Colorful Nuclei and Condensed Matter

Prof M K Pal 2nd Memorial Lecture

March 29, 2019

G Baskaran

Chennai

Waterloo, Canada

Professor Mamoj Kumar Pal

1932-2016

Distinguished Theoretical Nuclear Physicist

Former Director of SINP

Great Teacher

School of Nuclear Physics establshed by M K Pal and M K Banerjee

Co Director of Schools and Workshops in Nuclear Physics at the International Center for Theoretical Physics, Trieste, Italy for 16 years

Books by Prof M K Pal

Theory of Nuclear Structure

Special Theory of Relativity

General Theory of Relativity

Forever Free (Historical Novel)

Old Wisdom and New Horizon
(on Science, Religion and Philosophy)

Cosmology (unfinished)

Friends and colleagues describe him as
Multifaceted genius ... highly spiritual person

ICTP

I am fortunate to have met Prof M K Pal during 1976 – 1984 at ICTP

Acknowledgement

Discussions with Colleagues at Matscience

M.V.N. Murty, Sayanthan Sharma, Mukul Laad, G Rajasekaran, Rahul Sinha ...

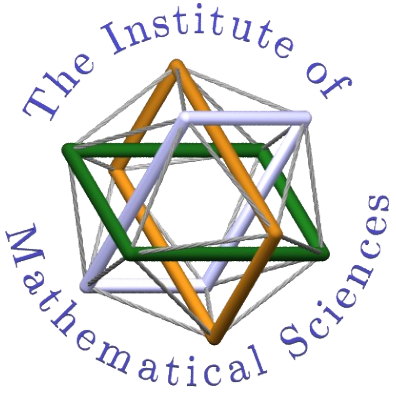
Supported By

SERB, DST, India
Perimeter Institute for Theoretical Physics, Canada

About my Institute

http://www.imsc.res.in

Institute of Mathematical Sciences



Research in

Theoretical Physics
Pure Mathematics
Computer Science

~ 60 faculy
100 Ph.D. students
20 PDF's
10 visitors

Junior Research Fellow

Entrance through **JEST** Exam

Autonomous Institute

similar to
IIT's
IISc, Bangalore

SINP, Kolkota
TIFR, Bombay
DAE Aided Institute

Post Doctoral Fellowship
Visiting Research Scholar
Summer Program for BSc, BE, MSc students
Faculty Associateship
Adjunct Faculty
Visiting Professor…

Stephen Hawking Center

PERIMETER INSTITUTE

Waterloo, Ontario, Canada

www.perimeterinstitute.ca

Research Institute similar to Matscience
but extensive visitor program

PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

Perimeter Scholars International (PSI) Program
(hosts a wealth of Videos of Lecture Courses)

An example of respect by an individual for theoretical physics
as something that helps transform society (Maxwell Equations)

other examples – Kavli, Yuri Millner, Simons
Mahendra Lal Sarkar, Tata, Alagappa, Birla, Mehta, Annamalai,
Azhagappa, A C Muthiah, K B Chandrasekaran ... Krish Gopalakrishnan ..
Azim Premji, Narayanamurthy, Shiv Nadar, …

Donor of
~ 400 Million $
(Black Berry Chief)

Private Funding for Basic Science in india ?

Science Philanthropy Alliance (USA)

Boldness of the Philanthropists – David Baltimore (Science Magazine)

Usefulness of Useless Science

There is a long tradition of exchange of ideas between

nuclear physics and quantum condensed matter physics.

1902-1995

Eugene Wigner Nobel Prize for Nuclear Physics

An early bridge between
Nuclear and Solid State Physics

Wigner Eckart Theorem, Wigners 3-j symbol
Symmetry principle in nuclear physics
Random matrix theory of nuclear spectra
Crystalline Correlation inside Nuclei
Jordan-Wigner transformation

Wigner-Seitz cell, Wigner (electron) crystal
Wigner-Huntington (metallization of solid hydrogen
Route to Room Temperature Superconductivity ?

John Bardeen, Ph.D. student of Wigner won 2 Nobel Prizes
Discovery of Transistor and BCS Theory of Superconductivity

Traditionally we discuss nucleus of atoms using shell model, as atomic mass increases. Filling of shells is well known for electrons in atoms, where positively charged nucleus bind together mutually repelling electrons.

In a nucleus there is no attracting center. Protons and neutrons hold themselves together using strong-mutual nuclear forces. Physics beyond shell model has been suggested ... (liquid droplry model, alpha clustering ...)

That is, certain nuclei may support novel quantum novel many body states.

Quantum crowd of electrons in some crystalline solids or liquid He4 droplets could help understand this.

Attraction between two nucleons via exchang of Meson (Yukawa)

Phonon mediated attraction between two electrons in a metal (Frohlich)

and BCS theory of pairing superconductivity

Pairing in Nuclei - Superfluidity in Neutron Stars
Vortex lattice, pinning, neutron star quakes, ...

Color Superconductivity, Quark Gluon Plasma

Alpha particle Clusering ...

Linear chain of alpha particles !

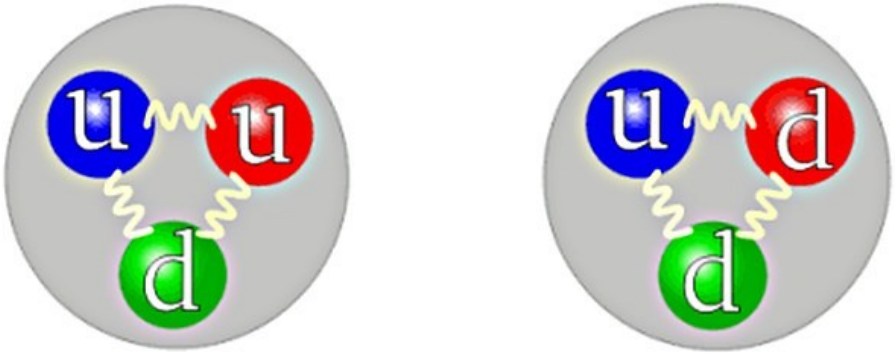
Bose Condensation ... Quantized Vortices in rotating Nuclei

Skyrmion Model of Nucleon .....

