The FCC Structure of the Nucleus and the Magnetic Interaction among Nucleons

Norman D. Cook
Kansai University, Osaka

Valerio Dallacasa
Verona University, Verona

ICCF 15, Rome, October, 2009

The field of “cold fusion” still needs developments in three distinct areas:

(1) reliable experimental data

(2) hypotheses concerning the underlying phenomena

(3) integration into established nuclear structure theory

Nuclear Structure Theory
(since the 1950s)

Empirically-known Nuclear Phenomena

Independent-particle (~shell) Model

Collective (~liquid-drop) Model

Alpha-particle, Cluster and Lattice Models

Gaseous-phase assumptions

Liquid-phase assumptions

Solid-phase assumptions

More than 30 (!) nuclear structure models reviewed in Greiner & Maruhn, *Nuclear Models*, Springer, 1996 (not including any of the cluster and lattice models)

Eugene Wigner,
Physical Review, 1937

JANUARY 15, 1937 PHYSICAL REVIEW VOLUME 51

On the Consequences of the Symmetry of the Nuclear Hamiltonian on the Spectroscopy of Nuclei

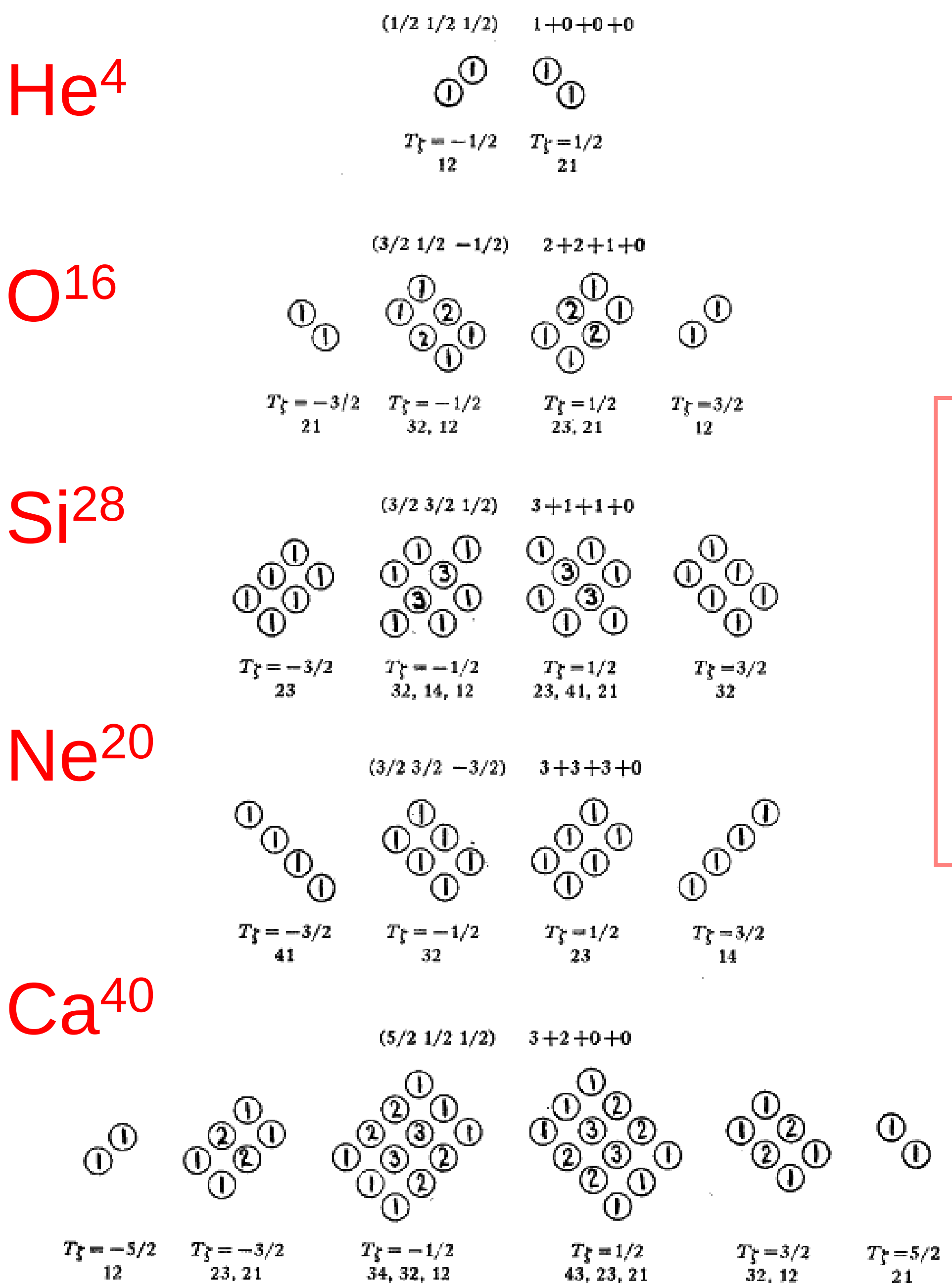
E. WIGNER*
Princeton University, Princeton, New Jersey

(Received October 23, 1936)

The structure of the multiplets of nuclear terms is investigated, using as first approximation a Hamiltonian which does not involve the ordinary spin and corresponds to equal forces between all nuclear constituents, protons and neutrons. The multiplets turn out to have a rather complicated structure, instead of the S of atomic spectroscopy, one has three quantum numbers S, T, Y. The second approximation can either introduce spin forces (method 2), or else can discriminate between protons and neutrons (method 3). The last approximation discriminates between protons and neutrons in method 2 and takes the spin forces into account in method 3. The method 2 is worked out schematically and is shown to explain qualitatively the table of stable nuclei to about Mo.

Eugene Wigner,
Physical Review, 1937

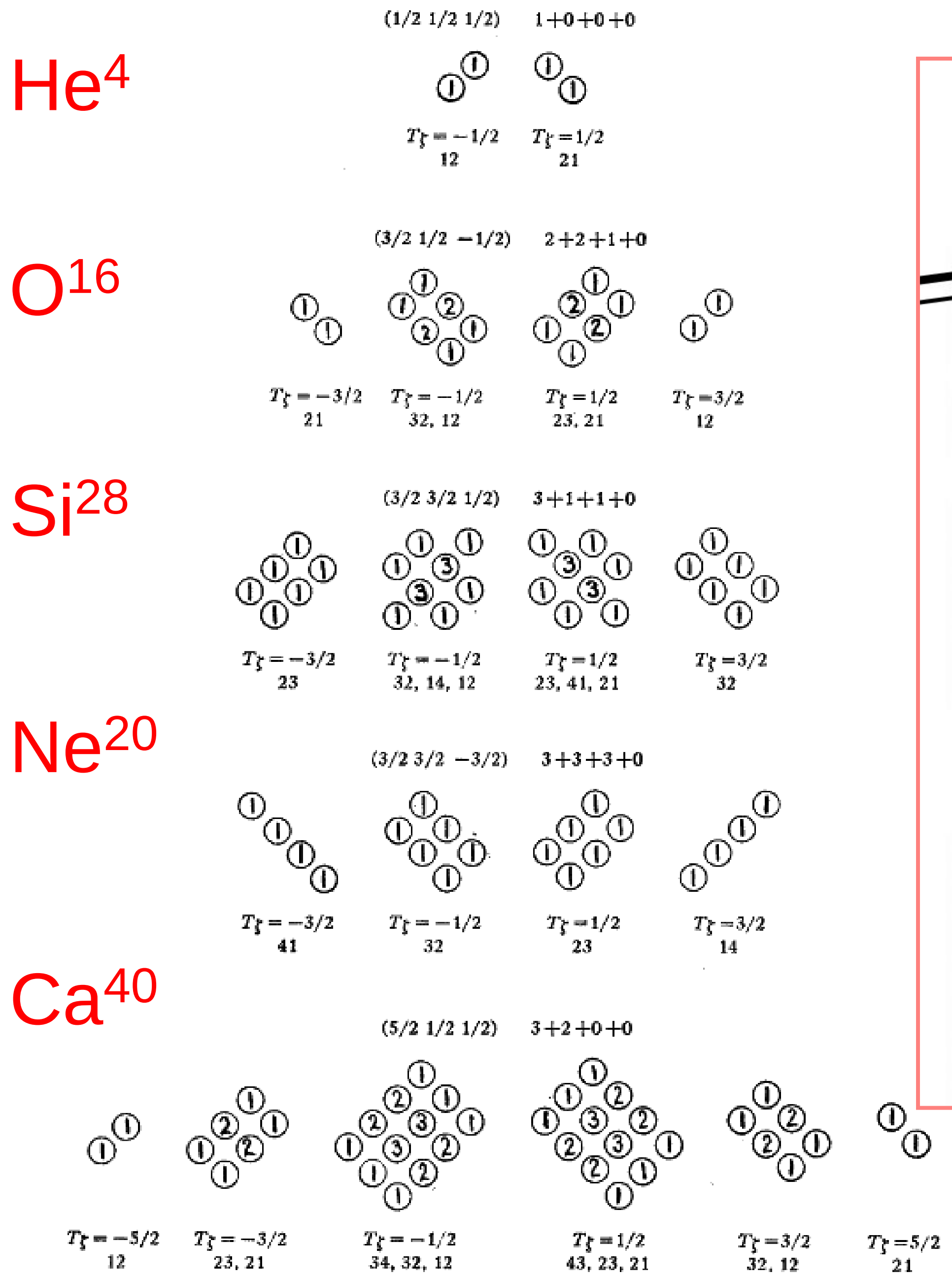
FIG. 1.



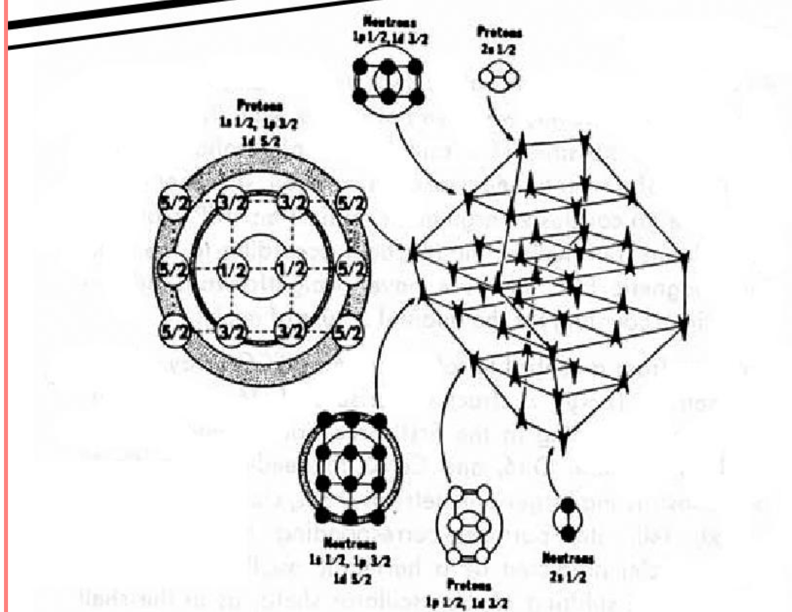
The symmetries of nuclear "quantum space" are face-centered-cubic.

Eugene Wigner,
Physical Review, 1937

FIG. 1.



1976



An FCC lattice model for nuclei

By Norman D. Cook

Fig. 3: The proton and neutron layers in Ca 40. In each layer the nucleons have opposite spins to all nearest neighbors, as indicated by the arrows. The middle proton level, on the left, shows the relationship between the nuclear z axis and the individual nucleon angular momentum quantum values

112 SYMMETRY OF NUCLEAR HAMILTONIAN

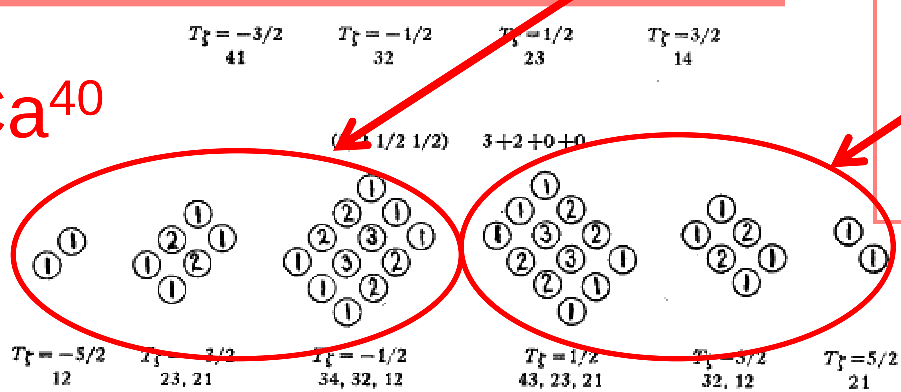
FIG. 1. (1/2 1/2 1/2) 1+0+0+0

Eugene Wigner,
Physical Review, 1937

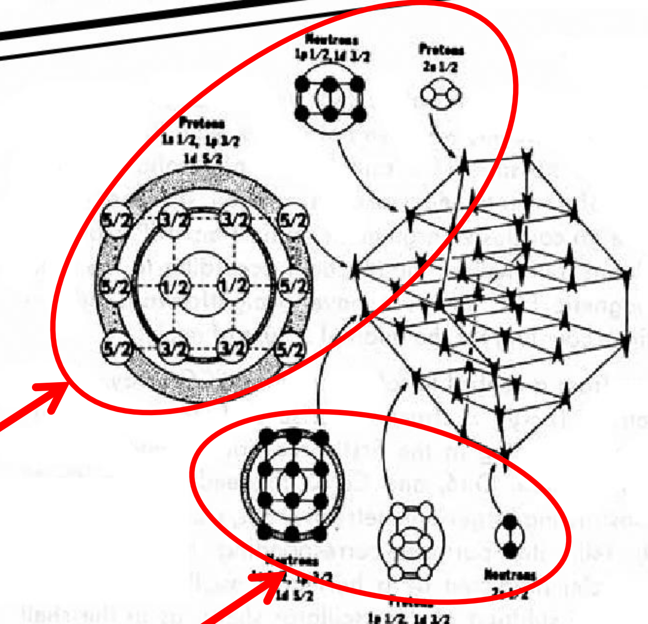
The symmetries of nuclear "quantum space" correspond to FCC lattice symmetries in 3D "coordinate space"

(Lezuo, Cook, Dallacasa, Stevens, Bobezko, Everling, Palazzi, Goldman, Bauer, Chao, Chung, Santiago, Campi, Musulmanbekov, DasGupta, Pan, Bevelacqua, et al.)

Ca^{40}



1976



An FCC lattice model for nuclei

By Norman D. Cook

Fig. 3: The proton and neutron layers in Ca 40. In each layer the nucleons have opposite spins to all nearest neighbors, as indicated by the arrows. The middle proton level, on the left, shows the relationship between the nuclear z axis and the individual nucleon angular momentum quantum values

196 Atomkernenergie (ATKE) Bd. 28 (1976) Lfg. 3

Atomkernenergie 1976, 1981, 1982;

Int. J. Theoretical Physics 1978;

Physical Review C 1987;

Il Nuovo Cimento 1987a, 1987b;

Journal of Physics G 1987, 1994, 1997, 1999;

Physics Bulletin 1988;

New Scientist 1988;

Computers in Physics 1989;

Modern Physics Letters 1990a, 1990b;

IEEE Comp. Graph. Appl. 1999;

Yadernaya Fizika, 2007;

Models of the Atomic Nucleus, Springer, 2006; etc.

1976

An FCC lattice model for nuclei

By Norman D. Cook

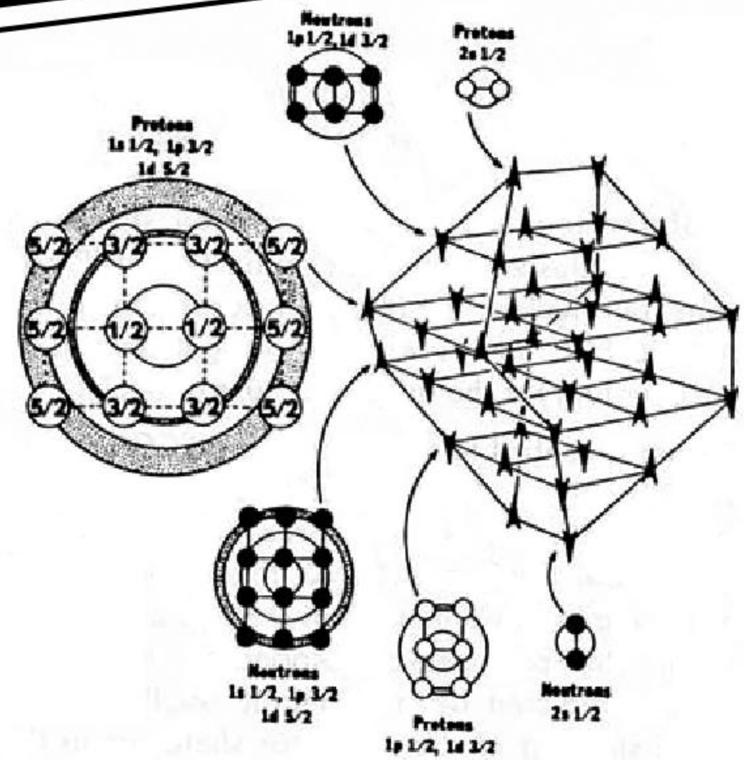


Fig. 3: The proton and neutron layers in Ca 40. In each layer the nucleons have opposite spins to all nearest neighbors, as indicated by the arrows. The middle proton level, on the left, shows the relationship between the nuclear z axis and the individual nucleon angular momentum quantum values

The lattice model potentially unifies nuclear structure theory, but it also leads to answers concerning transmutation results in LENR.

Let us build nuclei based on what is known about protons, neutrons and the nuclear force…

At energies less than 300 MeV…

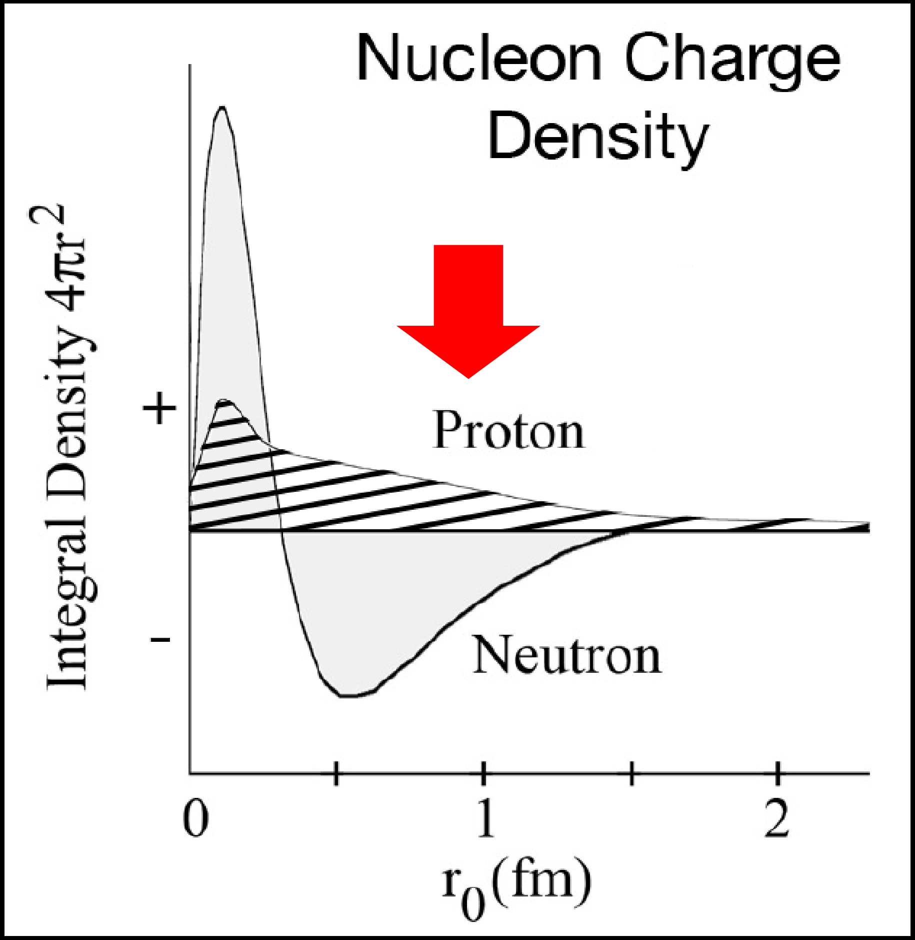
Electric and magnetic rms radii of nucleons

Particle	r^e_{rms}	r^m_{rms}
Proton	0.895 ± 0.018 fm	1.086 ± 0.012 fm
Neutron	-0.113 ± 0.003 fm	0.873 ± 0.015 fm

I. Sick, *Progress in Particle and Nuclear Physics* 55, 440, 2005.

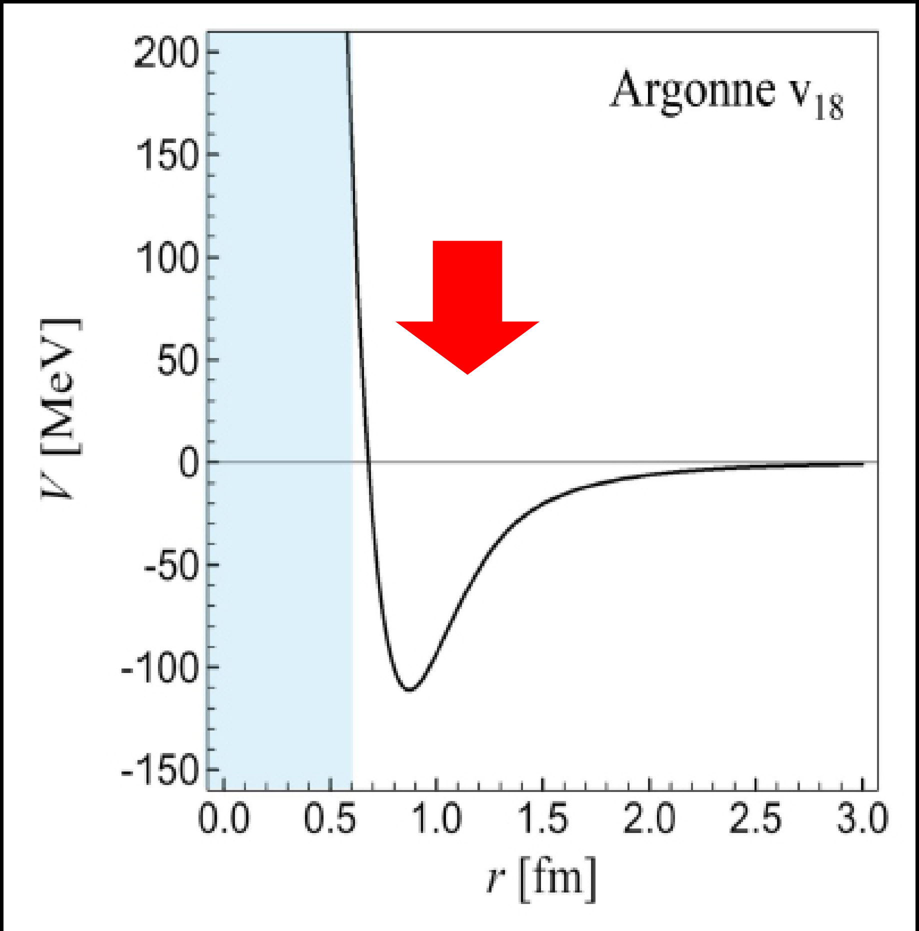
nucleons are particles with radii of ~1 fm.

