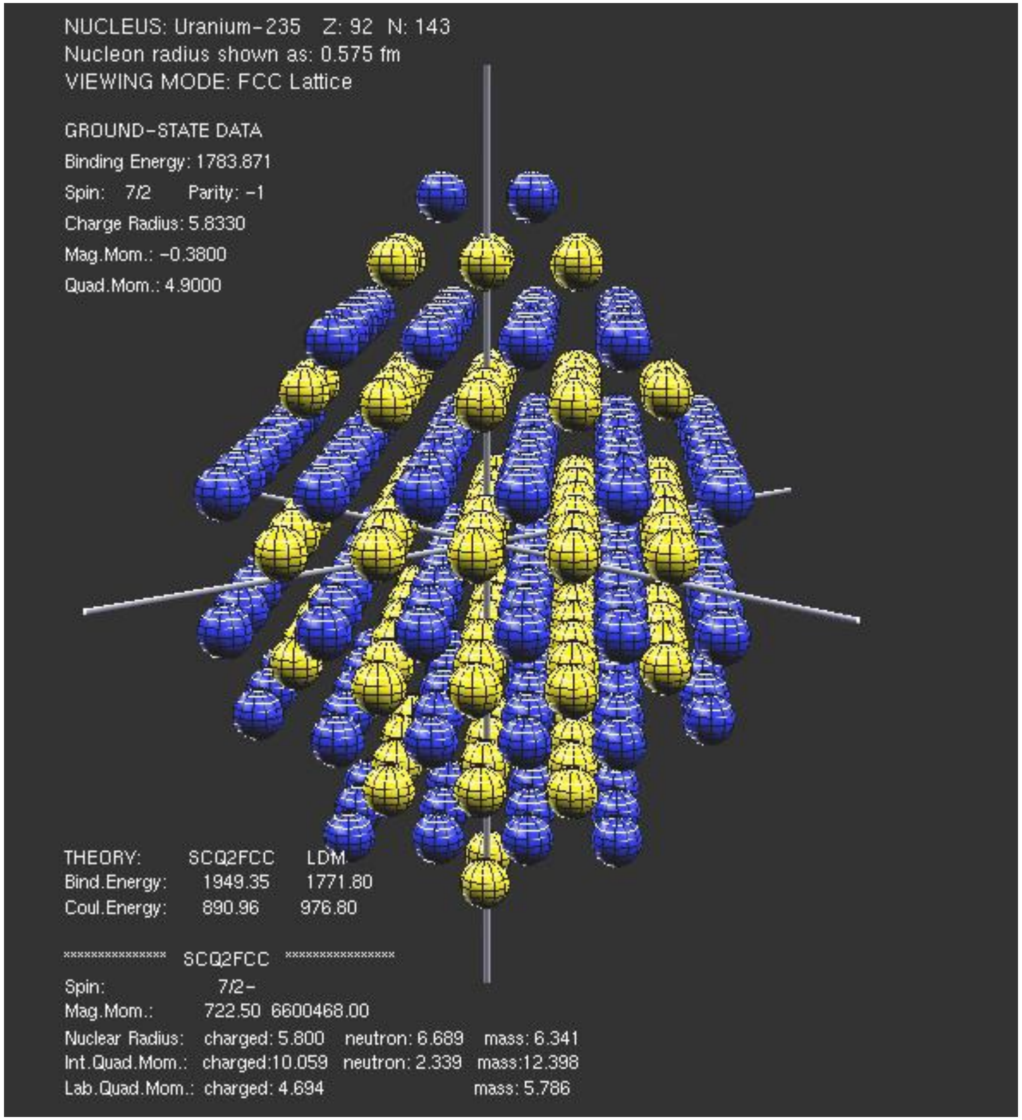
Nucleon radius shown as: 0.934 fm
VIEWING MODE: FCC Lattice
GROUND-STATE DATA
Binding Energy: 1103.511
Spin: 3/2 Parity: 1
Charge Radius: 4.7780
Mag.Mom.: 0.6910
Quad.Mom.: −0.1200
THEORY: SCQ2FCC LDM
Bind.Energy: 1132.65 1090.70
Coul.Energy: 428.31 405.74
SCQ2FCC

^{207}Pb



Nuclear Visualization Software
File
Viewing Mode
Nucleons
Actions
Particles
Display
Potentials
NUCLEUS: Lead-208 Z: 82 N: 126
Nucleon radius shown as: 1.078 fm
VIEWING MODE: FCC Lattice
GROUND-STATE DATA
Binding Energy: 1636.446
Spin: 0 Parity: 1
Charge Radius: 5.5050
Mag.Mom.: 0.0000
Quad.Mom.: 0.0000
THEORY: FCC IPM LDM
Binding Energy: 1654.39 ? 1611.71
Coulomb Effect: 860.33 ? 807.13
Spin 0 Parity: 1 ?
Charge Radius: 5.471 Mass Radius 5.84
Mag.Mom.: -0.00 ~ -0.00 -0.00 ~ -0.00 ?
Quad.Mom.: -0.320 -5.440 -5.760 0.000 0.000

^{235}U



NUCLEUS: Uranium-235 Z: 92 N: 143
Nucleon radius shown as: 0.575 fm
VIEWING MODE: FCC Lattice
GROUND-STATE DATA
Binding Energy: 1783.871
Spin: 7/2 Parity: -1
Charge Radius: 5.8330
Mag.Mom.: -0.3800
Quad.Mom.: 4.9000
THEORY: SCQ2FCC LDM
Bind.Energy: 1949.35 1771.80
Coul.Energy: 890.96 976.80
SCQ2FCC
Spin: 7/2-
Mag.Mom.: 722.50 6600468.00
Nuclear Radius: charged: 5.800 neutron: 6.689 mass: 6.341
Int.Quad.Mom.: charged:10.059 neutron: 2.339 mass:12.398
Lab.Quad.Mom.: charged: 4.694 mass: 5.786

Thank you for your attention!

Resume on Nucleus structure

1. Quarks and nucleons inside nuclei are correlated.
2. Quark loops are building blocks of nuclear binding.
3. Close **link between the nodes of a lattice** with **quantum numbers** of **Shell Model**.
4. **Nuclei possess crystal-like structure**:
   - Nucleon centers are arranged according to FCC lattice
   - Even-even nuclei are composed of **virtual *α*-clusters**
   - Closed Shells ≡ Octahedral Faces
   - All nuclei are deformed, even with shell closure!
   - Nuclear deformations are multipolar
5. ‘Halo’ nuclei – **fruits of quark-loop bindings**