(Baby) Skyrmion Crystals in Magnets (MnSi)

In a nucleus, colorful quarks and gluons are confined by strong QCD forces, It results in integer electric charges and color singlet states.

Is it possible to get a transient glimpse of color of gluons and quarks or fractional charges of quarks, in some low energy nuclear physics experiments, without use of high energy collider machines ?



Proton Neutron

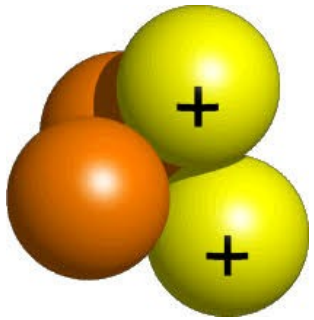
Quark composition of a proton and a neutron (diagrams from *Wikipedia*)

Alpha clusters in Nuclei

Molecules of alpha particles …. Bose Condensation

Alpha – chain (statistics transmutation ?)

2 protons and 2 neutrons



Bound State of 2 Deutrons ?

Deutron is an Isospin Singlet & Spin Triplet

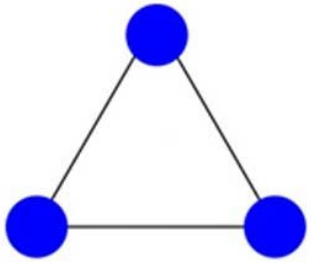
Nature of the singlet

Spin = 0

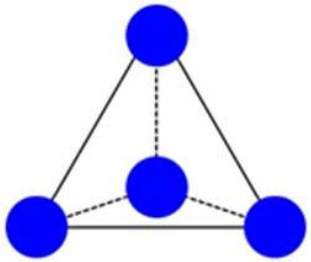
Charge = + 2e ***a Boson***

Alpha clusters in Light Nuclei
Molecules of alpha particles

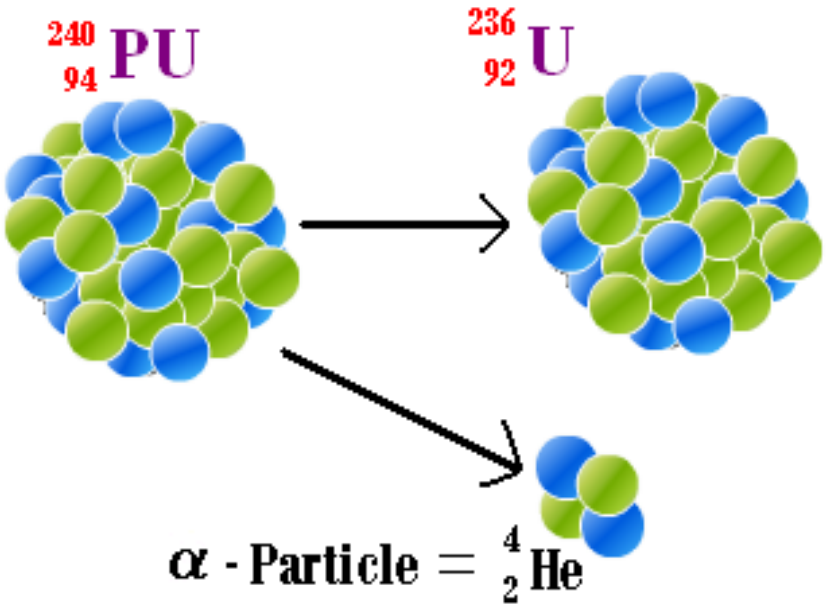
^{8}Be Dumbbell Z_2

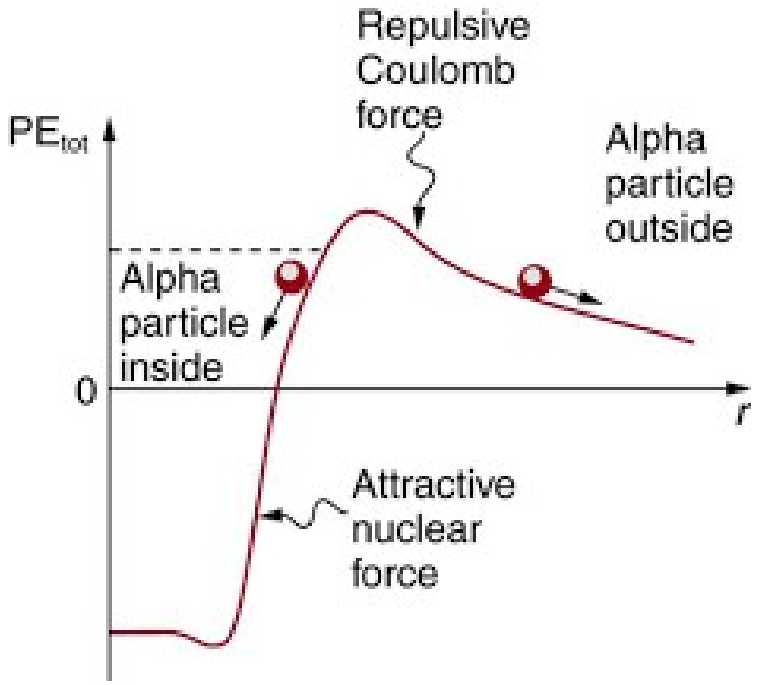


^{12}C Triangle D_{3h}



^{16}O Tetrahedron T_d


$^{240}_{94}$PU
$^{236}_{92}$U
α - Particle = $^{4}_{2}$He


Repulsive Coulomb force
PE$_{tot}$
Alpha particle outside
Alpha particle inside
0
r
Attractive nuclear force