The internal charge density…



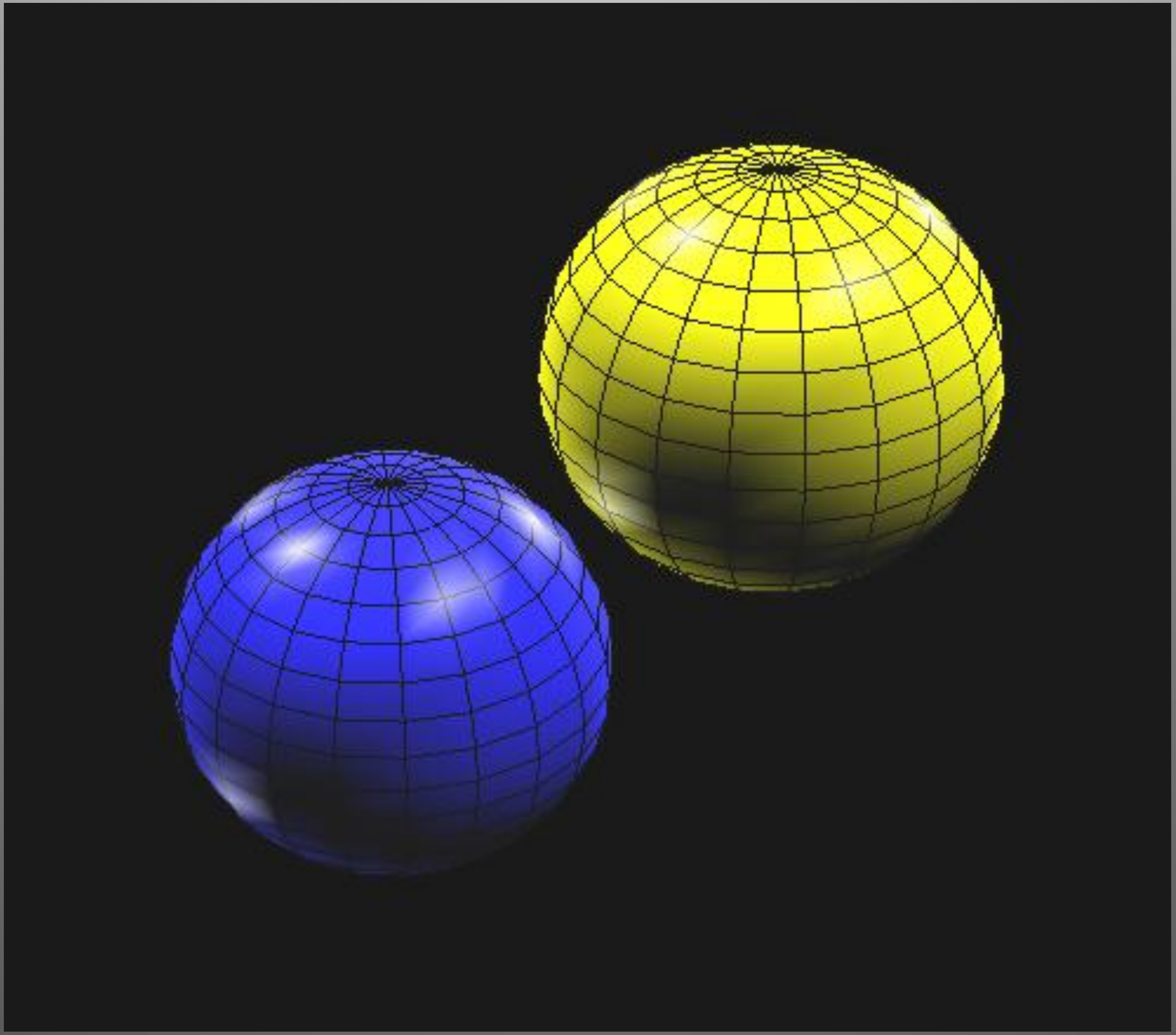
is experimentally <u>known</u> ….

and is consistent with what is known…



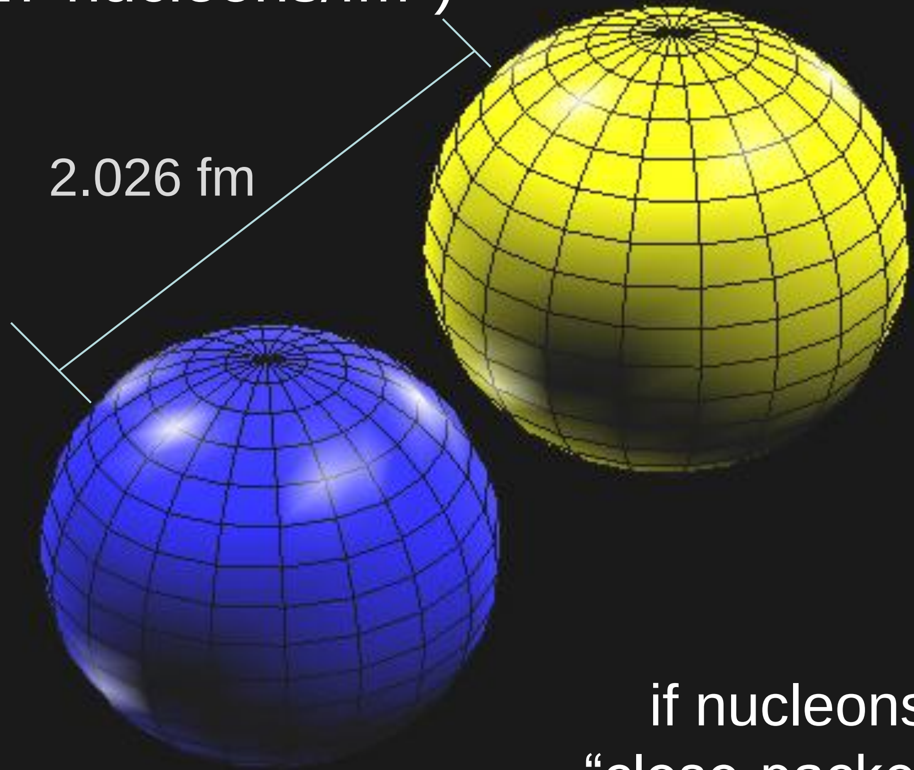
about the nuclear force from
nucleon-nucleon scattering experiments.

The first question about nuclear structure concerns the mean distance between nucleons.



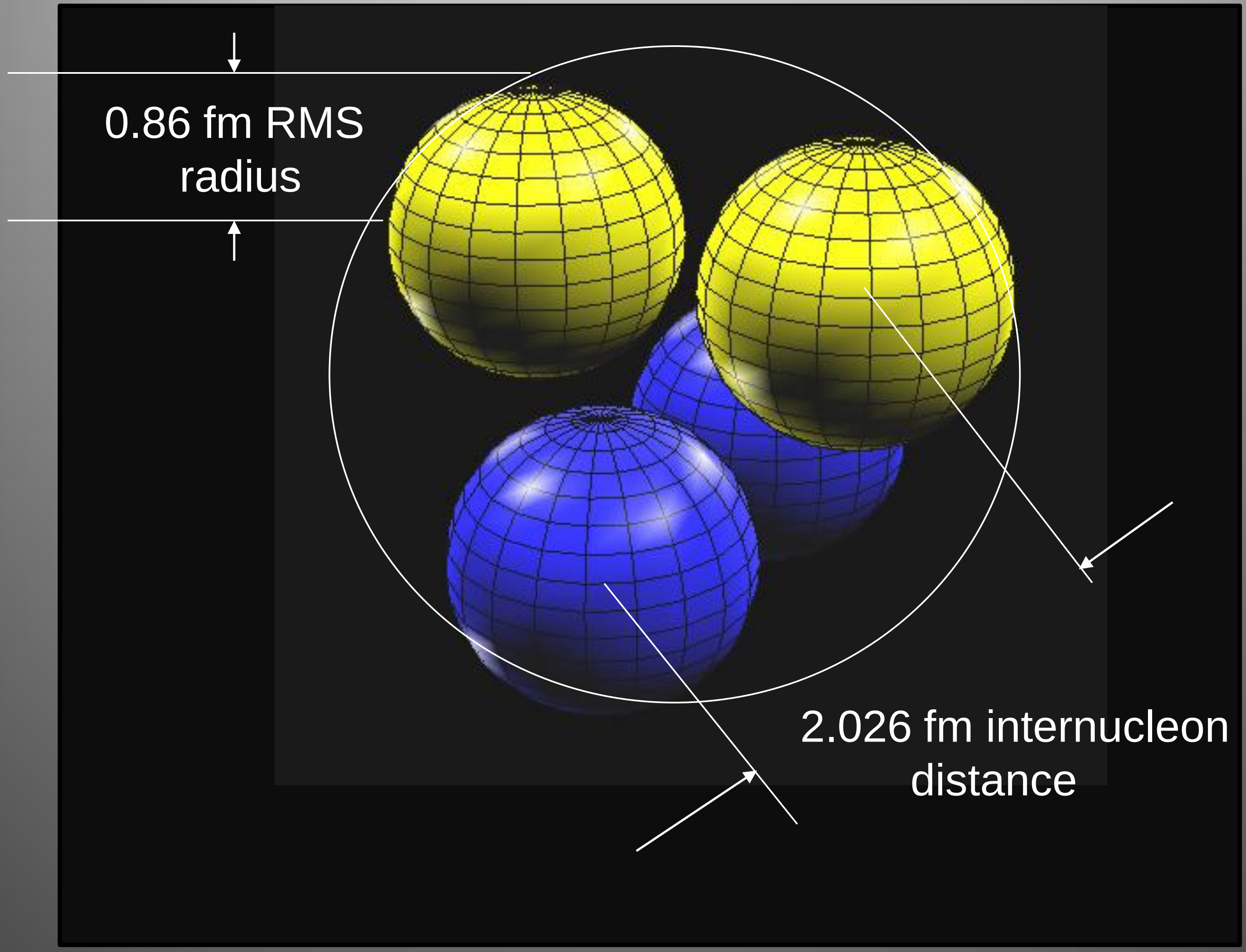
An internucleon distance of about 2 fm

reproduces the known nuclear core density (0.17 nucleons/fm^3)

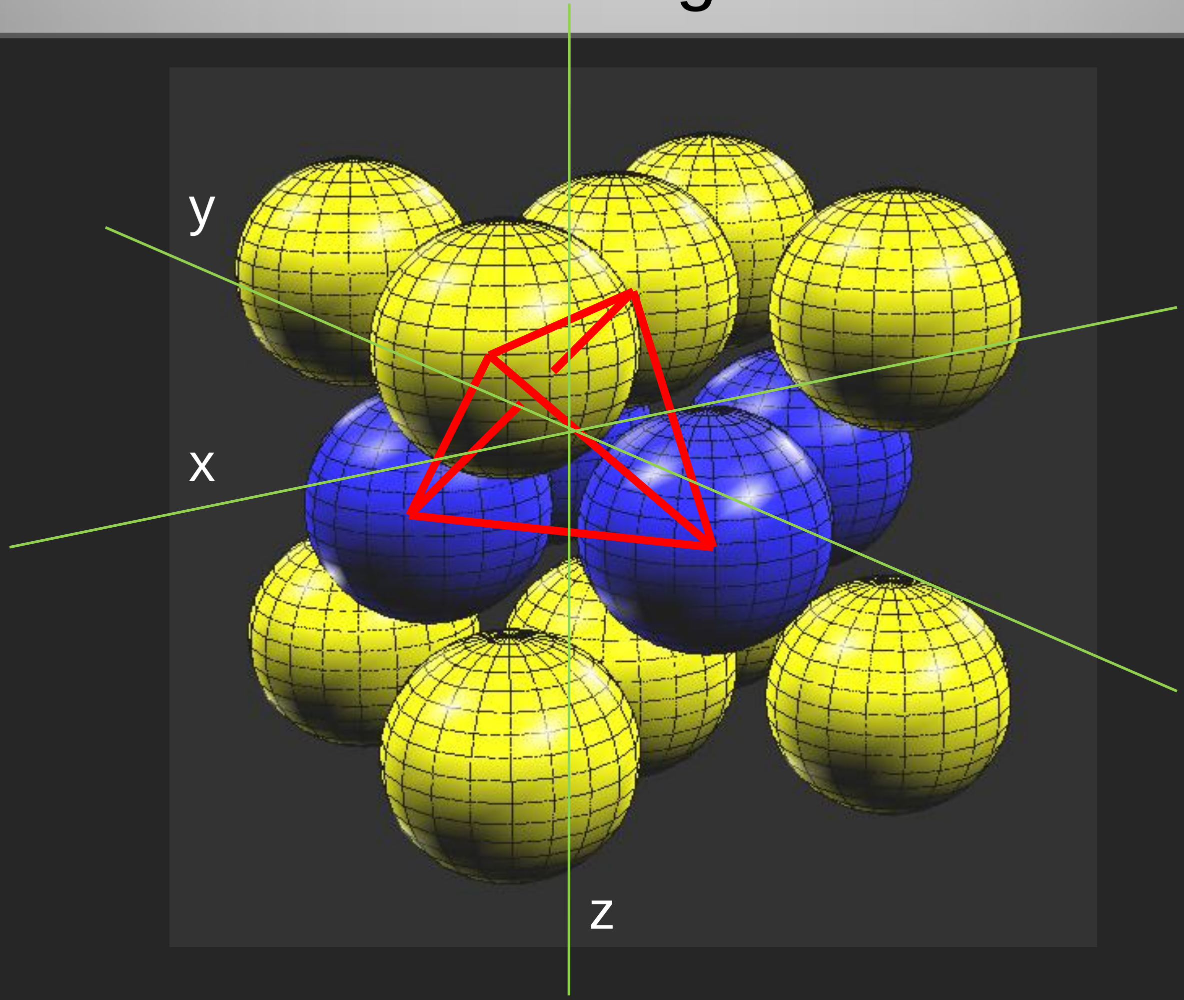


if nucleons are
“close-packed” in
the nuclear interior.

First, the He^4 nucleus…



What do we get if we continue to "close pack" nucleons with a nearest-neighbor distance of ~2 fm?

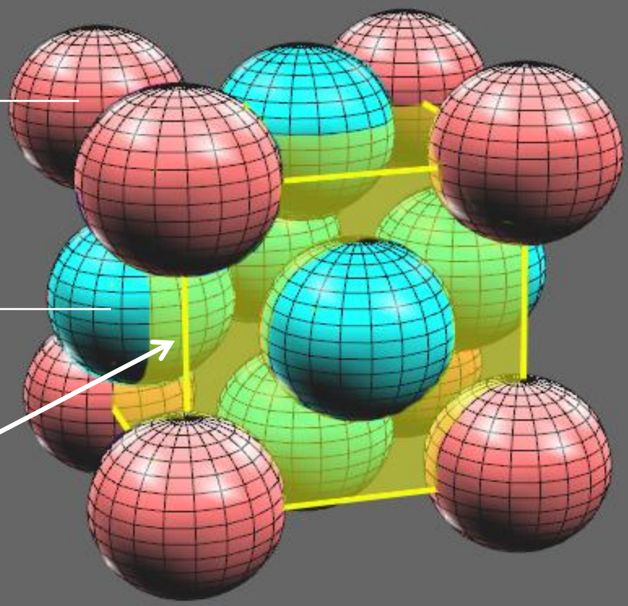


The unit structure of the face-centered-cubic lattice
(Cook & Dallacasa, Physical Review C36, 1883, 1987)

A nuclear core density of 0.17 nucleons/fm^3

A nearest-neighbor distance of 2.026 fm

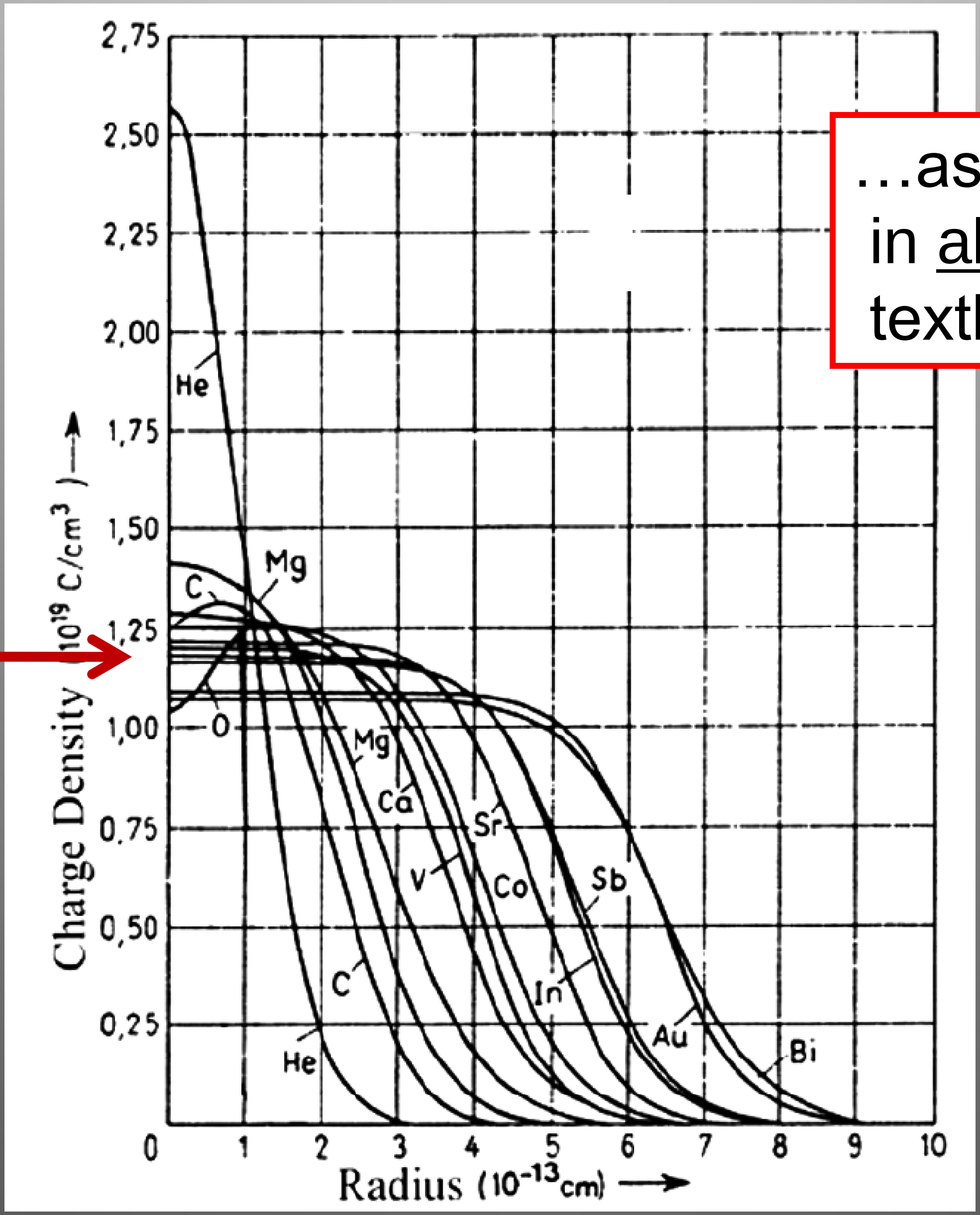
Edge-length of the cube is 2.865 fm



6 nucleon hemispheres +
8 nucleon octants
= 4 nucleons/23.517 fm^3
= 0.170 nucleons/fm^3

The unit structure of the face-centered-cubic lattice
(Cook & Dallacasa, Physical Review C36, 1883, 1987)

Experimental Data on Nuclear Sizes



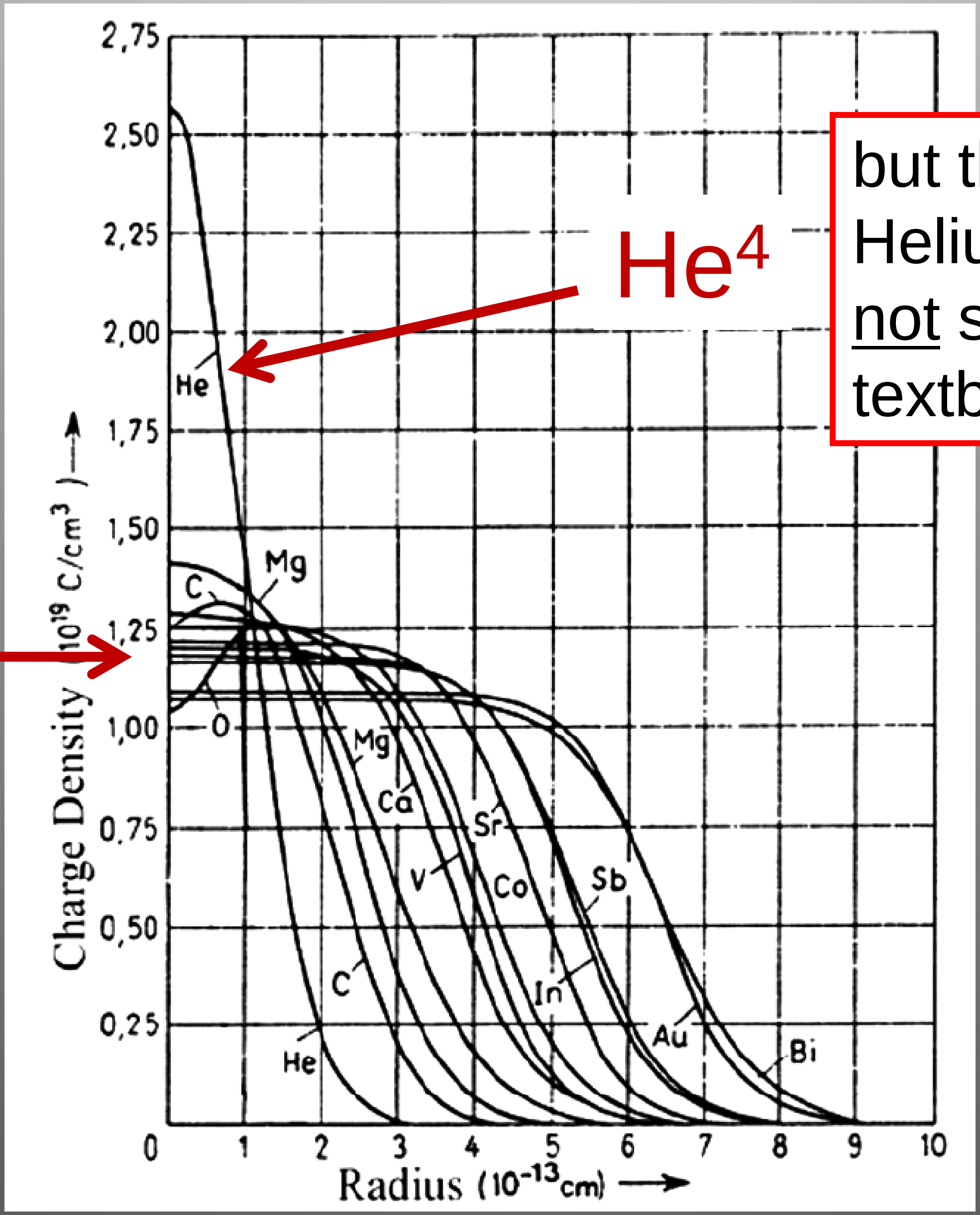
…as reported in <u>all</u> of the textbooks…

0.17 nucleons per fm^3

A constant nuclear core density is indication of a "liquid-drop" texture.