Alpha clusters in Nuclei
Molecules of alpha particles …. Bose Condensation

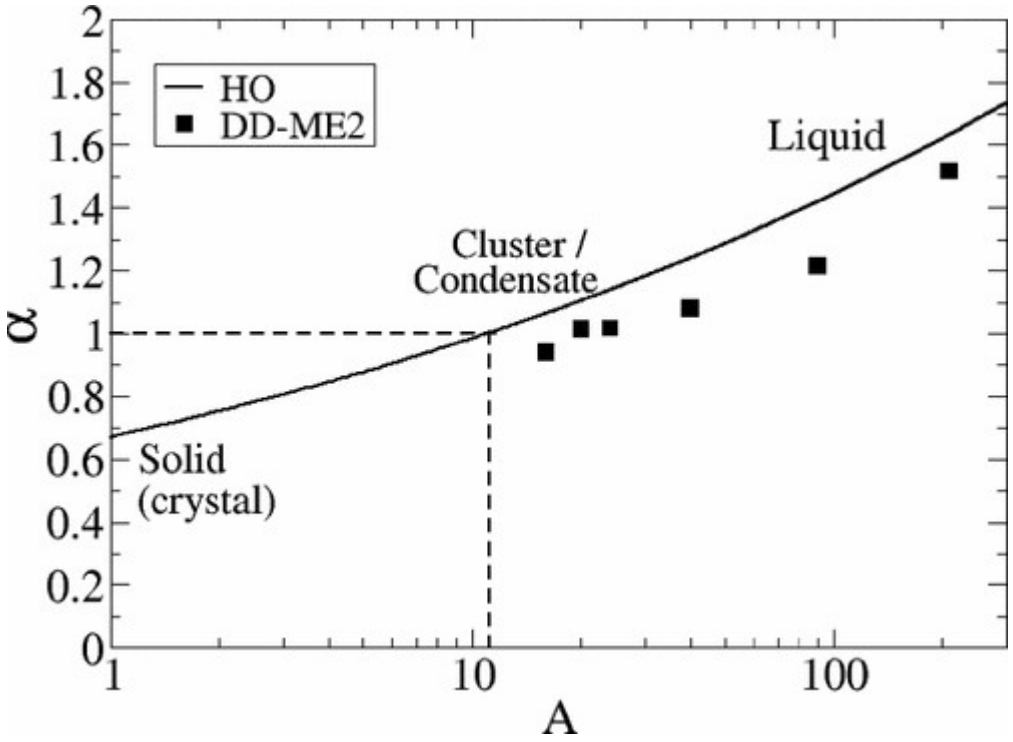
Deutron is an Isospin Singlet & Spin Triplet

P N P N P N P …
Isospin Heisenerg AFM Chain ?
Rotating nuclei ?

Resonating Valence Bond State ?

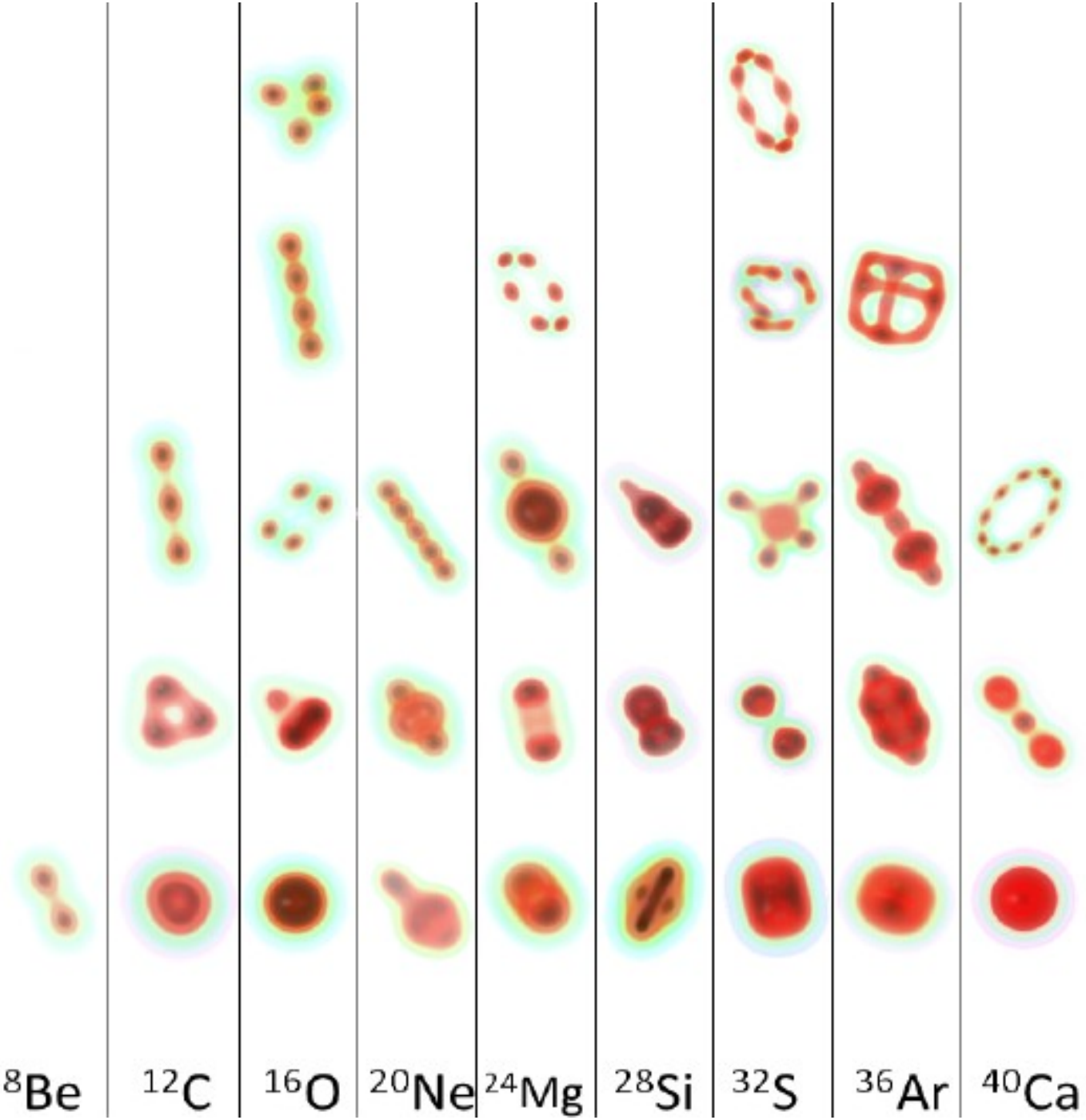
IsoSpinon Excitation - Isospin half charge e/2 ?

(GB 2019)



Density Functional Theory studies of cluster states in nuclei

J.-P. Ebran,[1] E. Khan,[2] T. Nikšić,[3] and D. Vretenar[3]

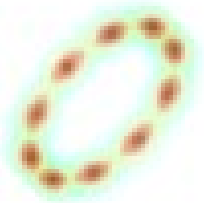

^{8}Be
^{12}C
^{16}O
^{20}Ne
^{24}Mg
^{28}Si
^{32}S
^{36}Ar
^{40}Ca

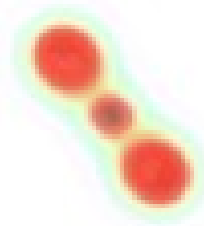
Consider Calcium nucleus

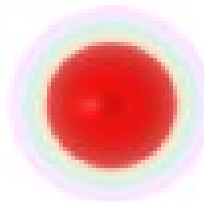
Alpha particles are hard core bosons

Jordan-Wigner Transformation

Alpha particles in the Chain behaves like Fermions !







^{40}Ca

Is heavy nucleus like Plutonium or Uranium a Superfluid of alpha particles ?

Lattice Nuclear Physics

Ulf-G. Meißner, Univ. Bonn & FZ Jülich

Quantum phase transition from Bose gas of α's to nuclear liquid for α-type nuclei

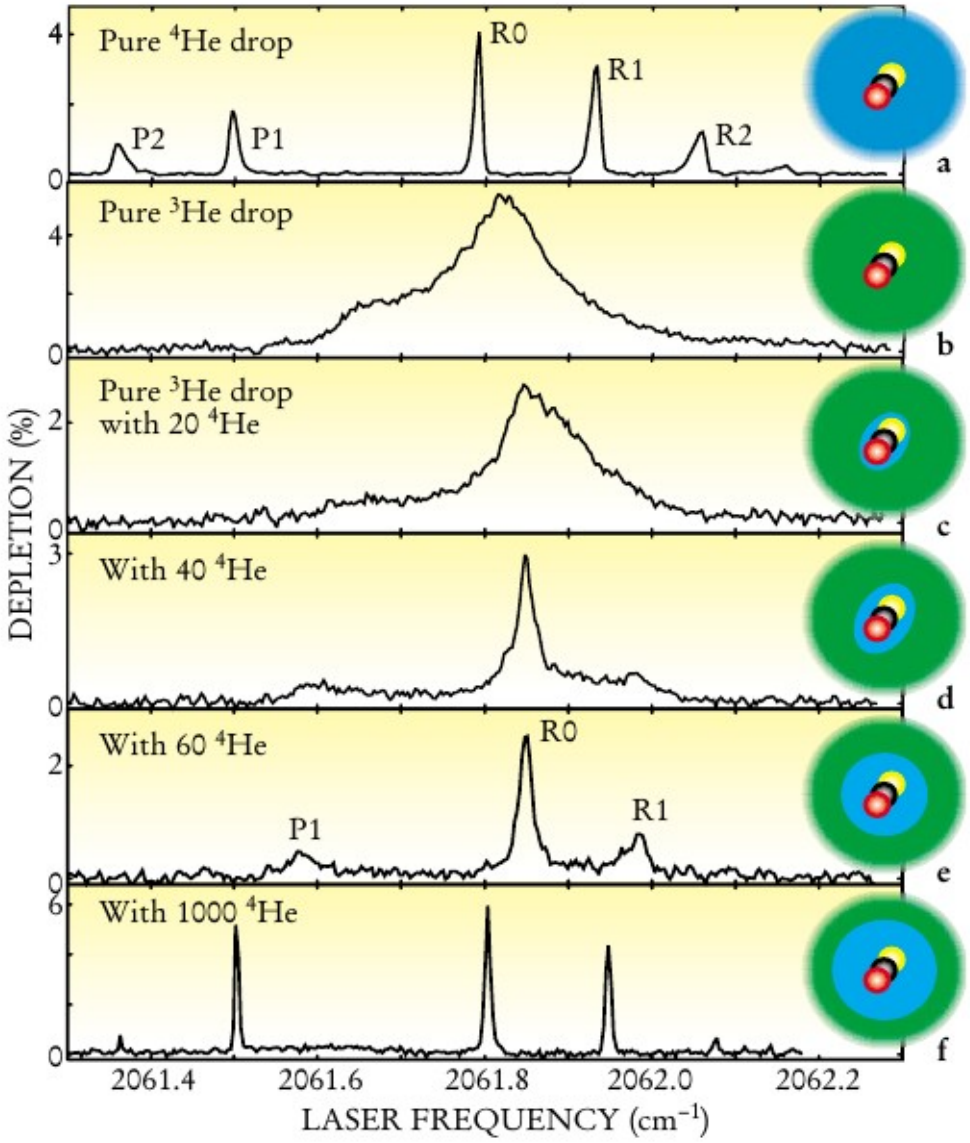
Experiments (Gotingen)