Hofstadter, 1956

Experimental Data on Nuclear Sizes



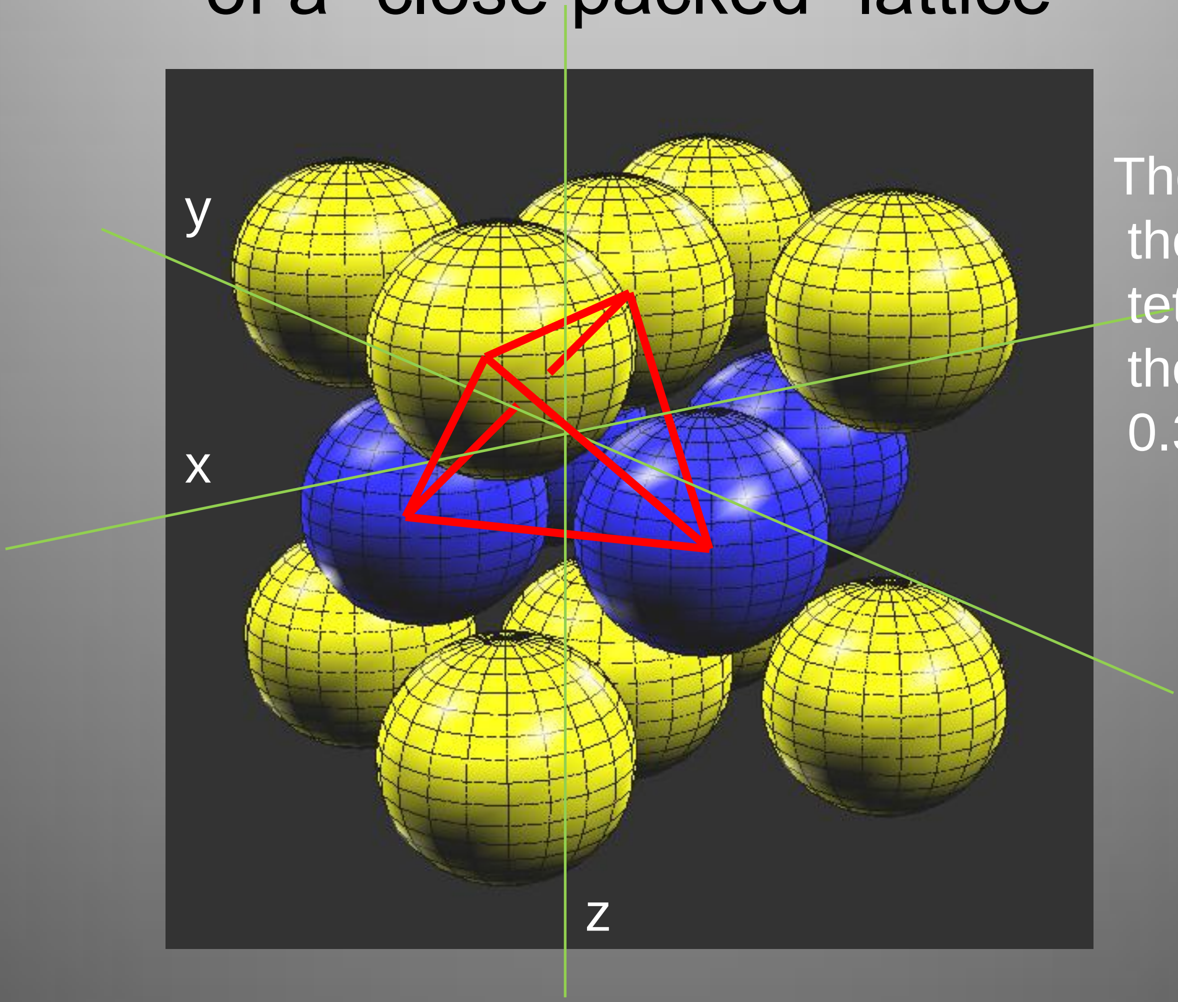
but the high-density Helium-4 curve is not shown in the textbooks !

0.17 nucleons per fm^3

A constant nuclear core density is indication of a “liquid-drop” texture.

Hofstadter, 1956

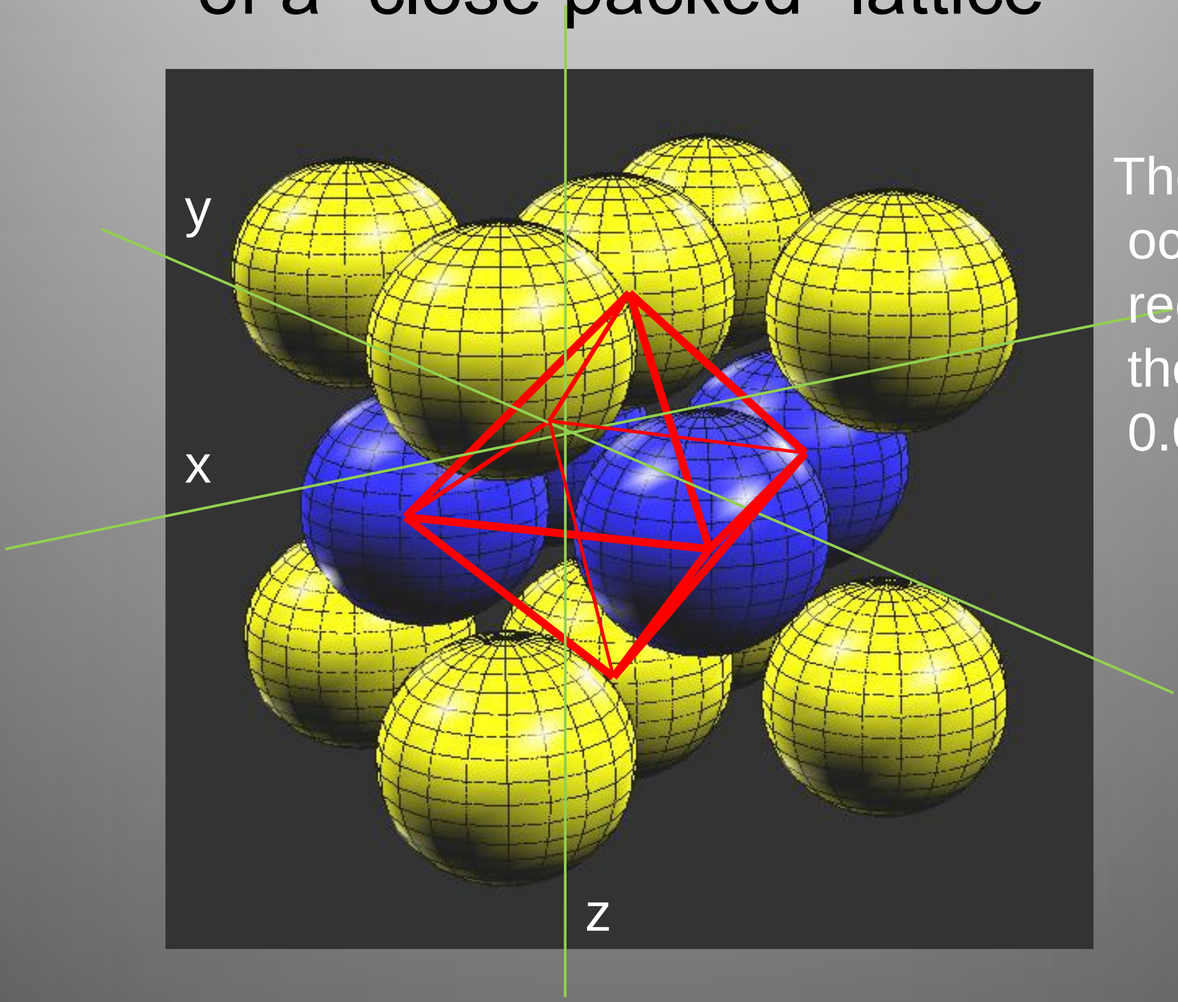
There are high-density tetrahedral regions inside of a "close packed" lattice



The density of the Helium-4 tetrahedron in the FCC lattice is 0.31 nucleons/fm^3.

The unit structure of the face-centered-cubic lattice
(Cook & Dallacasa, Physical Review C36, 1883, 1987)

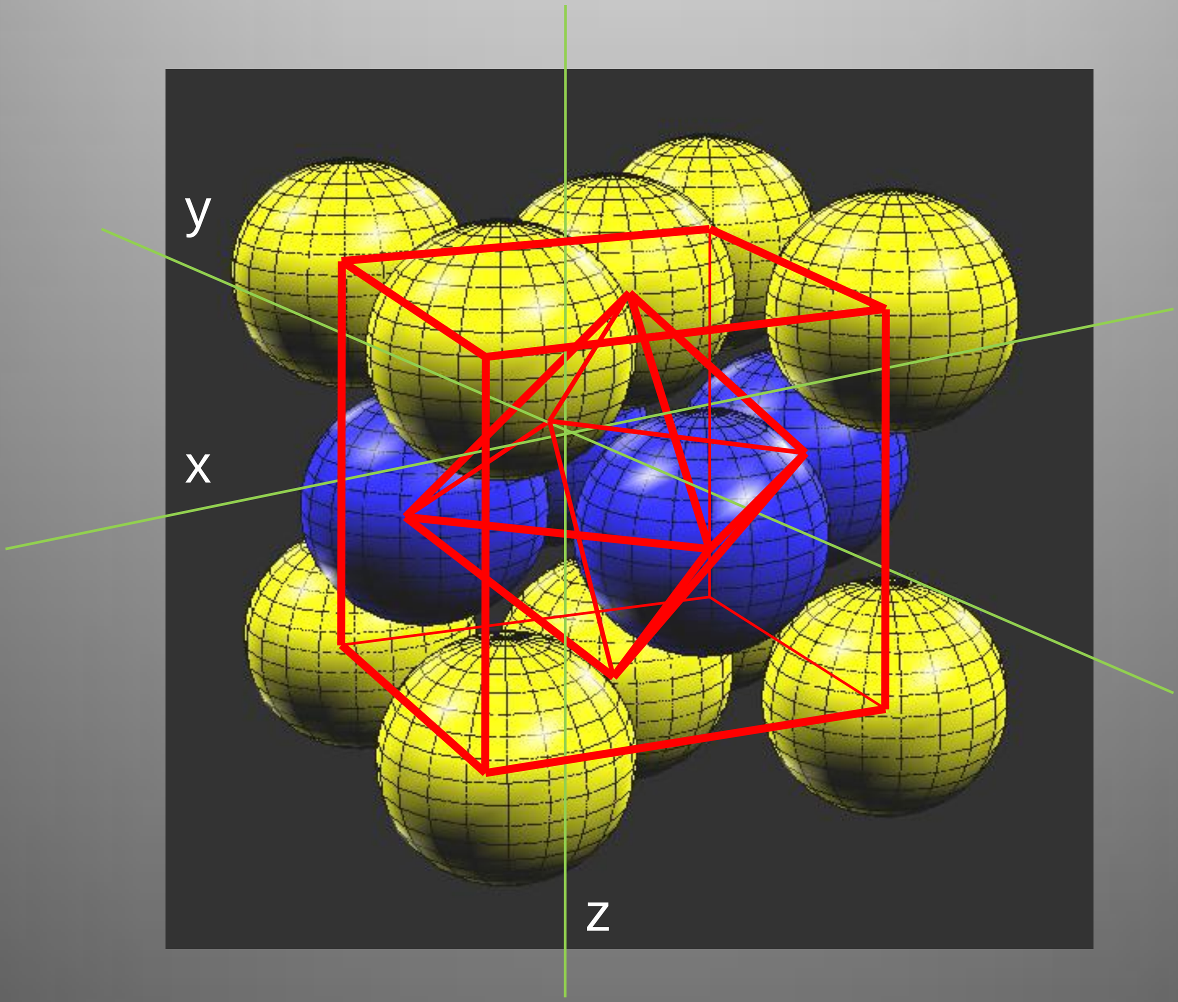
and <u>low</u>-density octahedral regions inside of a "close packed" lattice



The density of octahedral regions in the FCC lattice is 0.09 nucleons/fm^3.

The unit structure of the face-centered-cubic lattice
(Cook & Dallacasa, Physical Review C36, 1883, 1987)

…giving a mean density of 0.170 n/fm^3

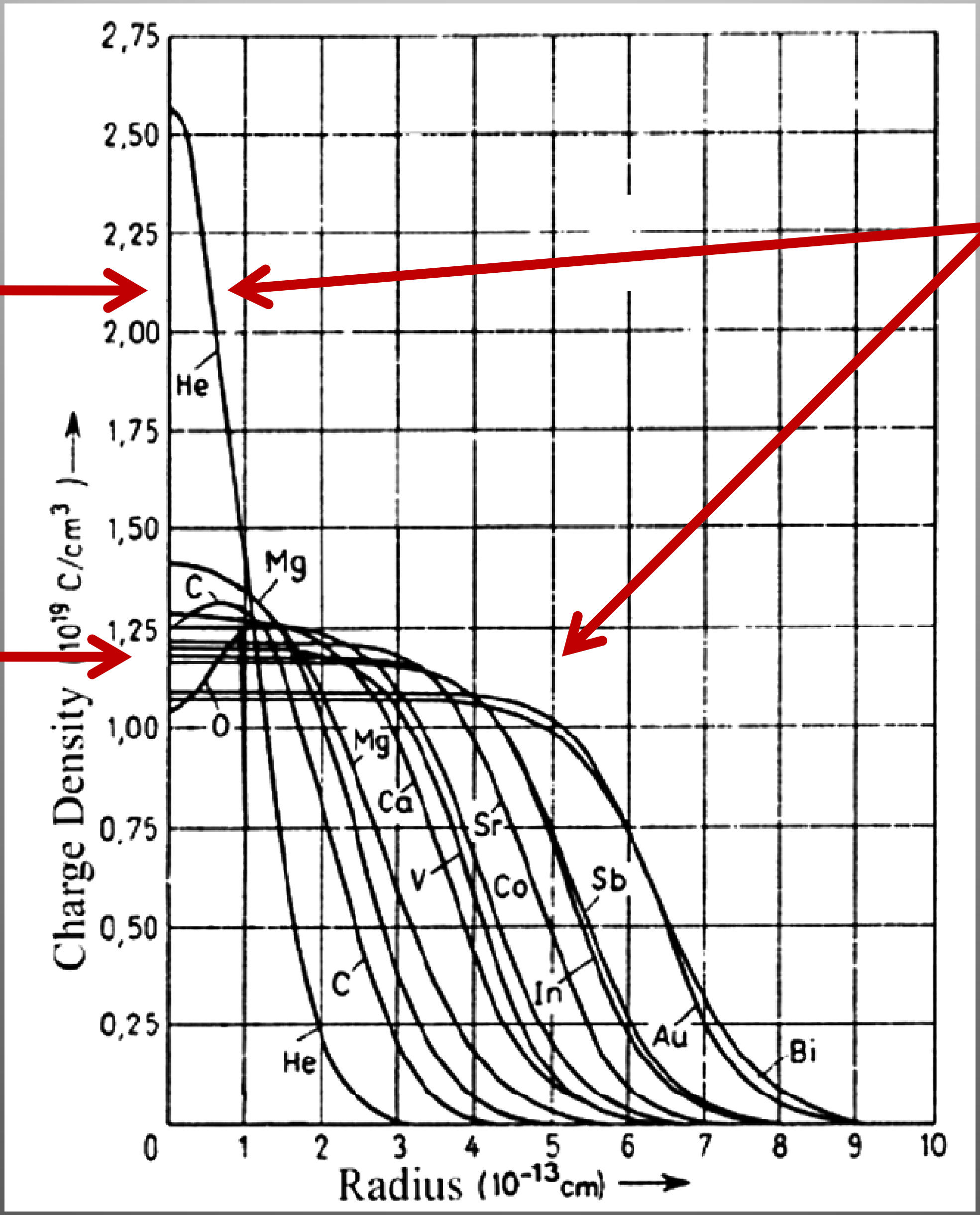


The unit structure of the face-centered-cubic lattice
(Cook & Dallacasa, Physical Review C36, 1883, 1987)

Experimental Data on Nuclear Sizes

0.31 nucleons per fm^3

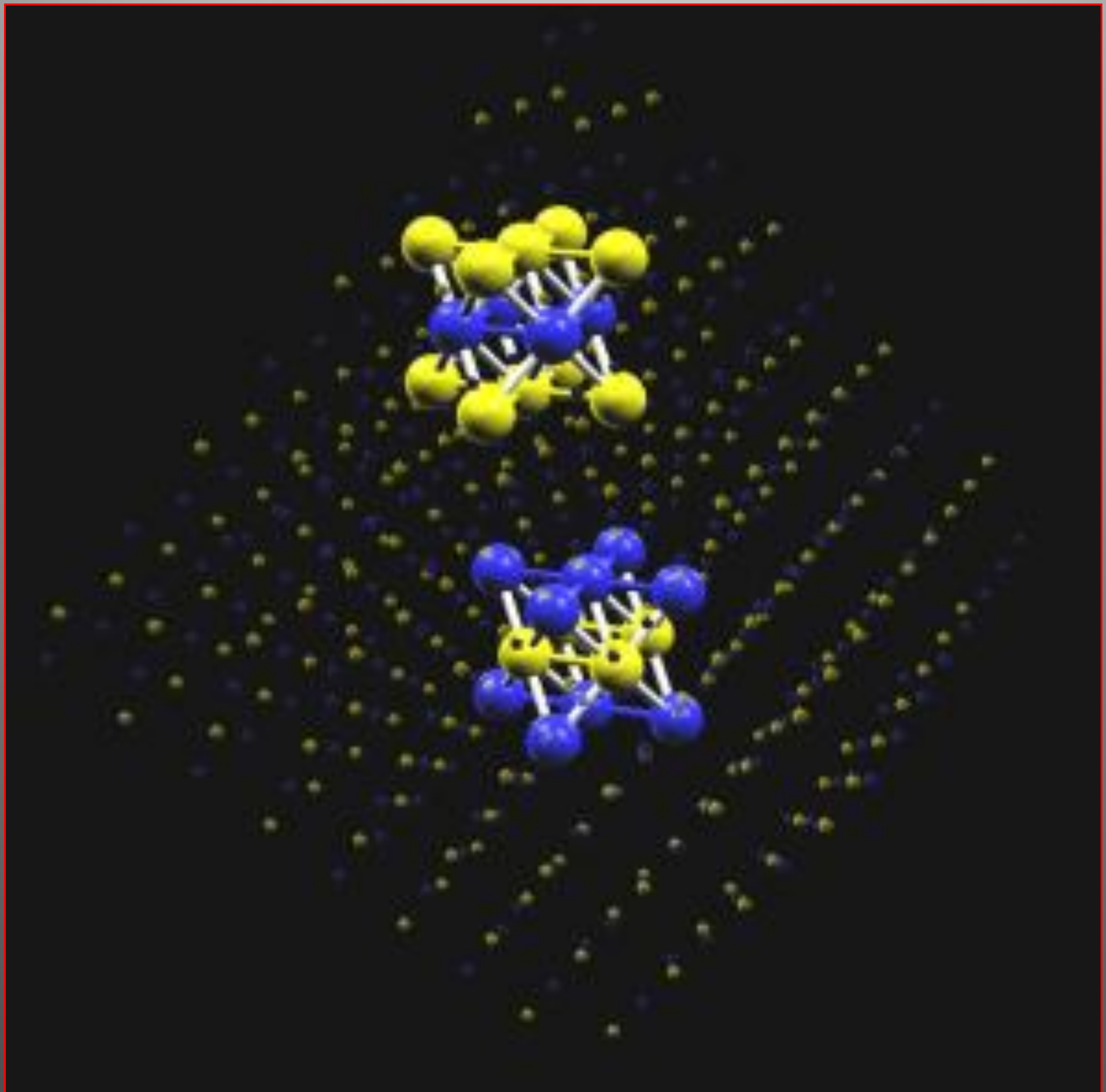
0.17 nucleons per fm^3



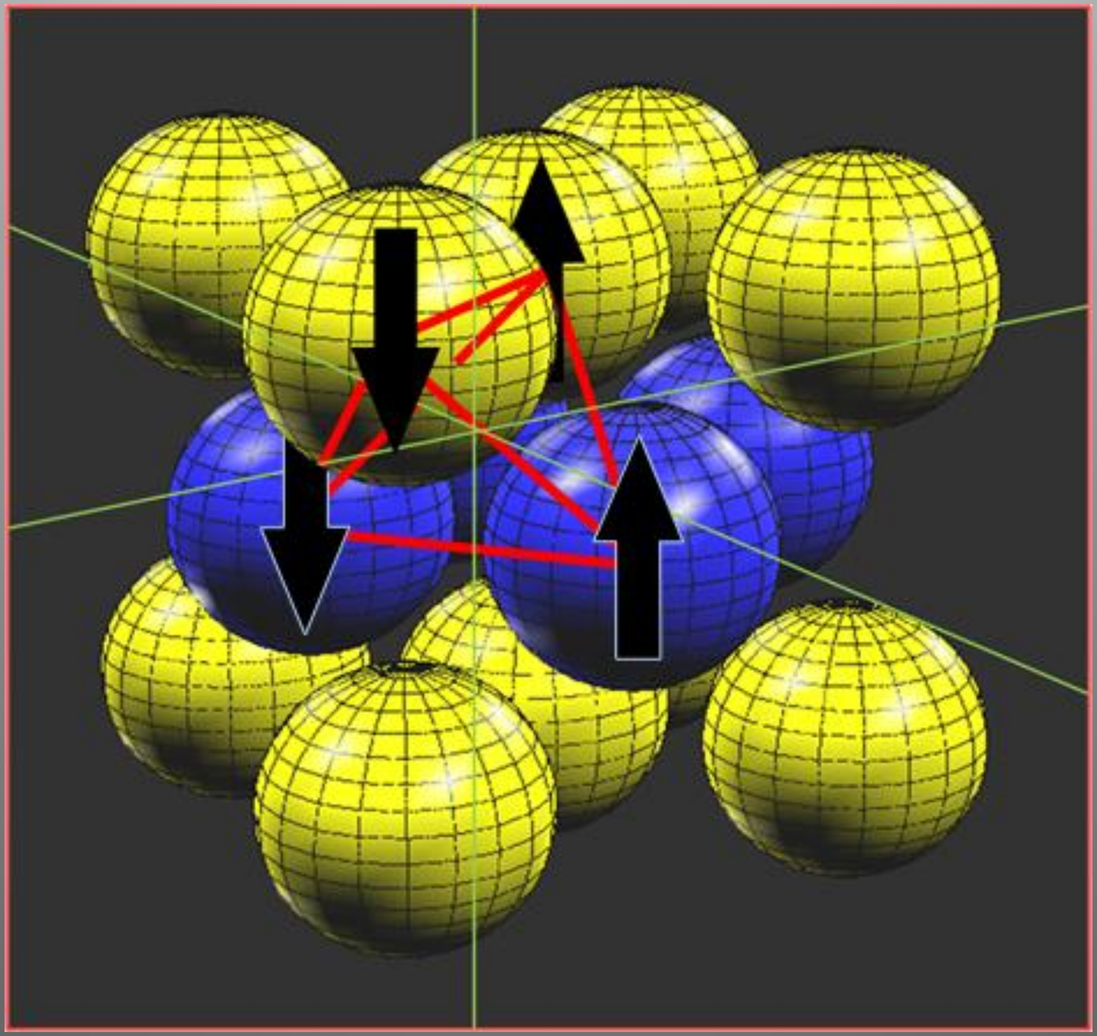
… which means that both density values are consistent with a close-packed lattice of nucleons.