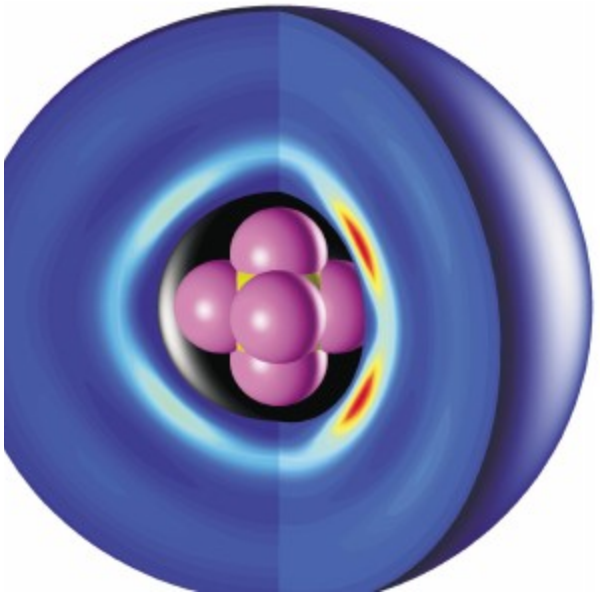
A droplet of He4 atoms becomes a superfluid
When number of He4 atoms exceeds 60 !

Superfluid Helium Droplets: An Ultracold Nanolaboratory

J. Peter Toennies, Andrej F. Vilesov, and K. Birgitta Whaley

Physics Today **54**, 2, 31 (2001)



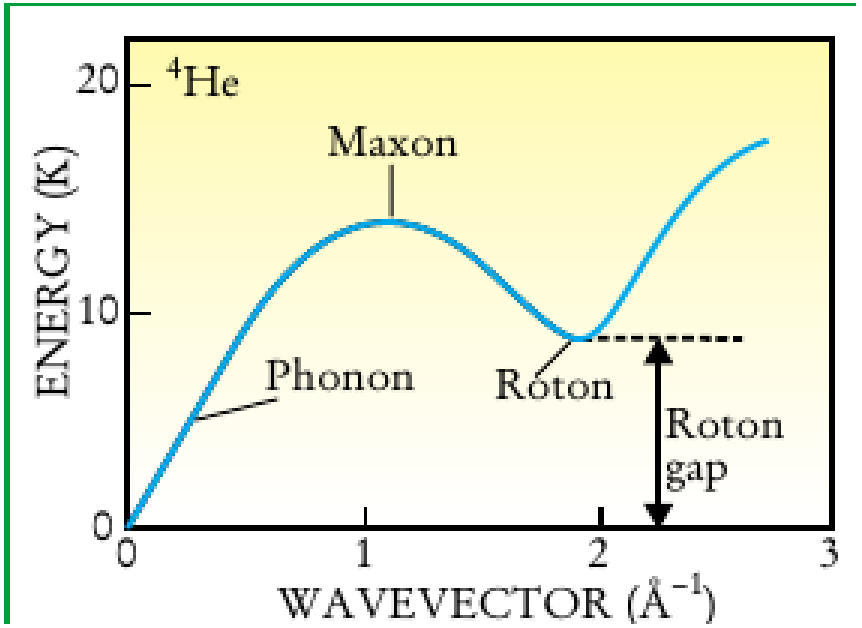


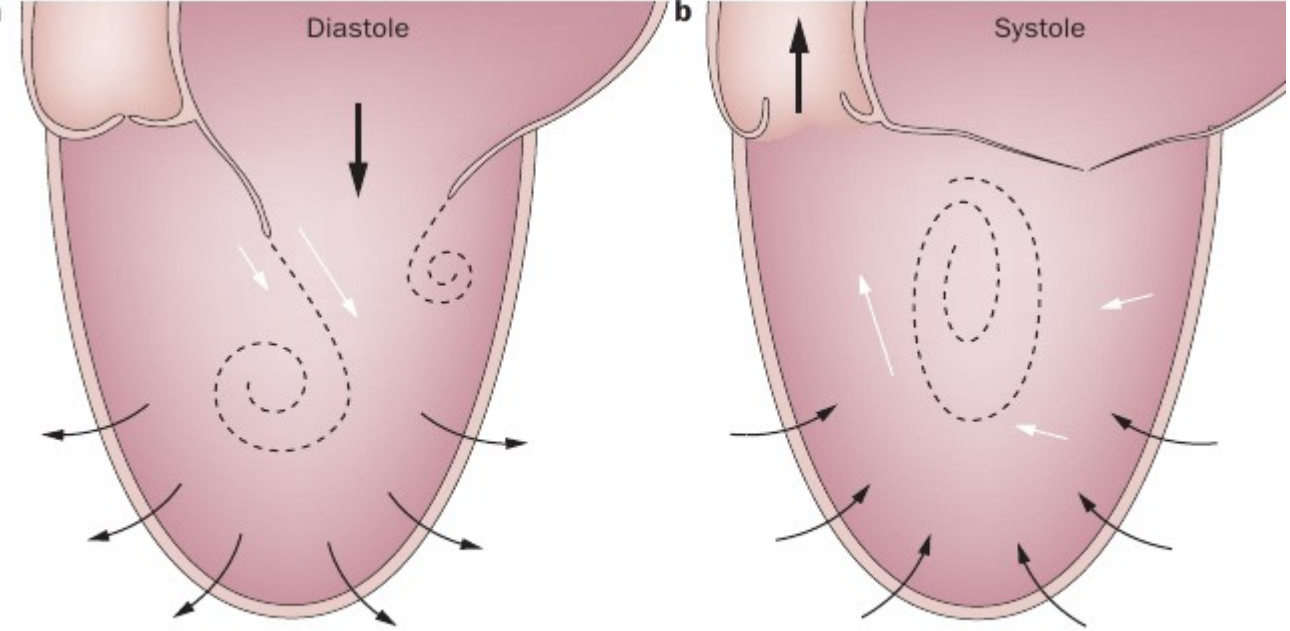
COS
molecule

Direct Spectroscopic Observation of Elementary Excitations in Superfluid He Droplets

M. Hartmann, F. Mielke, J. P. Toennies, and A. F. Vilesov
Max-Planck-Institut für Strömungsforschung, Bunsenstrasse 10, D-37073 Göttingen, Germany

G. Benedek
Istituto Nazionale di Fisica della Materia, Dipartimento di Fisica dell'Università, via Celoria, I-20133 Milano, Italy



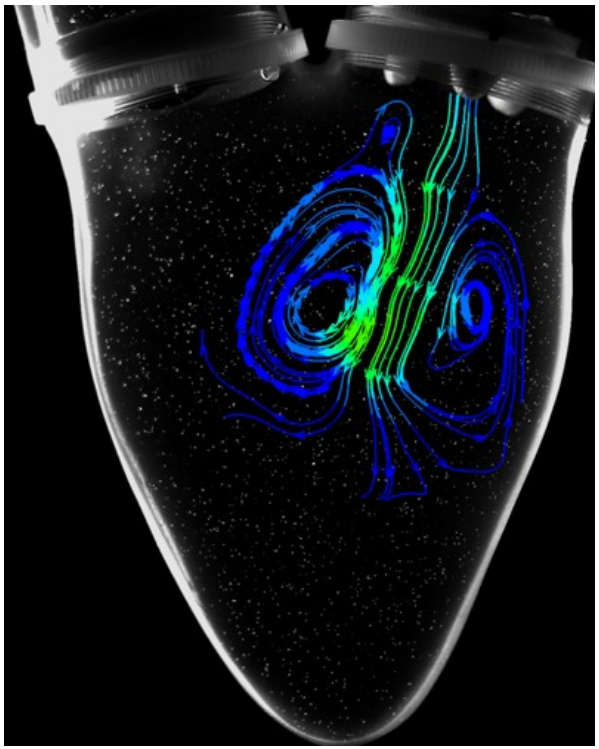


igure 1 | Blood flow in the healthy left ventricle. **a** | Blood flows into the left ventricle during iastole (thick black arrow), propelled by base-to-apex pressure gradients (thin black arrows).

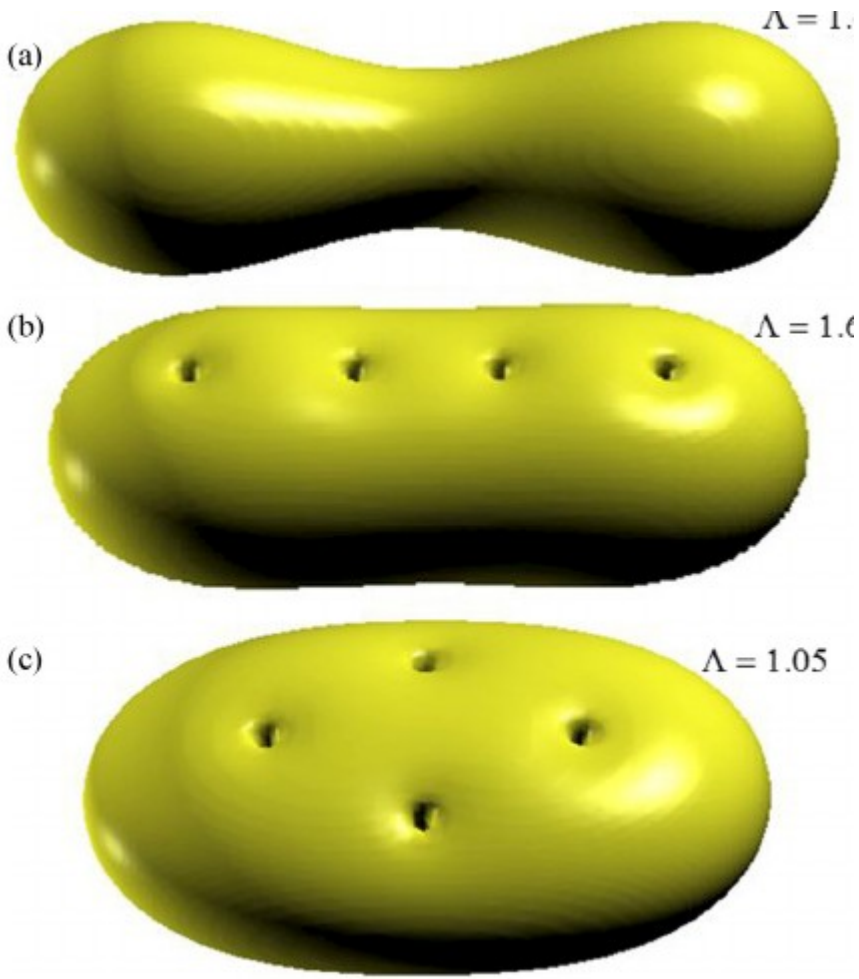
The vortex—an early predictor of cardiovascular outcome?