Hofstadter, 1956

The FCC "unit cube" buried within the many-nucleon system.

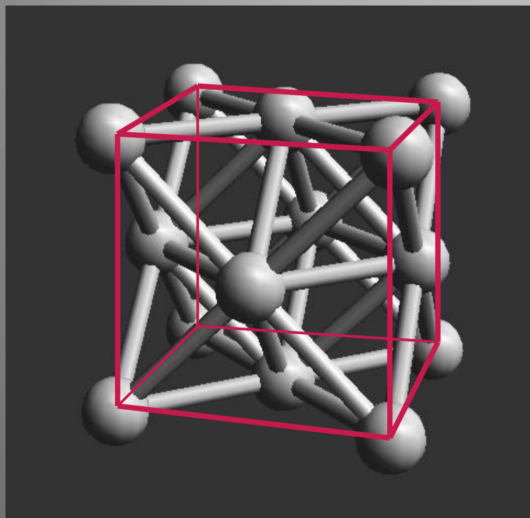


What is the substructure within the lattice?

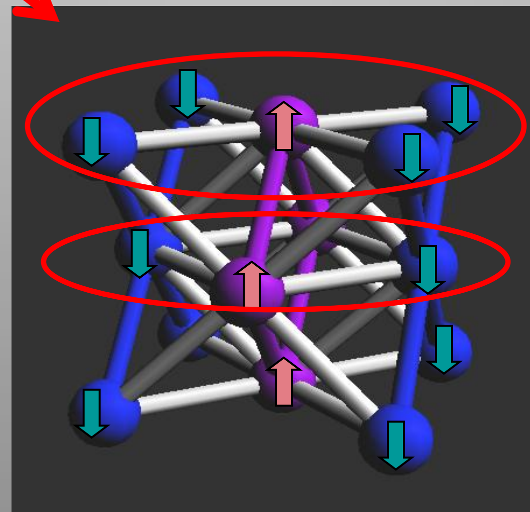


…spin and isospin symmetries are known.

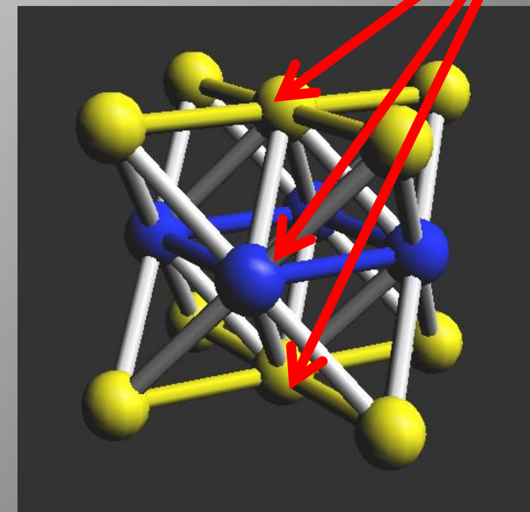
The antiferromagnetic FCC lattice with alternating isospin layers



The fcc unit cube…



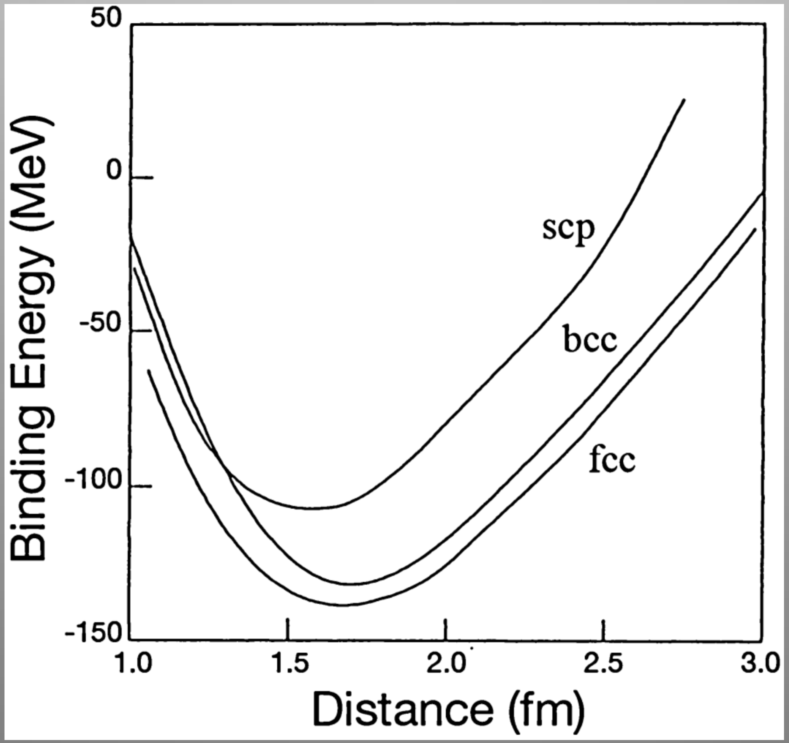
with antiferromagnetic spin alignment…



and alternating isospin layers.

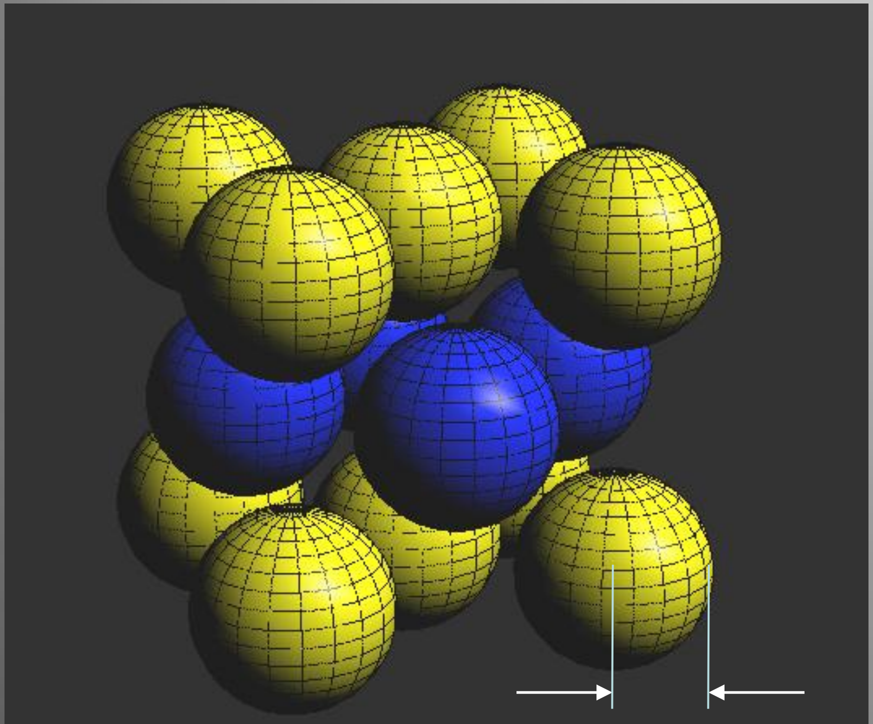
Quantum mechanical theoretical work on neutron stars has shown this lattice structure to be the <u>lowest</u> energy configuration of nuclear matter (N=Z) (Canuto & Chitre, ***Int. Astron. Astrophys. Union Symp.*** 53, 133, 1974; ***Annual Rev. Astron. Astrophys.***, 1974).

The antiferromagnetic FCC lattice with alternating isospin layers

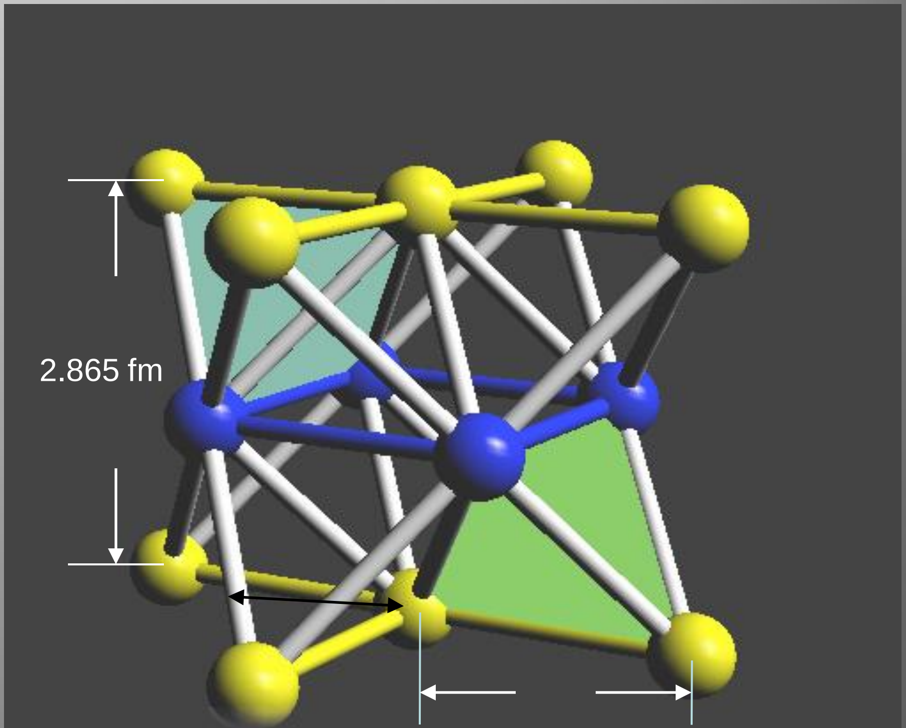


Quantum mechanical theoretical work on neutron stars has shown this lattice structure to be the lowest energy configuration of nuclear matter (N=Z) (Canuto & Chitre, ***Int. Astron. Astrophys. Union Symp.*** 53, 133, 1974; ***Annual Rev. Astron. Astrophys.***, 1974).

Alpha-particle clusters in the FCC lattice…

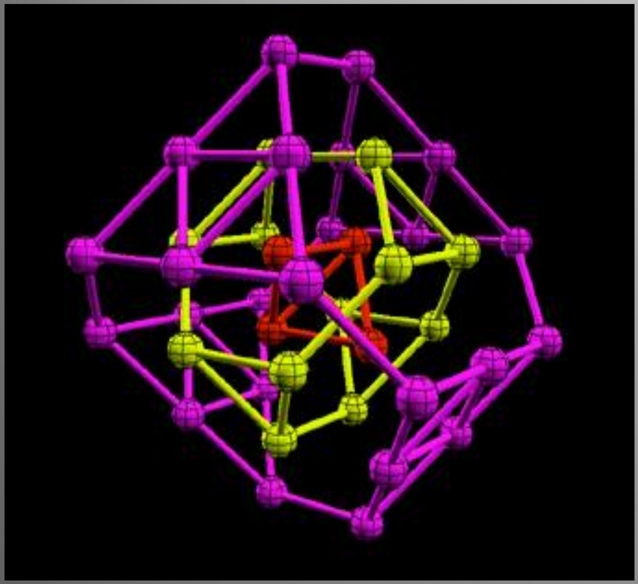


Nucleon radius = 0.86 fm

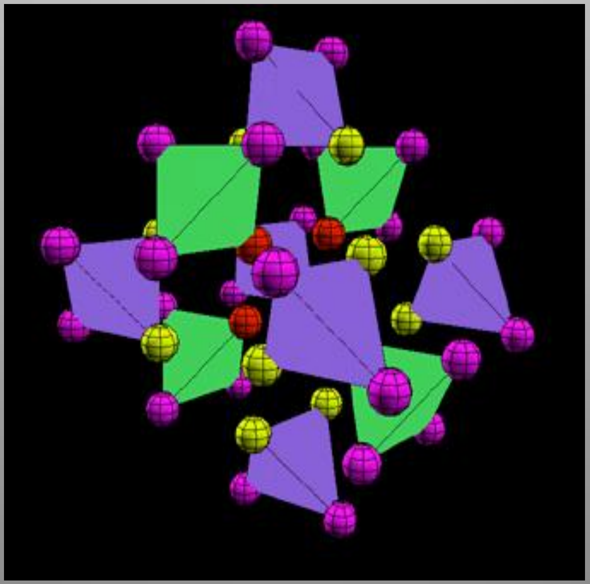


Internucleon distance = 2.026 fm

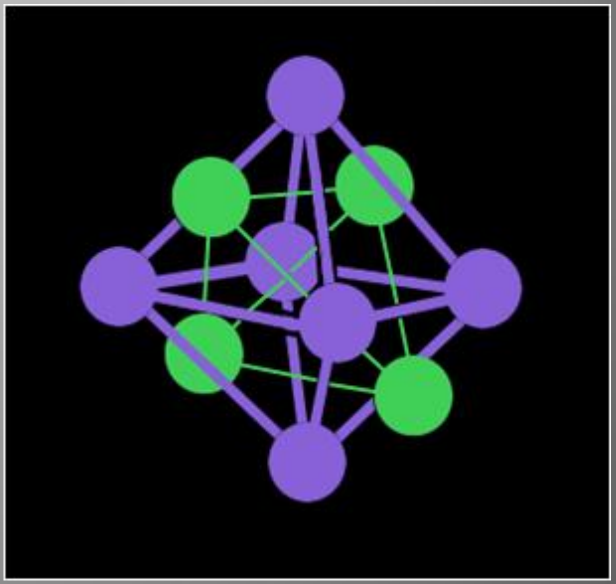
The alpha structure of Ca^{40} in the FCC lattice



The FCC lattice showing three spherical shells, corresponding to the first three doubly-magic nuclei.

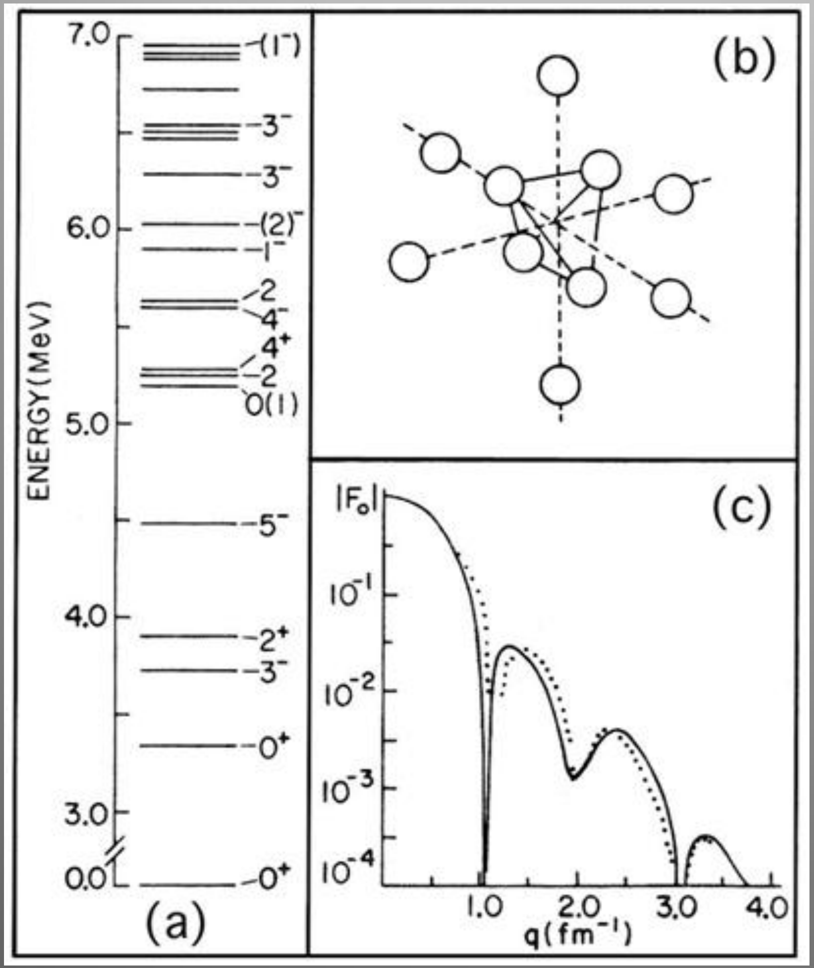


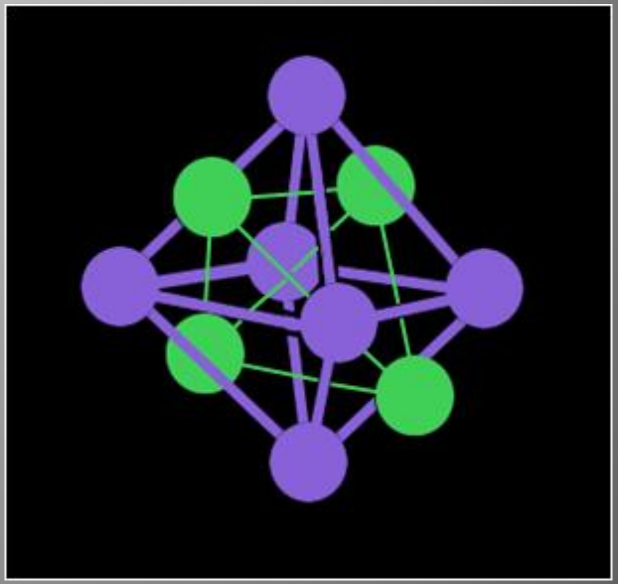
Ten tetrahedral alpha clusters are found in the FCC lattice…



and the alpha-particle structure is identical to the “classical” alpha structure for Ca-40.

The alpha structure of Ca^{40} in the FCC lattice

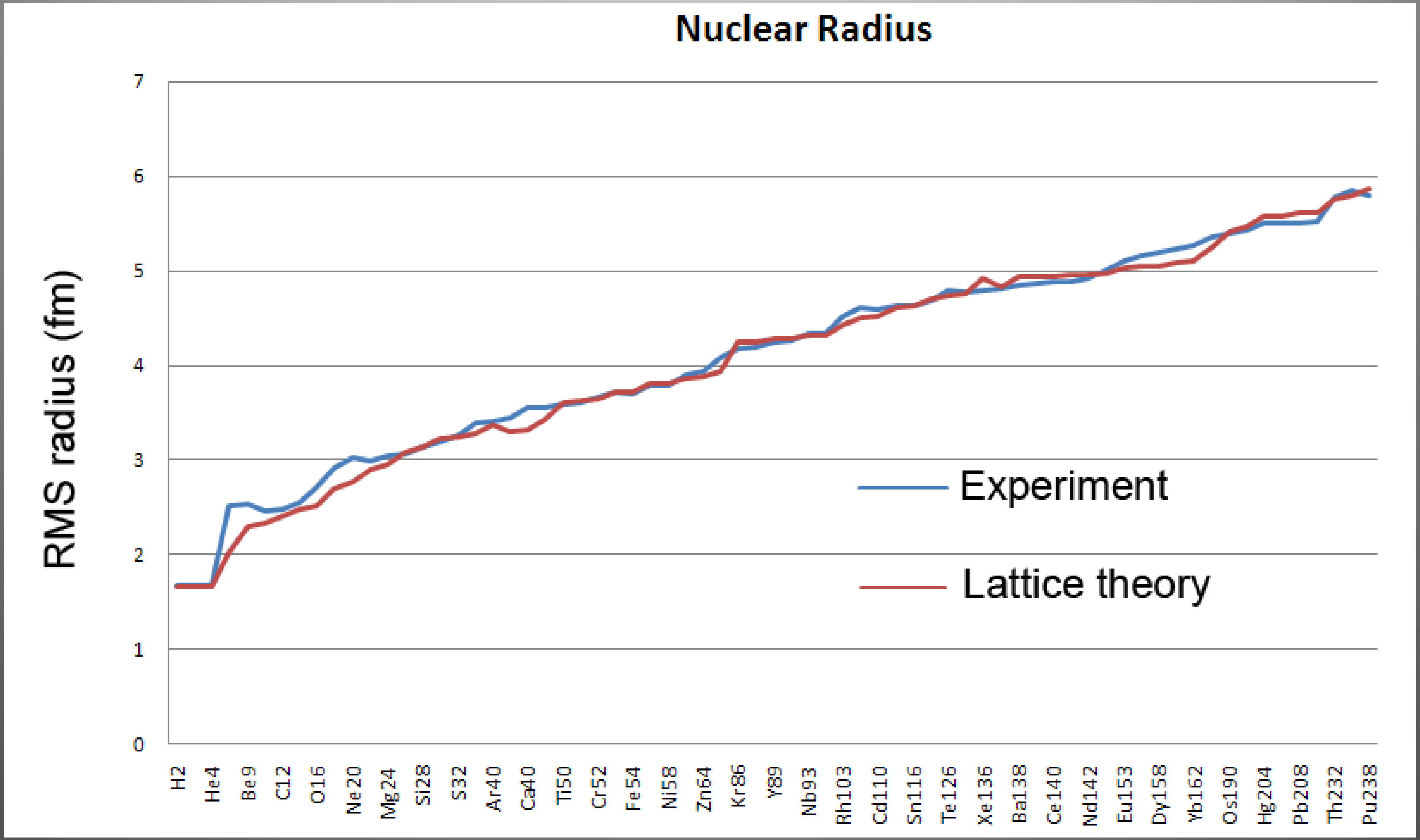




and the alpha-particle structure is identical to the “classical” alpha structure for Ca-40.