Gianni Pedrizzetti, Giovanni La Canna, Ottavio Alfieri and Giovanni Tonti

NATURE REVIEWS | CARDIOLOGY

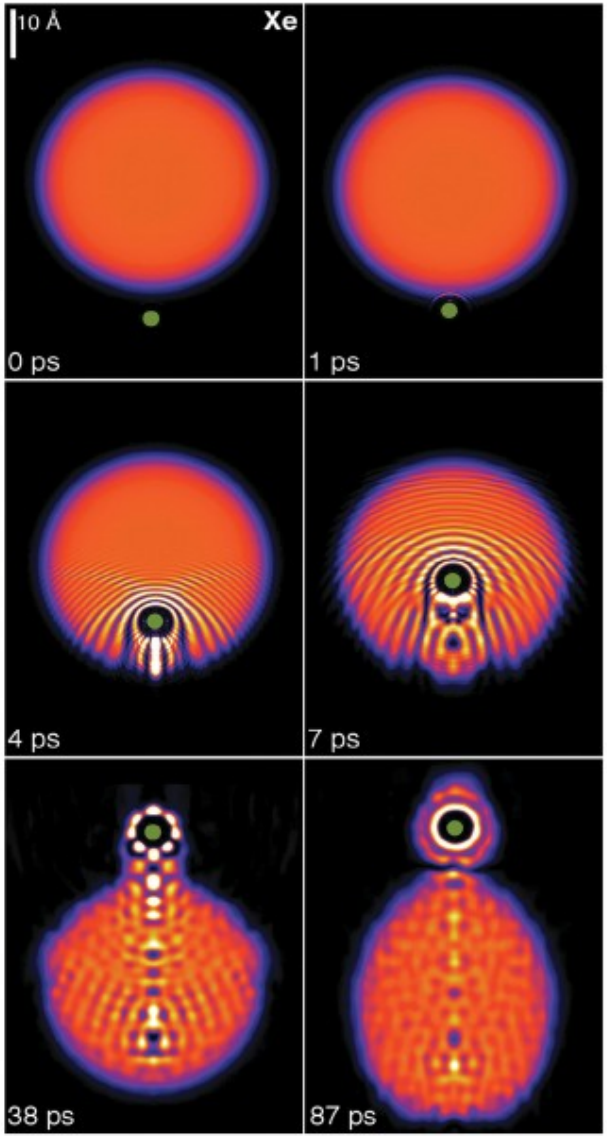


Spinning superfluid ^{4}He nanodroplets



Capture of Xe and Ar atoms by quantized vortices in ^{4}He nanodroplets†

François Coppens, *[ab] Francesco Ancilotto,[cd] Manuel Barranco,[abef] Nadine Halberstadt[ab] and Martí Pi[ef]



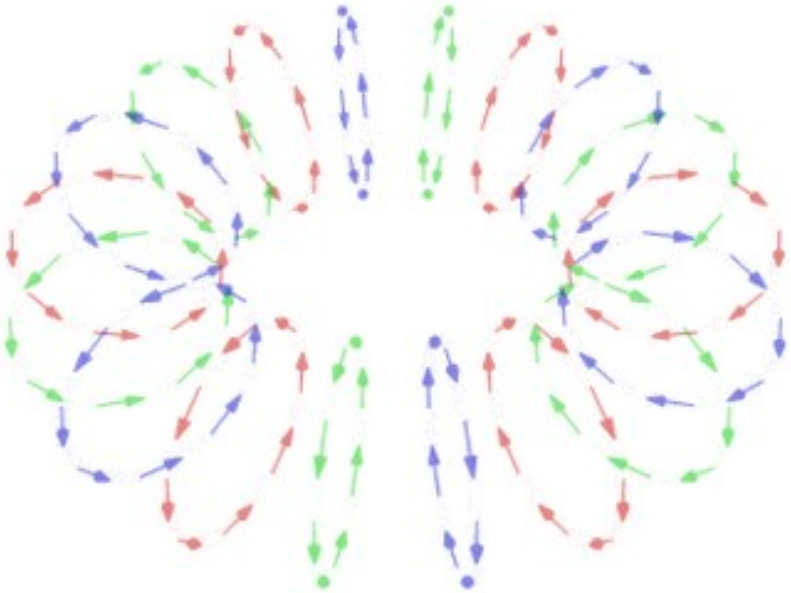
Phys. Chem. Chem. Phys., 2017, **19**, 24805–24818

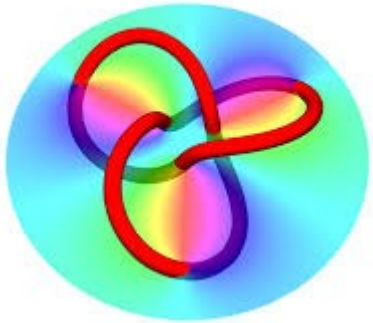
Is heavy nucleus like Plutonium or Uranium a Superfluid of alpha particles ?

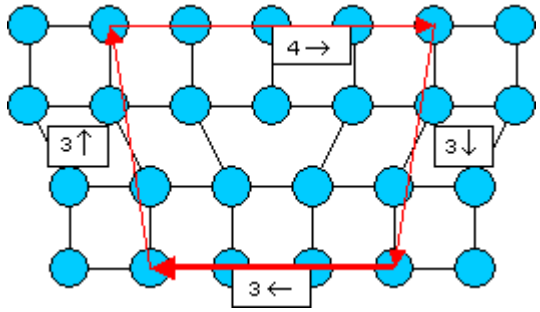
Do we produce quantized vortices in rotating Nuclei ?

Anomalous stability of some Isomers - Tangled Vortices ? Vortex Knots ?

GB 2019







Dislocation - Burgers vector

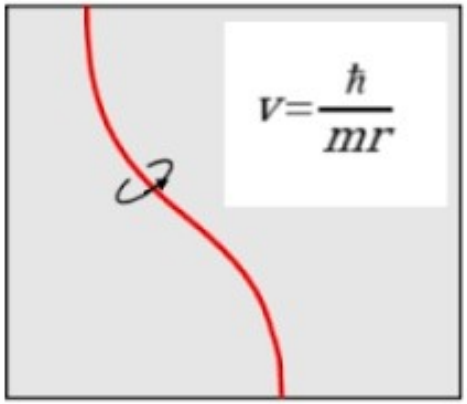
Quantized Vortices in supercuonductors, superfluids

Topological Soliton - Skyrmion in Nuclear Physics

Baby Skyrmion in Magnets

Skyrmion Crystals

Spintronics .....



A quantized vortex

Chiral symmetry breaking and Pion condensartion

Skyrme model of nucleon
Topologically non trivial configuration of pion condensate

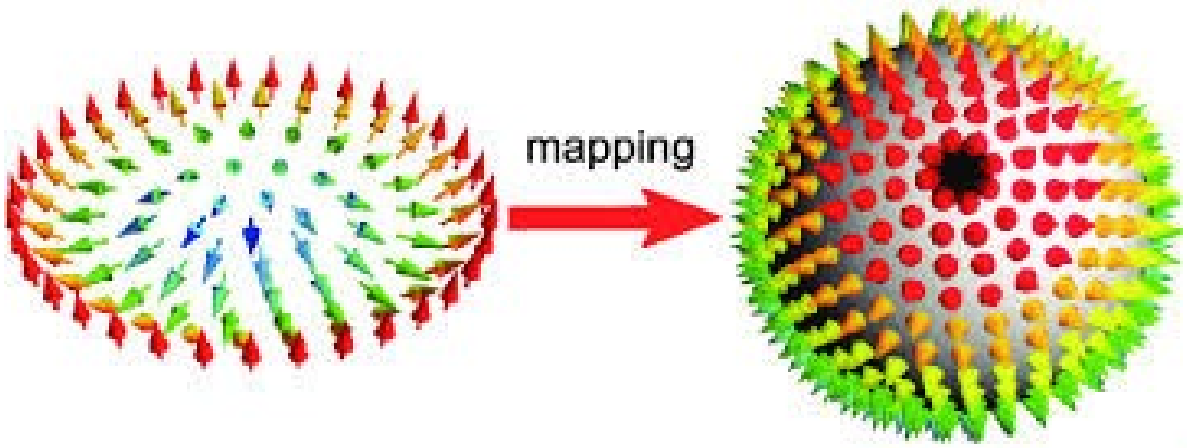
Topological Defects condensed matter He3, ...

Homotopy Theory

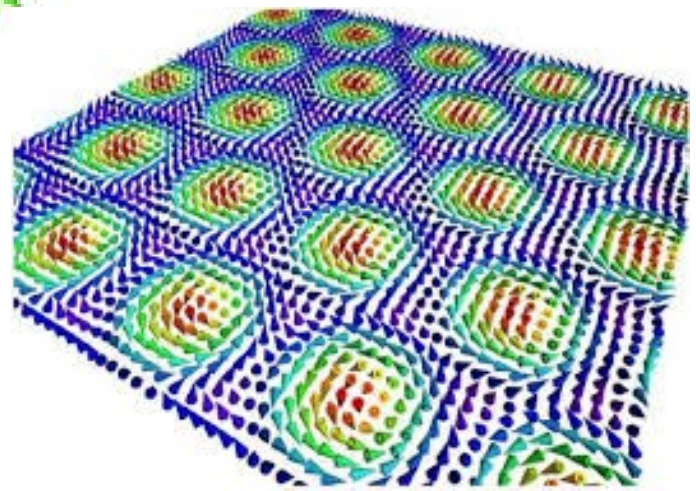
Skyrmion in ferromagnets and antiferromagnets, Hopf term, ...
Skyrmion as a two spinon state (GB 2001)

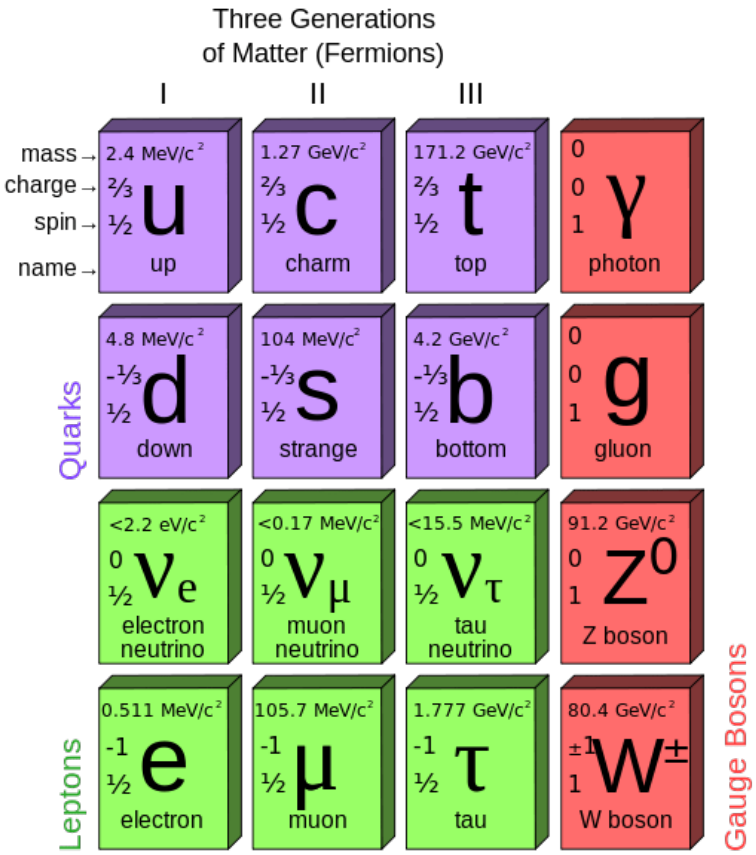
Skyrmion crystals in Magnetic Materials

Spintronics

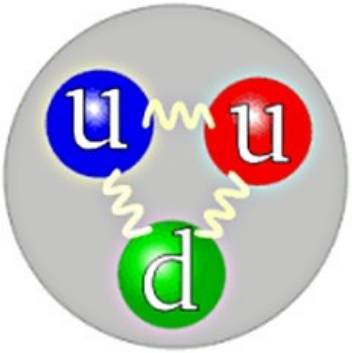


$$n = \frac{1}{4\pi} \int \mathbf{M} \cdot \left(\frac{\partial \mathbf{M}}{\partial x} \times \frac{\partial \mathbf{M}}{\partial y} \right) dxdy$$

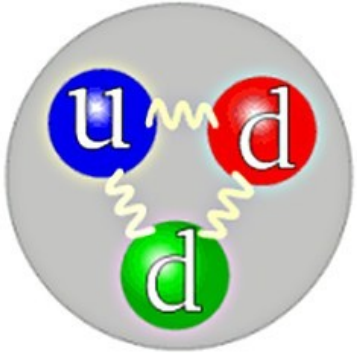




Can we get a glimpse of colors and fractional charges in Some low energy nuclear physics experiments ?



Proton



Neutron

Quark composition of a proton and a neutron (diagrams from *Wikipedia*)