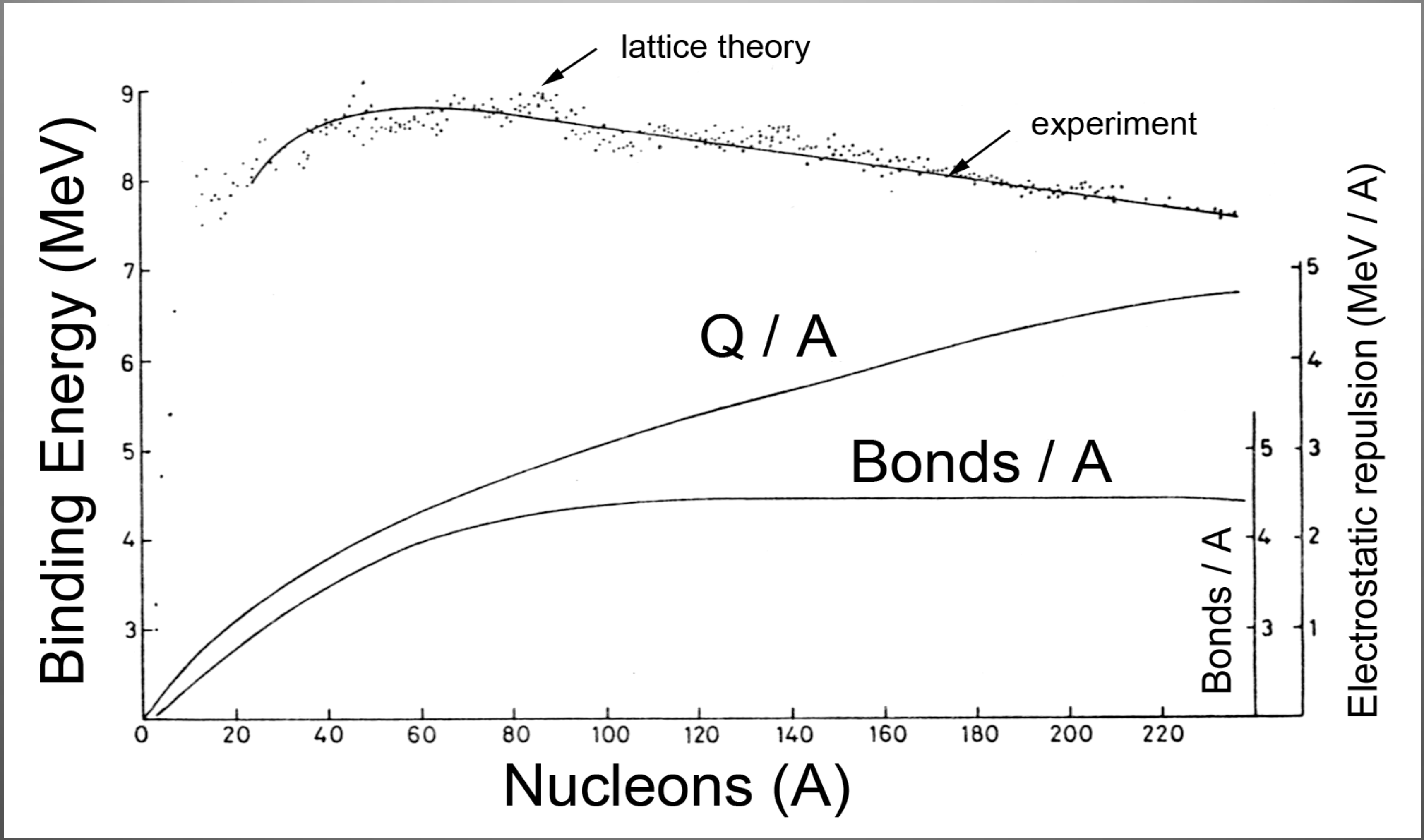
Hauge et al., *Physical Review C*4, 1044-1069, 1971;
Inopin et al., *Annals of Physics* 118, 307-333, 1979

Liquid-drop-like properties in the FCC lattice



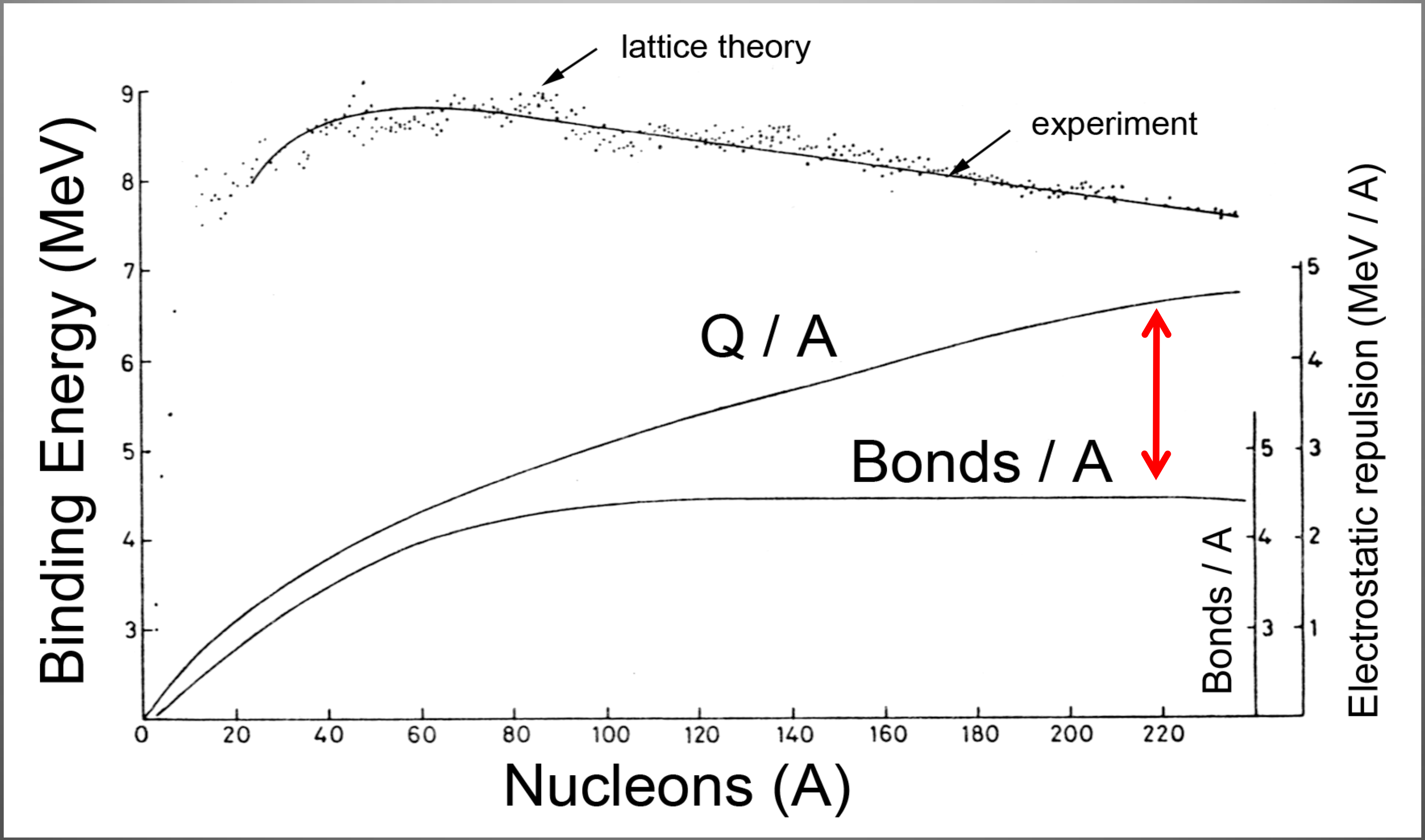
Lattice theory = Liquid-drop model = Experimental data
(Cook & Dallacasa, *Journal of Physics* G, 1987)

Liquid-drop-like properties in the FCC lattice



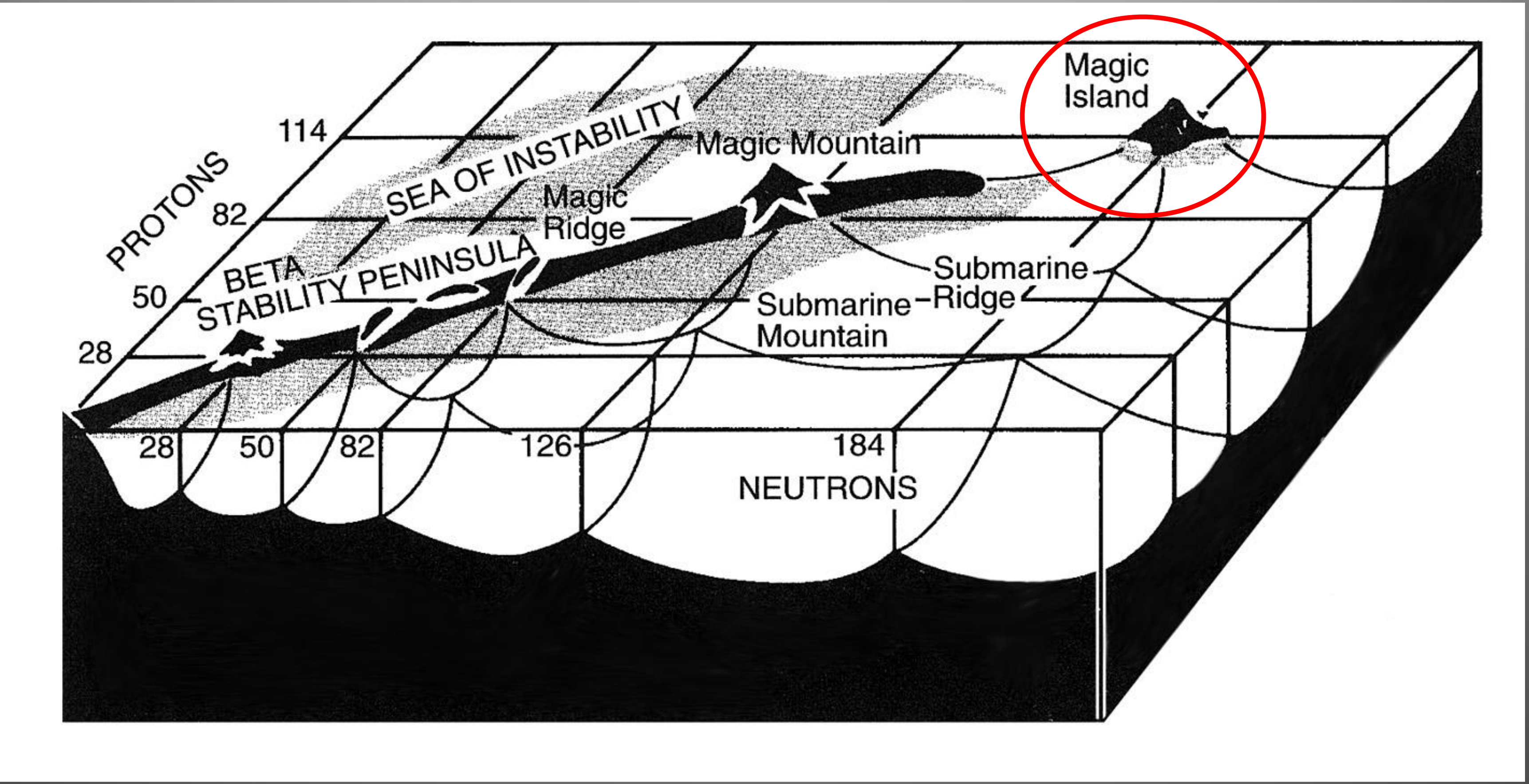
Lattice theory = Liquid-drop model = Experimental data
(Dallacasa & Cook, *Il Nuovo Cimento* A, 1987)

Quantitative prediction of the ***impossibility*** of super-heavy nuclei.



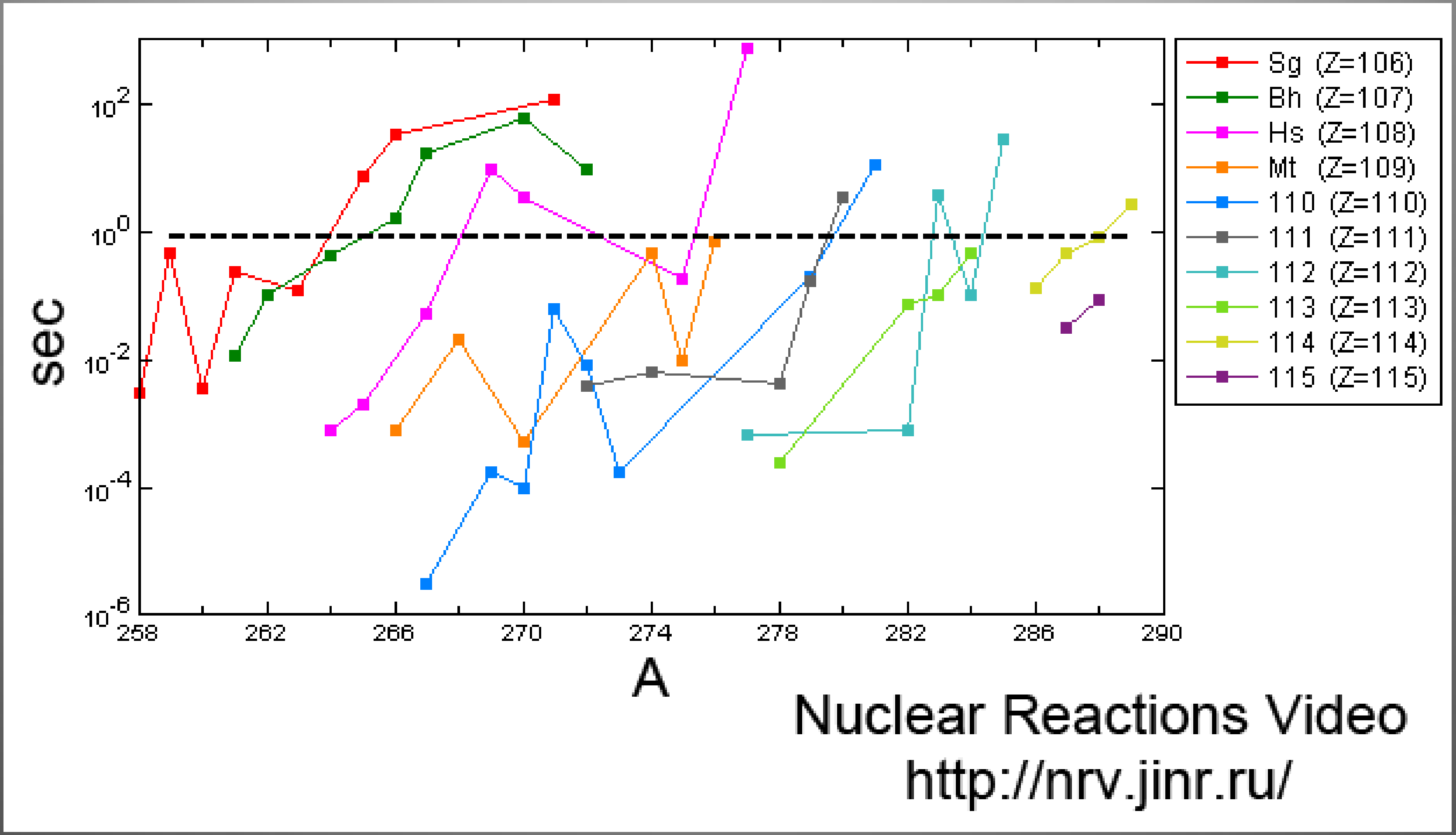
(Cook, *Modern Physics Letters* A, 1990)

All shell model predictions since the 1960s predict "stable" (~10^{15} years, Moller & Nix, 1994) super-heavy nuclei.



Seaborg & Bloom, *Science*, 1969

Experimental Data (2009)



After 40+ years, still no indication of long-lived super-heavies.

In fact, however, the independent-particle model (IPM=shell model) is the central paradigm in nuclear structure theory.

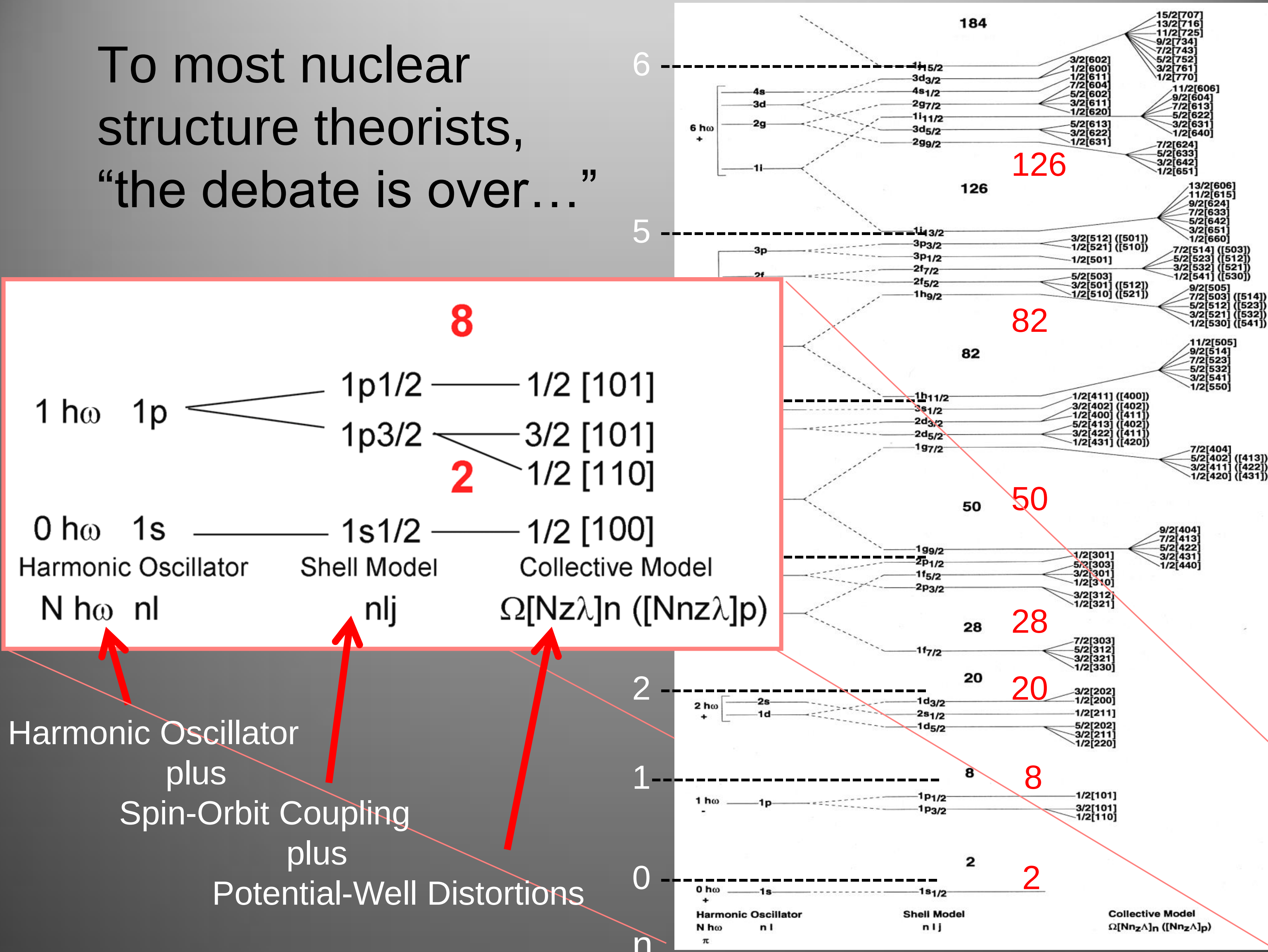
Why?

Unlike the liquid-drop model and the cluster models, the independent-particle (~shell) model is <u>quantum</u> <u>mechanical</u>.

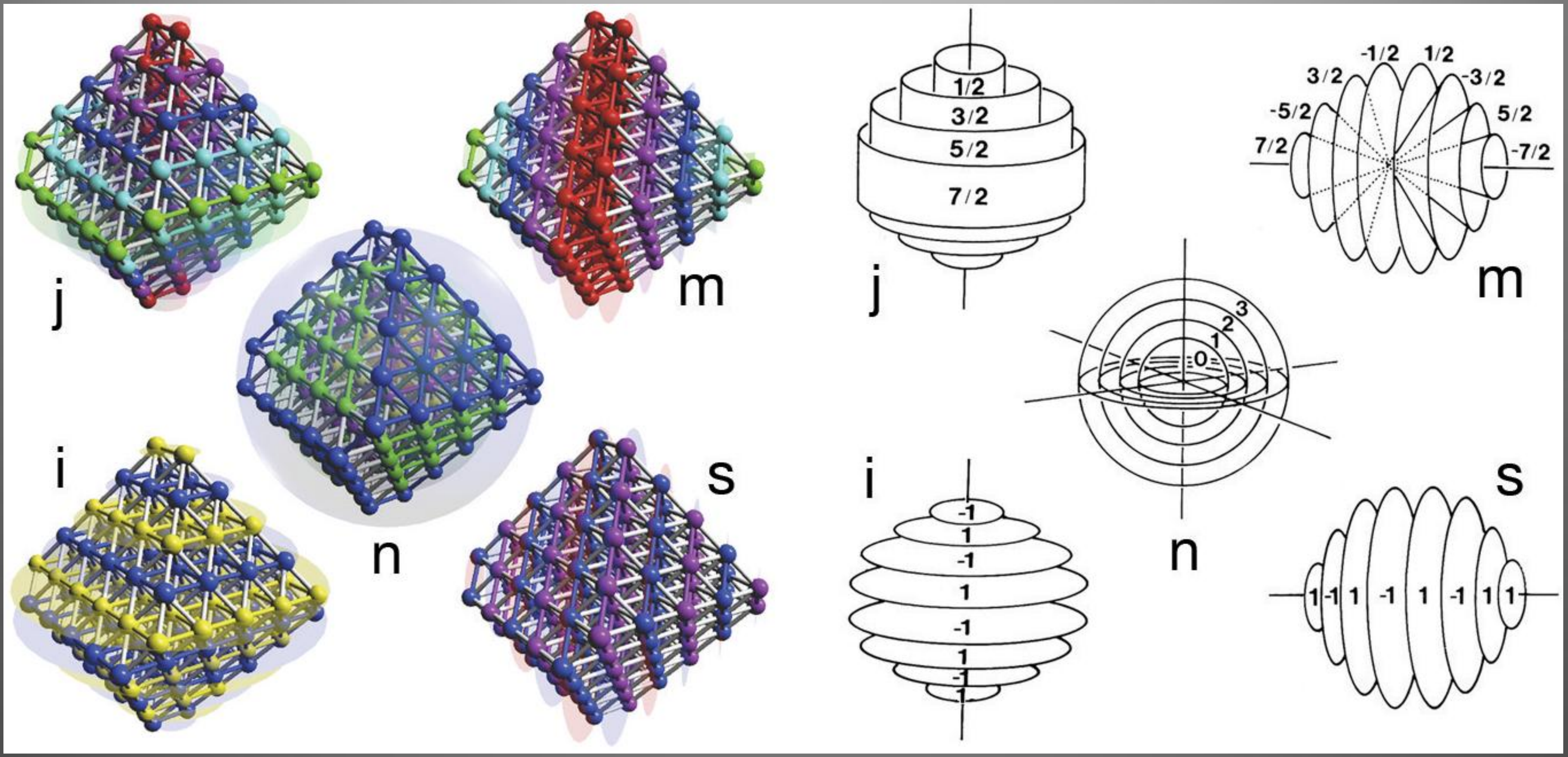
$$\Psi_{\mathrm{nlsjmi}} = R_{\mathrm{nlsjmi}}(r)\ \ Y_{\mathrm{nlsjmi}}(\theta,\varphi)$$

n = 0, 1, 2, 3, 4, …	(theory only)
l = 0, … n-2, n-1, n	(theory only)
s = $\pm$1/2	(theory and experiment)
i = $\pm$1/2	(theory and experiment)
j = l $\pm$ s	(theory and experiment)
m = $\pm$1/2, $\pm$3/2, …, $\pm$ j	(theory and experiment, Schmidt Lines)

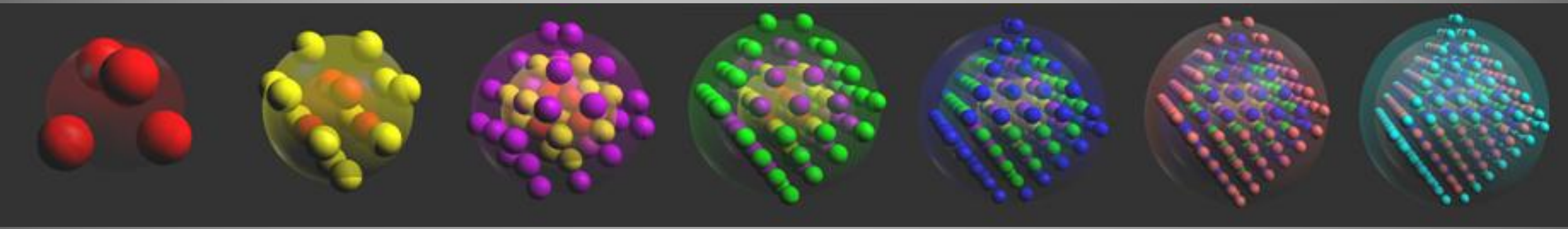
To most nuclear structure theorists, “the debate is over…”



<u>All</u> of the shells and subshells of the gaseous-phase IPM are also found in the solid-phase FCC lattice.



The n-shells of the IPM are closed (x=y=z) shells in the FCC lattice model

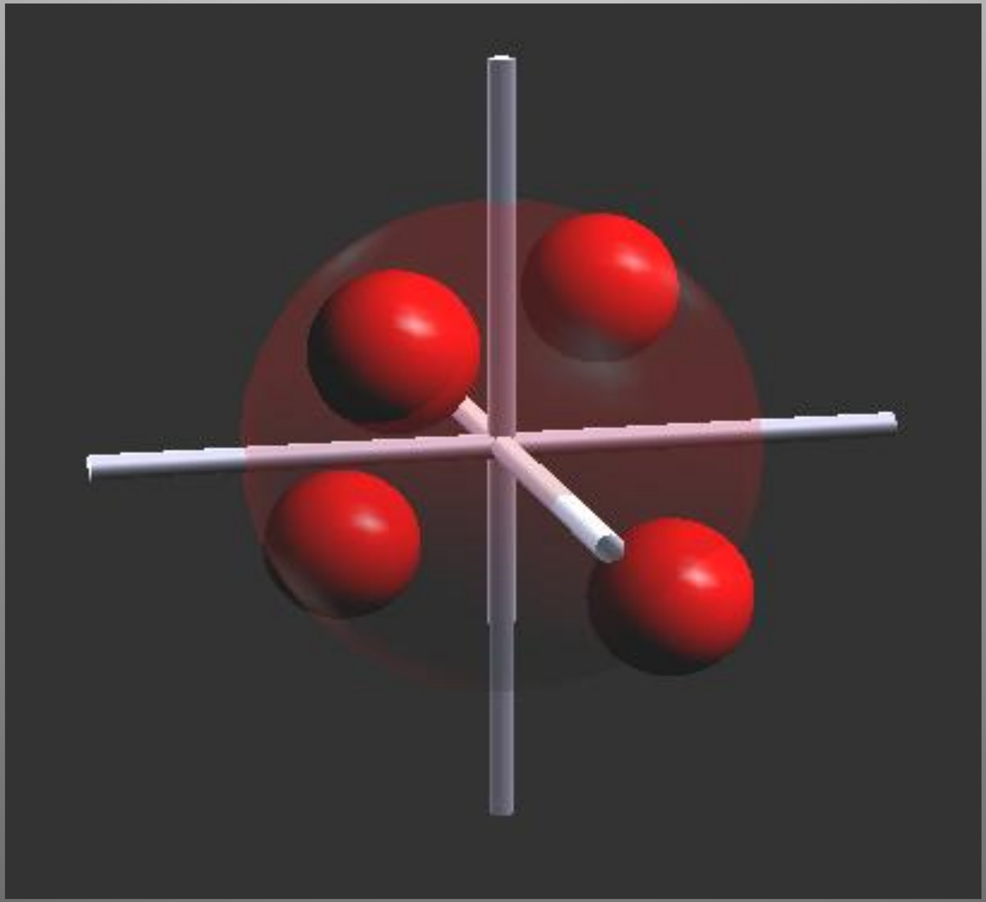


$_{2}He^{4}$ $_{8}O^{16}$ $_{20}Ca^{40}$ $_{40}Zr^{80}$ $_{70}Yt^{140}$ $_{112}Xx^{224}$ $_{168}Xx^{336}$

Principal quantum number, $n = (|x| + |y| + |z| - 3) / 2$

i.e., each nucleon's n-value is dependent on its distance from the nuclear center.

The FCC lattice n-shells

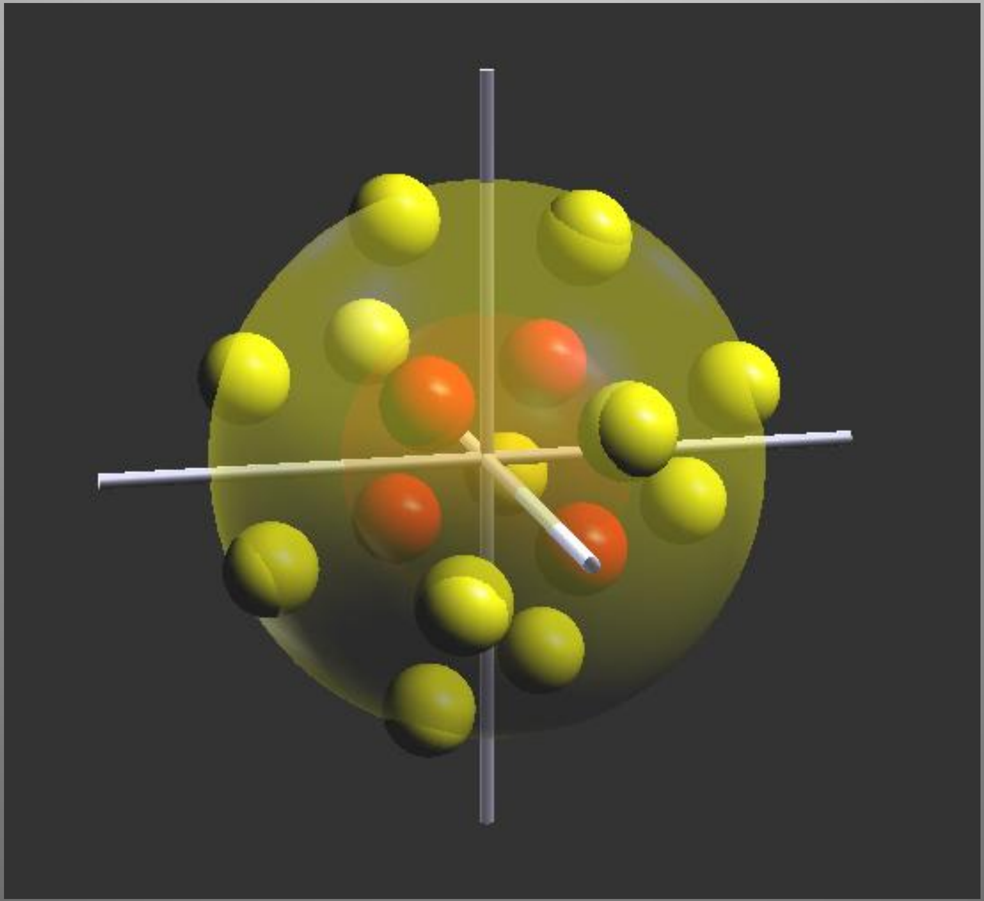


Occupancy

n	Z	N	Total
0	2	2	4

${}_{2}^{2}He^{4}$: the first "doubly-magic" nucleus,
principal quantum number $n = 0$

The FCC lattice n-shells

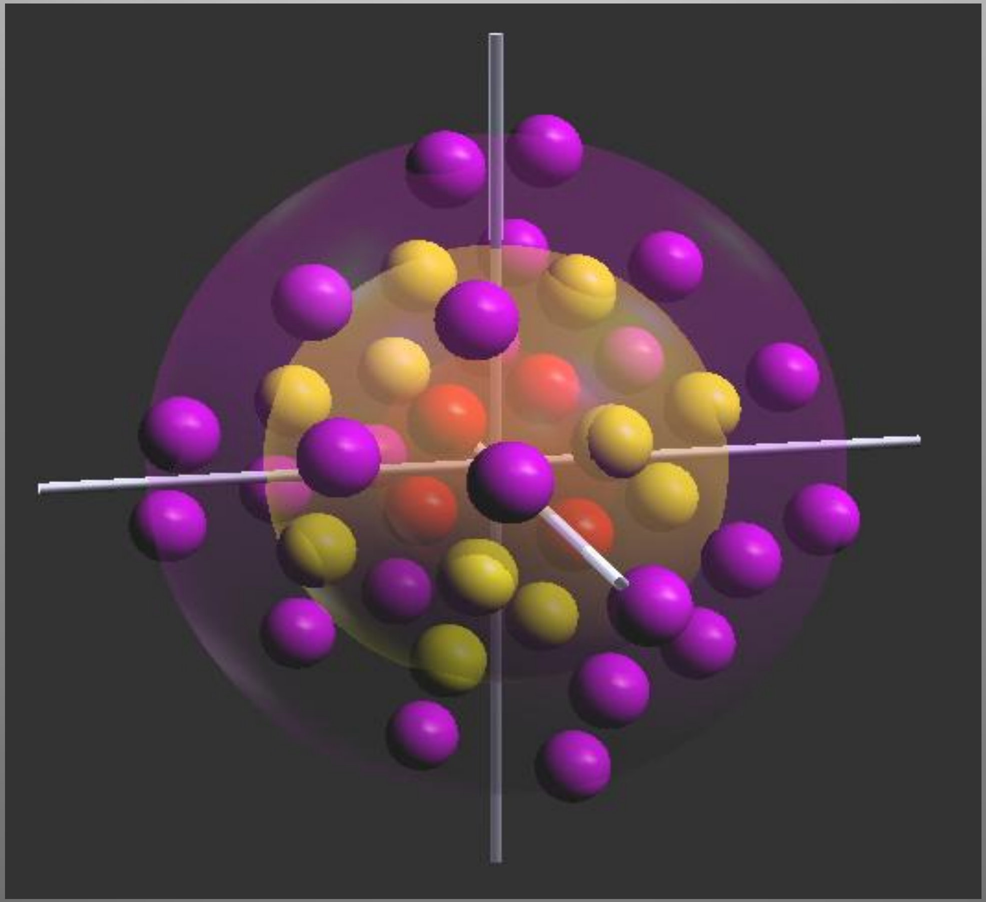


Occupancy

n	Z	N	Total
0	2	2	4
1	6	6	16

${}^{8}_{8}O^{16}$: the second "doubly-magic" nucleus, principal quantum numbers n = 0, 1

The FCC lattice n-shells

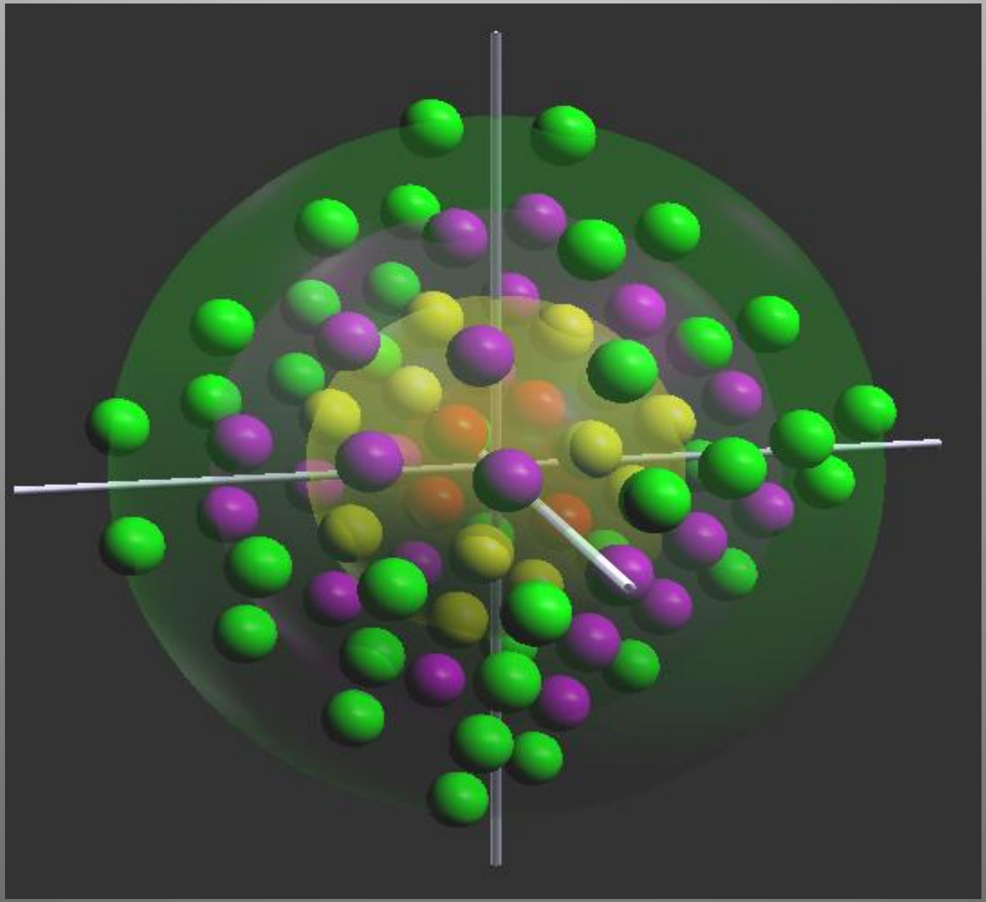


Occupancy

n	Z	N	Total
0	2	2	4
1	6	6	16
2	12	12	40

${}^{20}_{20}Ca^{40}$: the third "doubly-magic" nucleus, principal quantum numbers n = 0, 1, 2

The FCC lattice n-shells

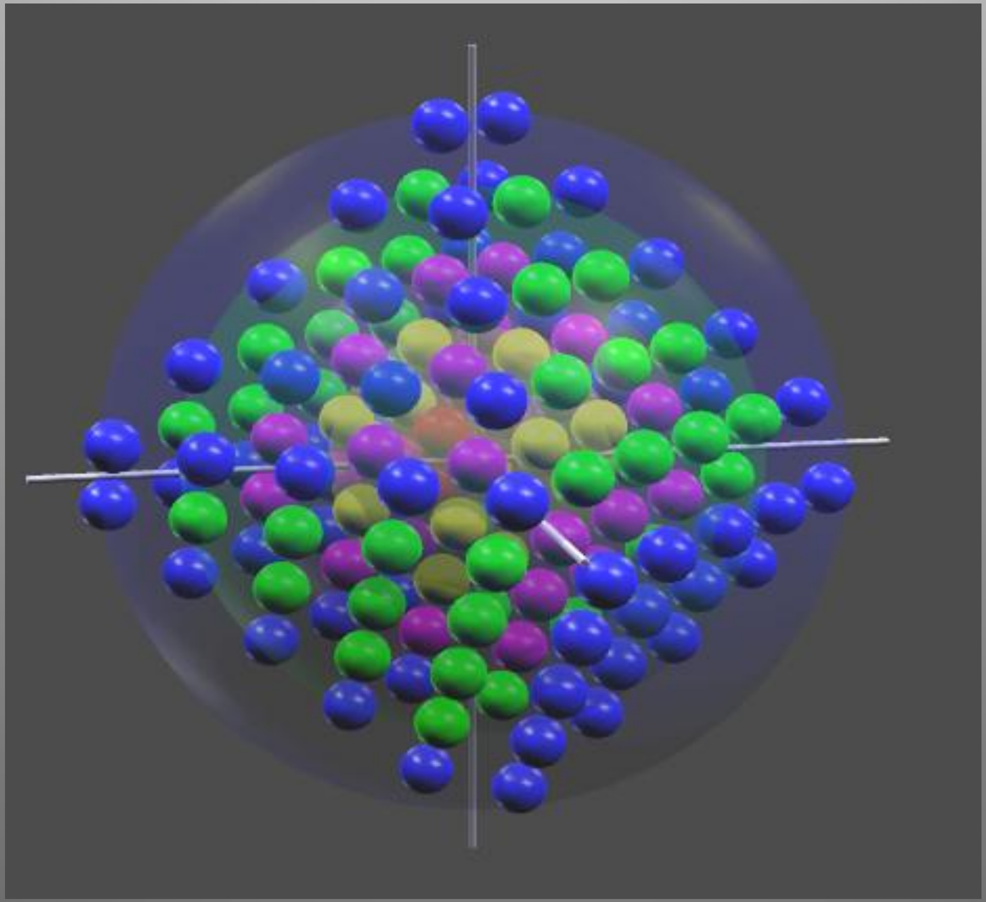


Occupancy

n	Z	N	Total
0	2	2	4
1	6	6	16
2	12	12	40
3	20	20	80

${}^{40}_{40}Zr^{80}$: an unstable closed-shell nucleus,
principal quantum numbers n = 0, 1, 2, 3

The FCC lattice n-shells

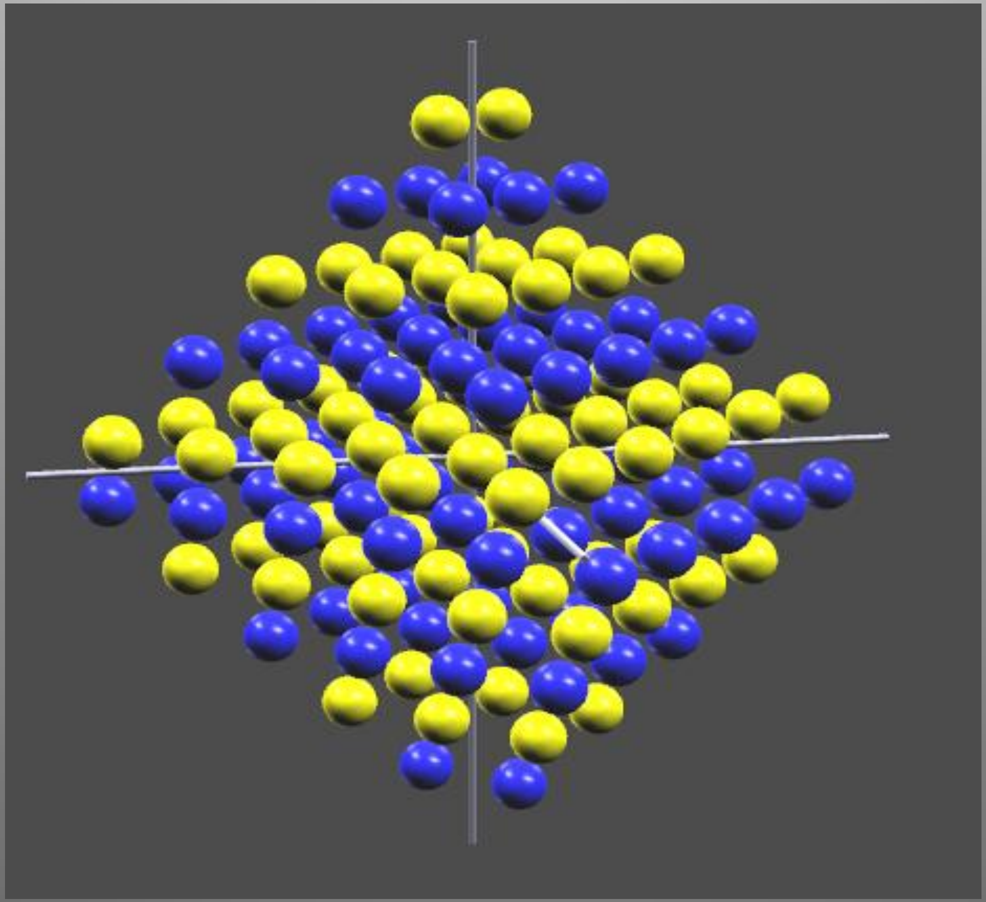


Occupancy

n	Z	N	Total
0	2	2	4
1	6	6	16
2	12	12	40
3	20	20	80
4	30	30	140

${}^{70}_{70}Yt^{140}$: an unstable closed-shell nucleus,
principal quantum numbers n = 0, 1, 2, 3, 4

The FCC lattice n-shells

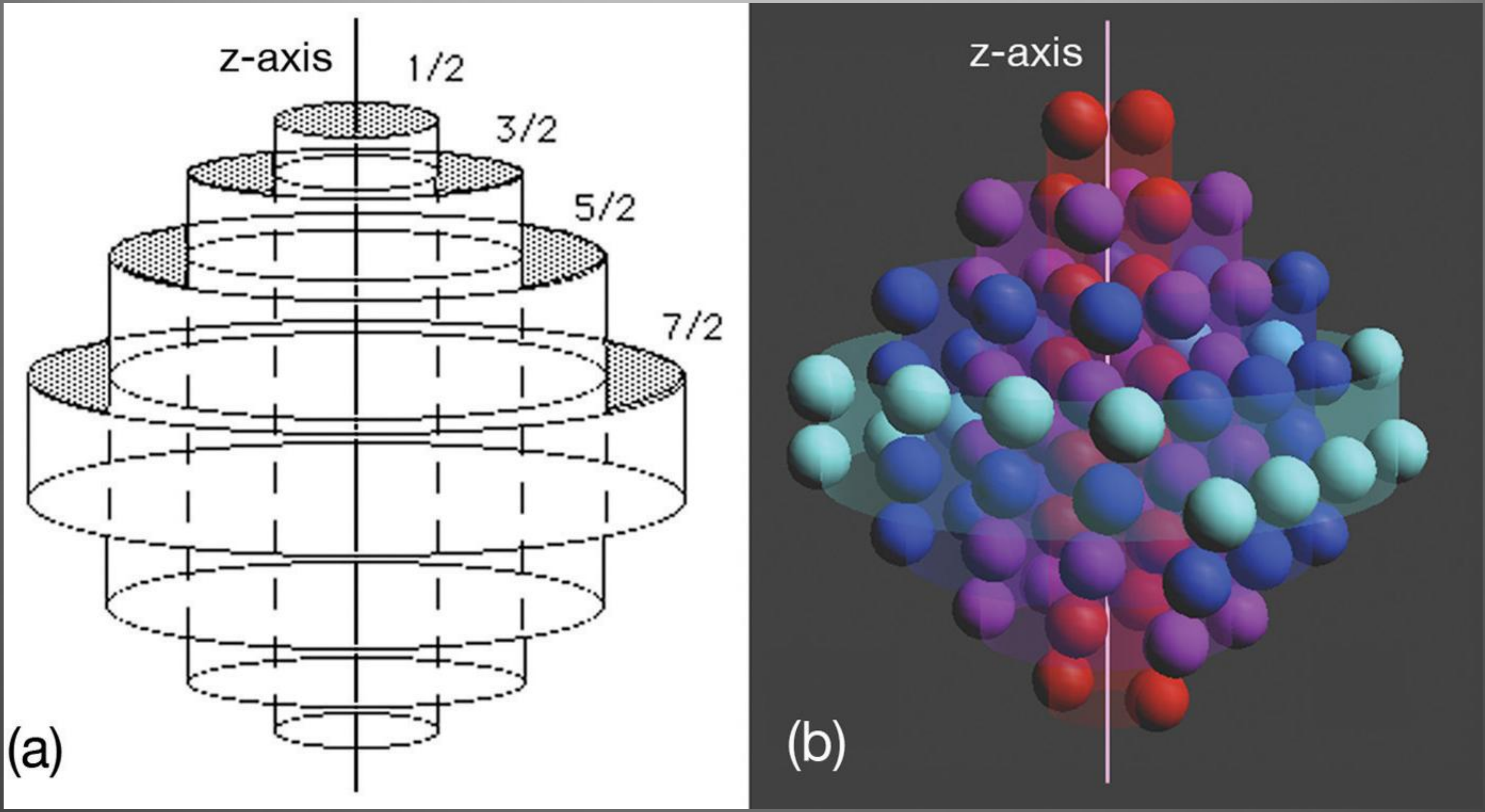


Occupancy

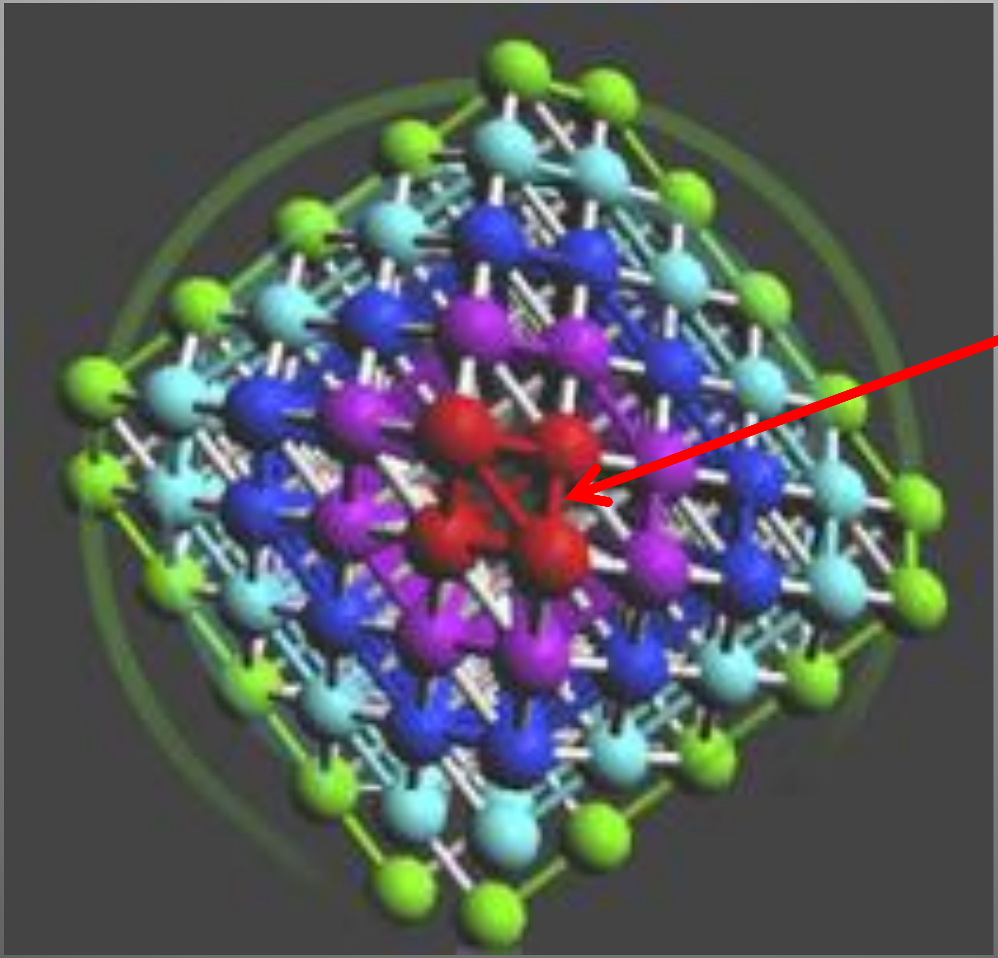
n	Z	N	Total
0	2	2	4
1	6	6	16
2	12	12	40
3	20	20	80
4	30	30	140

${}^{70}_{70}Yt^{140}$: an unstable closed-shell nucleus,
principal quantum numbers n = 0, 1, 2, 3, 4

And all of the j-subshells of the IPM correspond to cylindrical structures in the FCC lattice.



And all of the j-subshells of the IPM correspond to cylindrical structures in the FCC lattice.

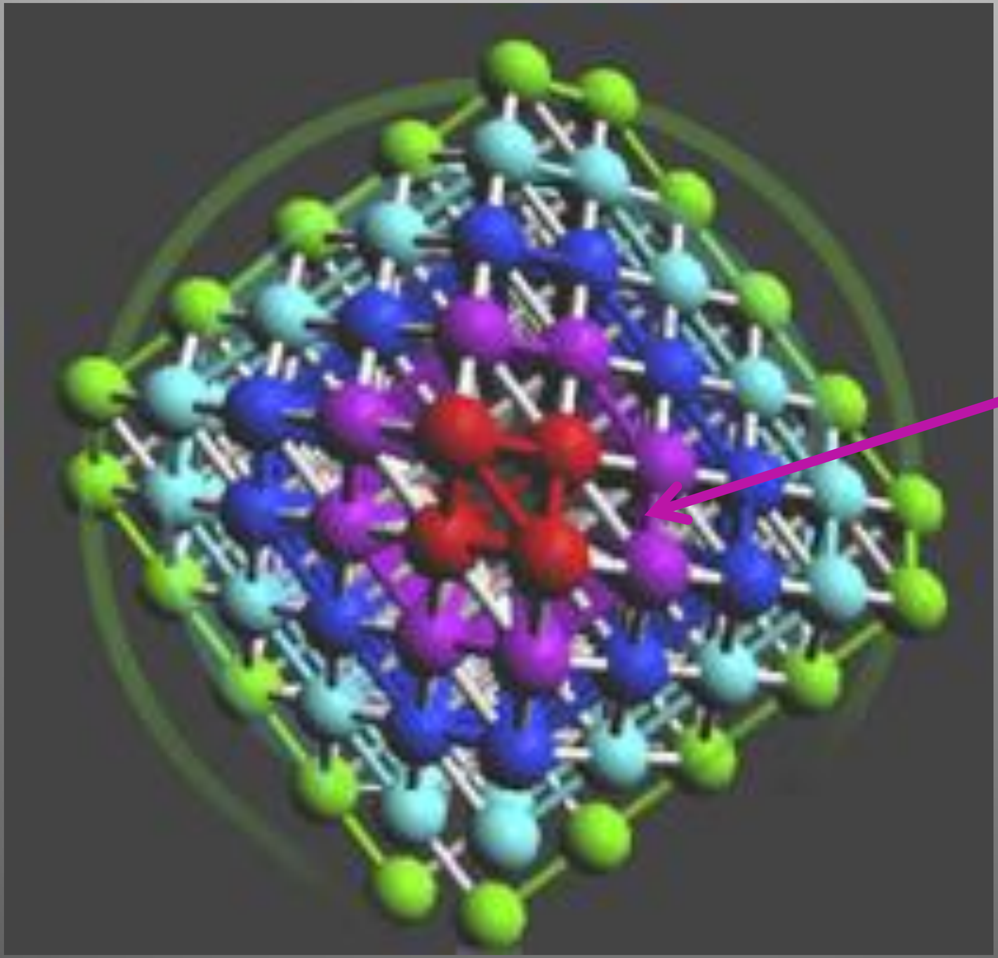


Occupancy

j	Z	N	Total
1/2	2	2	4

j = (|x| + |y| - 1) / 2 = 1/2, 3/2, 5/2, 7/2, …
where x and y are odd integers.

And all of the j-subshells of the IPM correspond to cylindrical structures in the FCC lattice.

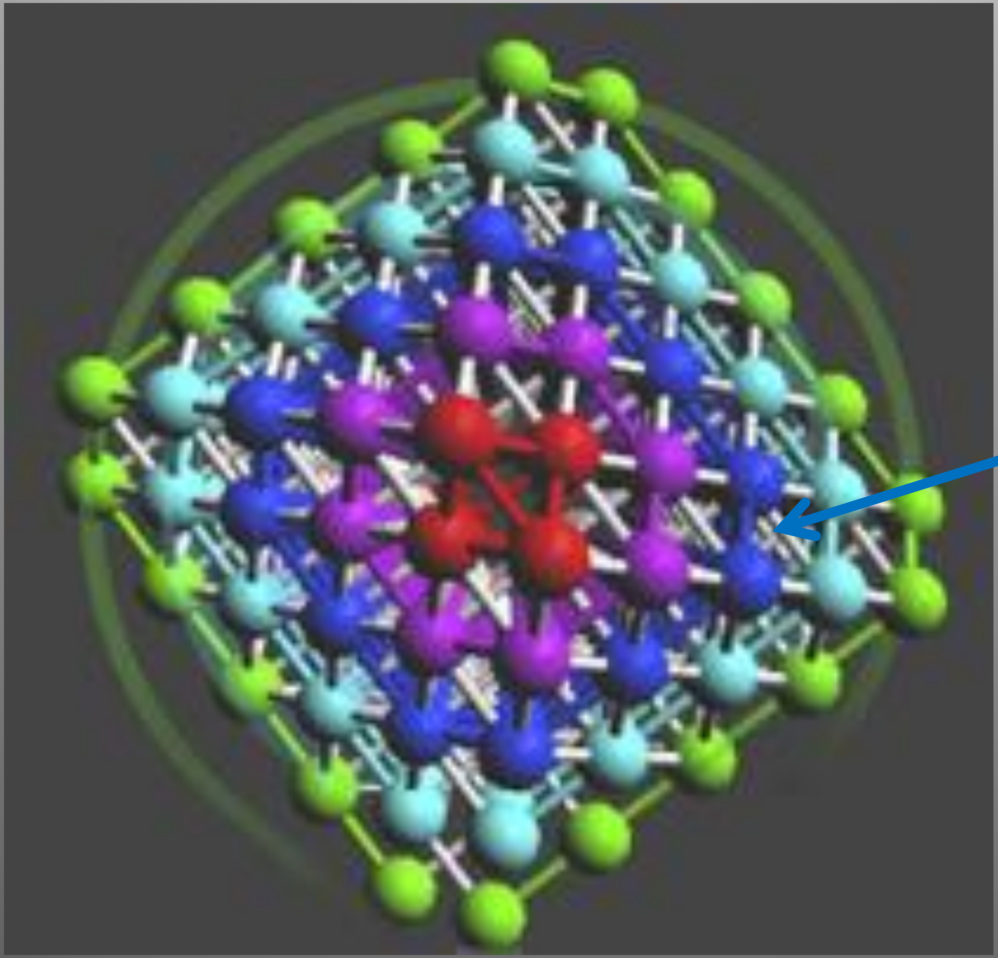


Occupancy

j	Z	N	Total
1/2	2	2	4
3/2	4	4	8

$j = (|x| + |y| - 1) / 2 = 1/2, 3/2, 5/2, 7/2, \ldots$
where x and y are odd integers.

And <u>all</u> of the j-subshells of the IPM correspond to cylindrical structures in the FCC lattice.

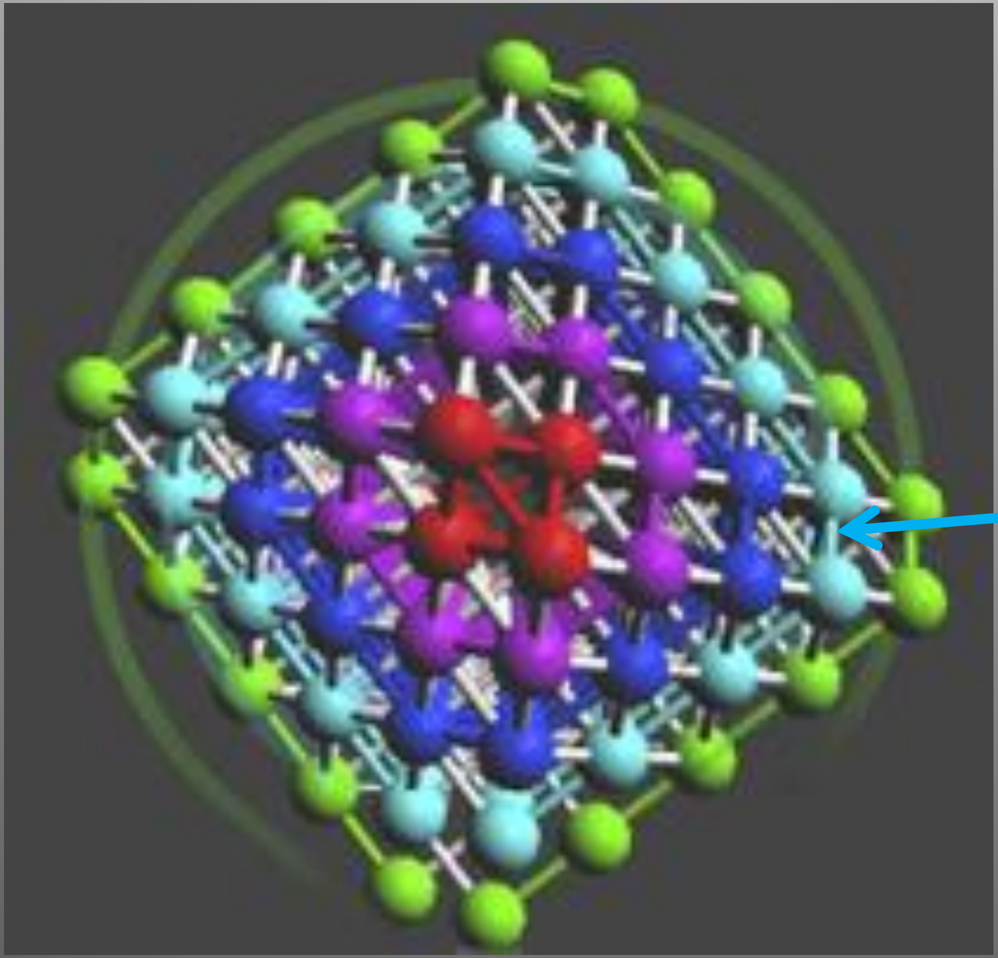


j = (|x| + |y| - 1) / 2 = 1/2, 3/2, 5/2, 7/2, …
where x and y are odd integers.

Occupancy

j	Z	N	Total
1/2	2	2	4
3/2	4	4	8
5/2	6	6	12

And all of the j-subshells of the IPM correspond to cylindrical structures in the FCC lattice.

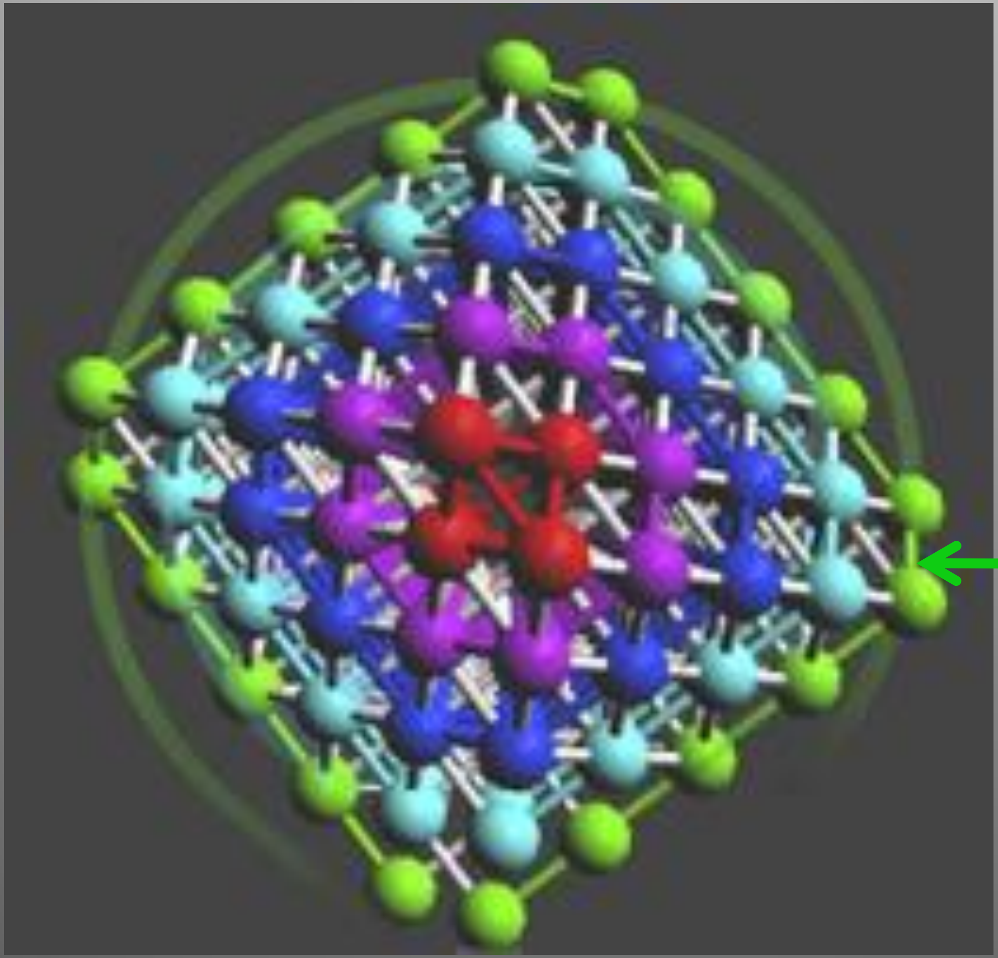


Occupancy

j	Z	N	Total
1/2	2	2	4
3/2	4	4	8
5/2	6	6	12
7/2	8	8	16

j = (|x| + |y| - 1) / 2 = 1/2, 3/2, 5/2, 7/2, …
where x and y are odd integers.

And <u>all</u> of the j-subshells of the IPM correspond to cylindrical structures in the FCC lattice.



$j = (|x| + |y| - 1) / 2 = 1/2, 3/2, 5/2, 7/2, \ldots$
where x and y are odd integers.

Occupancy

j	Z	N	Total
1/2	2	2	4
3/2	4	4	8
5/2	6	6	12
7/2	8	8	16
9/2	10	10	20

Every nucleon has a unique set of quantum numbers in the Schrodinger equation… and a unique position in the FCC lattice.

Principal: $n = (|x| + |y| + |z| - 3) / 2$

Angular momentum: $j = (|x| + |y| - 1) / 2$

Azimuthal: $m = s * |x| / 2$

Spin: $s = (-1)^{x-1}$

Isospin: $i = (-1)^{z-1}$

where x, y, z are odd-integer lattice coordinates.

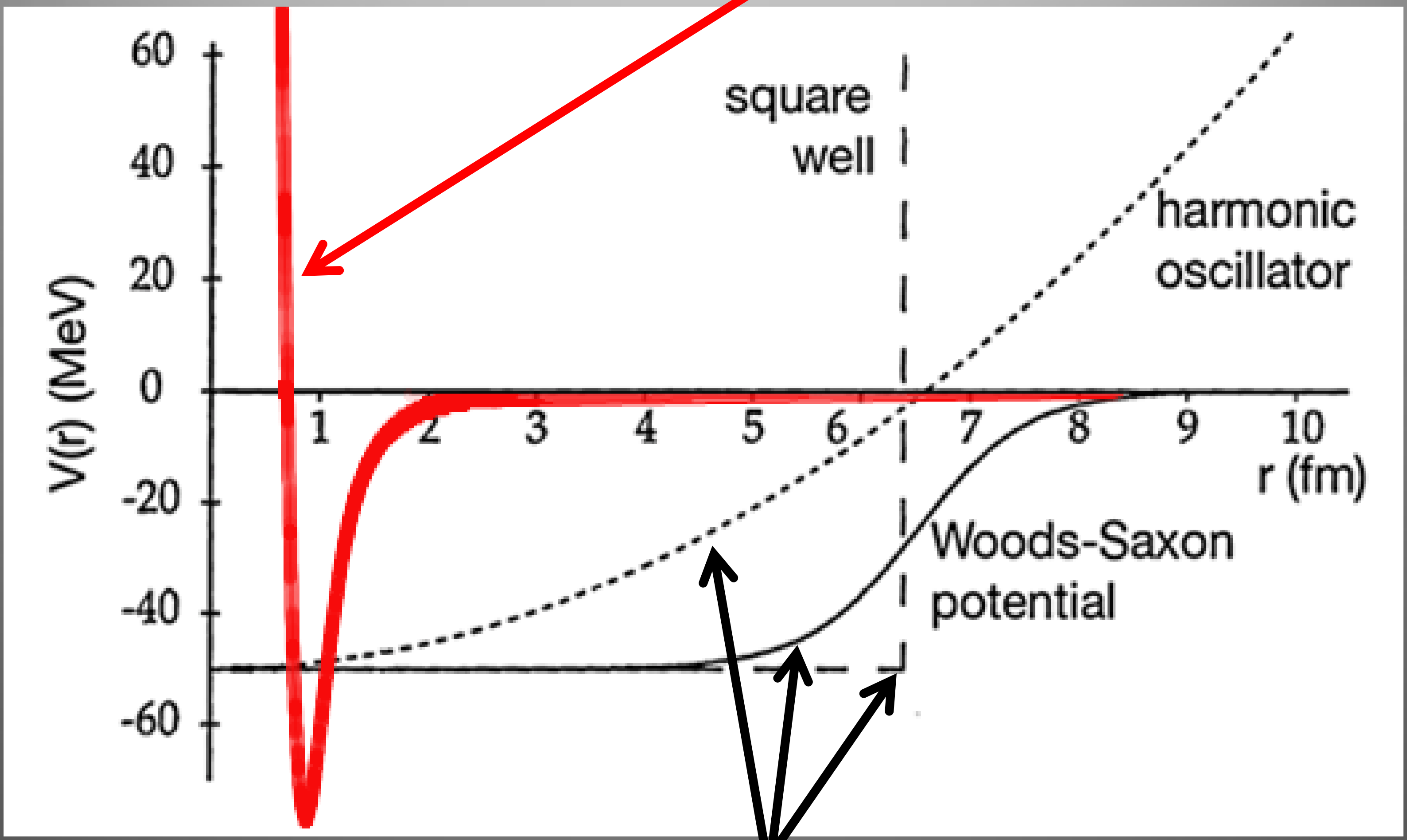
Conversely, if we know the quantal state of a nucleon, we can calculate its spatial coordinates.

$$x = |2m|(-1)(m + 1/2)$$
$$y = (2j + 1 - |x|)(-1)^{(i+j+m+1/2)}$$
$$z = (2n + 3 - |x| - |y|)(-1)^{(i+n-j-1)}$$

The correspondence between the IPM and the FCC model is exact.

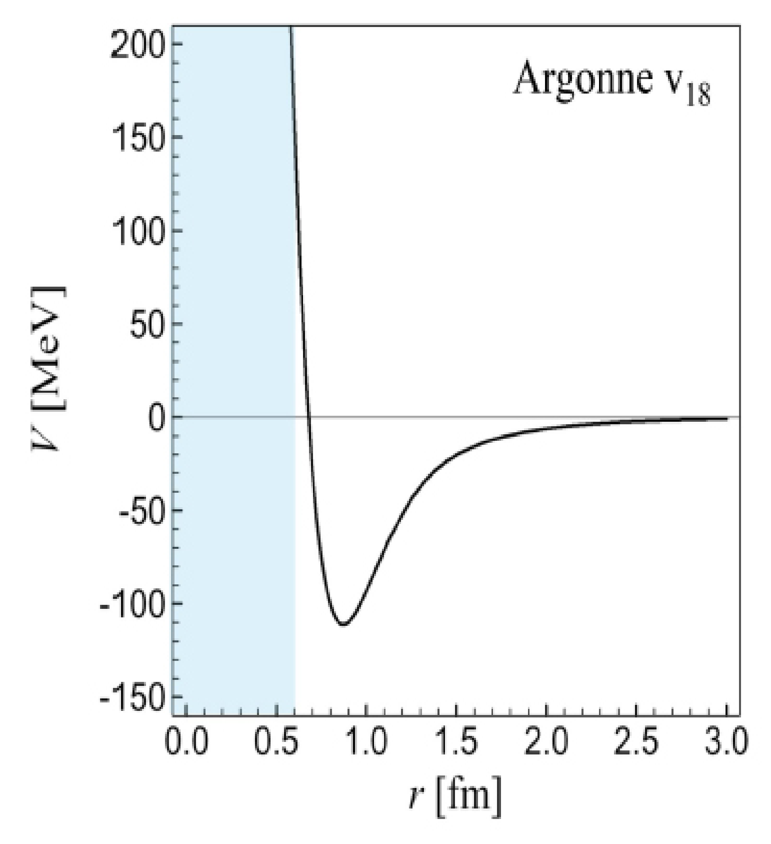
The symmetries of the IPM are also found in the lattice model… but without using a long-range “effective” nuclear potential-well.

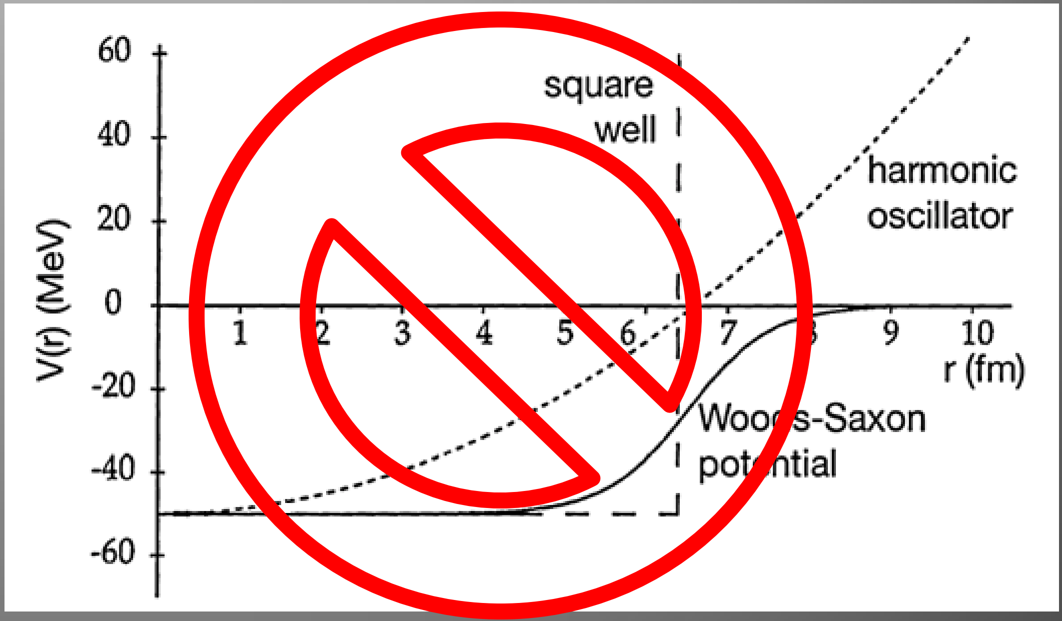
The realistic, short-range nuclear force known from nucleon-nucleon scattering experiments suffices…



The various long-range “effective” forces postulated in the independent-particle model are not needed.

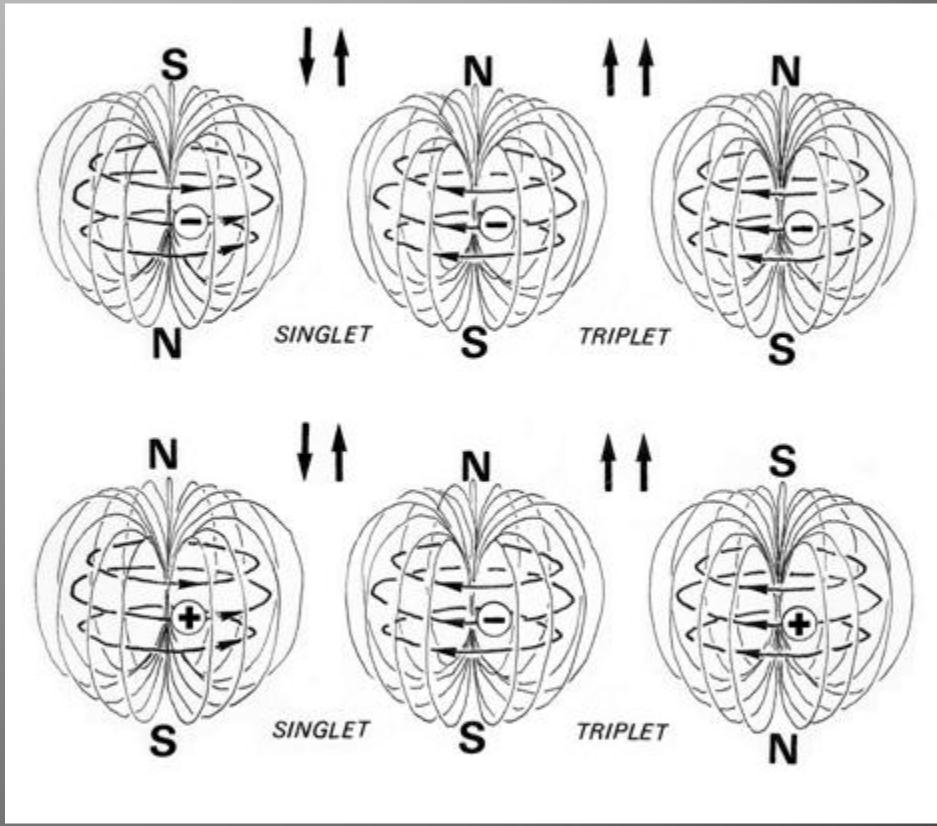
“Effective” forces are unnecessary since the lattice reproduces all of the shell model quantal symmetries using a realistic, short-range (~2 fm) force.

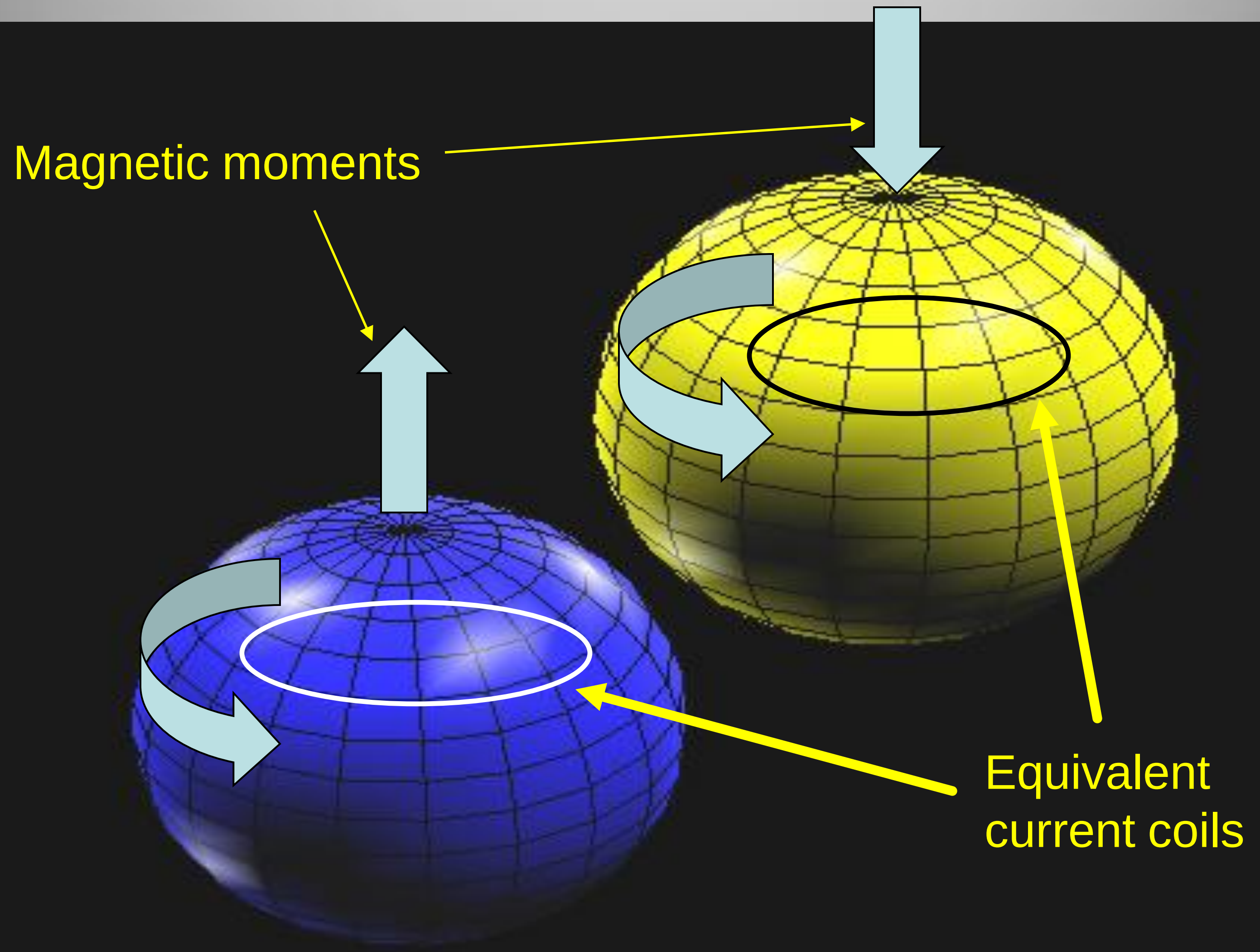




Electromagnetic theory at the Fermi level

Attractive magnetic force between nearest-neighbor nucleons ~3 MeV

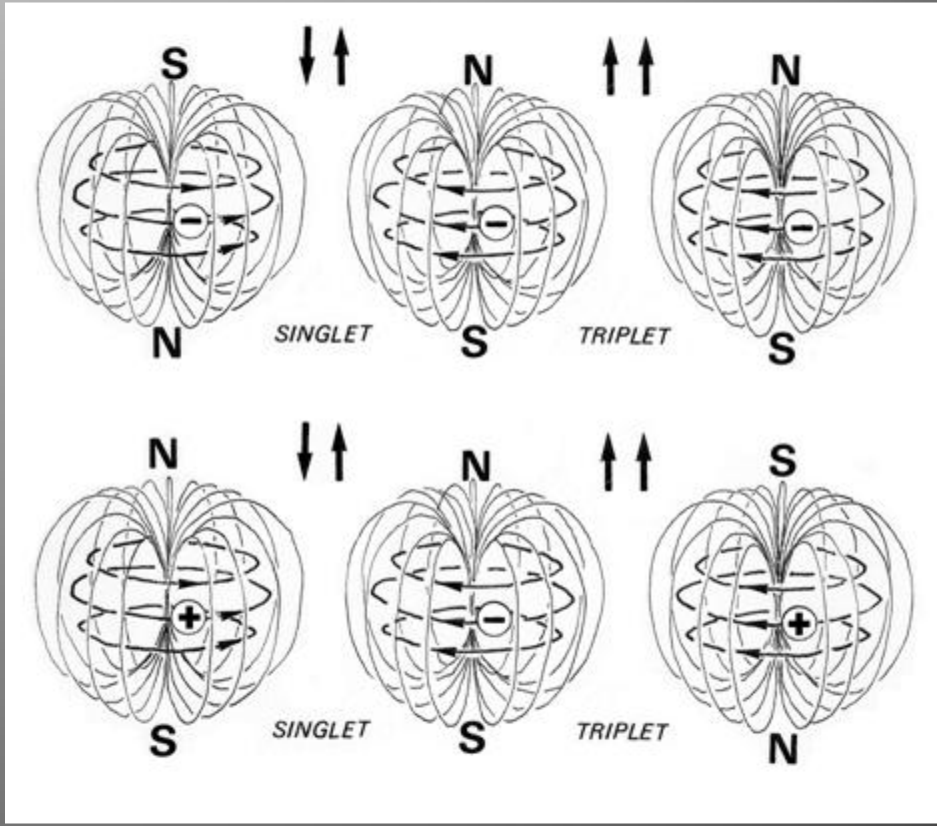




Magnetic force as a source of nucleon attraction

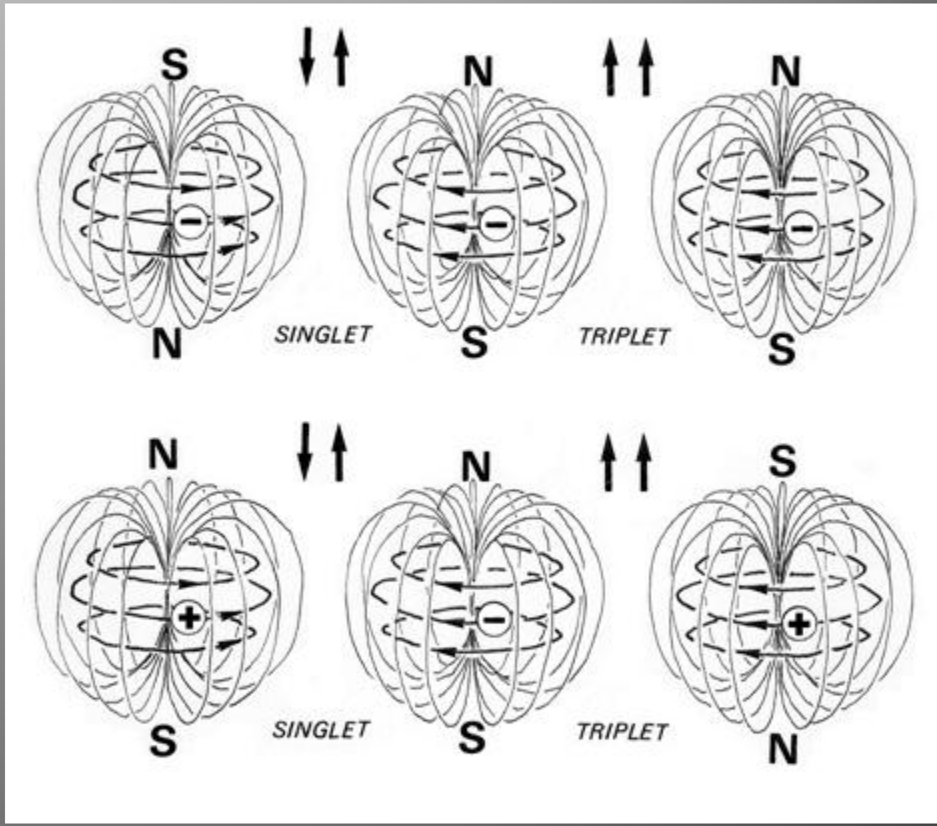
The magnetic components of the nuclear force

In the Biot-Savart formula, the mutual force between two coils is obtained as the contribution of infinitesimal length elements of currents, by ignoring any phase relationship between them. In contrast, the currents of two neighboring coils in a lattice are correlated since there is periodicity.



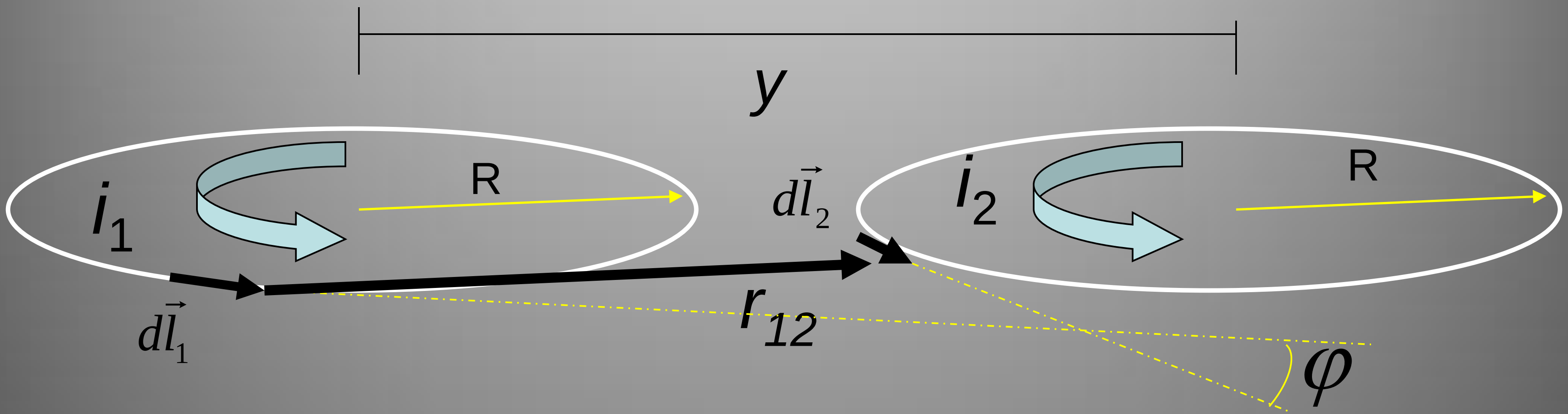
The magnetic components of the nuclear force

Contrary to the Biot-Savart result in which the potential energy of the two coils is dependent on their separation as y^{-3}, there is a strongly enhanced contribution which behaves as 1/y.



φ_1

Magnetic force between two coils



$$F_{12} = \frac{\mu o i_1 i_2}{4\pi} \int_{C2} d\vec{l}_2 \int_{C1} \frac{d\vec{l}_1 \wedge \vec{r}_{12}}{r^3_{12}}$$

i = coil current

R = coil radius

Magnetic force between two coils

$$\vec{F}_{12} = \frac{\mu o i_1 i_2}{4\pi} \oint_{C2} \oint_{C1} \frac{d\vec{l}_1 d\vec{l}_2}{r^3_{12}} \vec{r}_{12}$$

In cylindrical coordinates

$$\vec{F}_{12} = \frac{\mu_o i_1 i_2}{4\pi} \vec{j} \int\int \frac{yR^2 \cos(\varphi_1 - \varphi_2) d\varphi_1 d\varphi_2}{\left[(y^2 + 2R^2(1 - \cos(\varphi_1 - \varphi_2))\right]^{\frac{3}{2}}}$$

Note phases between currents

Expansion of the denominator:

$$\left[(y^2 + 2R^2(1 - \cos(\varphi_1 - \varphi_2))\right]^{-\frac{3}{2}} = \frac{1}{y^3}(1 - \frac{3R^2}{y2}(1 - \cos(\varphi - \varphi)) + ...)$$

Potential energy

$$V = \mu_o \frac{m_1 m_2}{\pi R^2 y} \cos\varphi + O(y^{-2})$$

$= 0$ when nucleons are randomly distributed in space

(gas/liquid models)

$< \cos\varphi > =$ exp(-y/d) when nucleons are in a lattice

(from periodicity conditions, the currents become correlated)

where d is the lattice constant

Numerical results

$$V = \mu_o \frac{m_1 m_2}{\pi R^2 y} \cos\varphi + O(y^{-2})$$

y = 2.0 fm;   R = 0.5 fm; cos φ = 1

Nucleon pair	V(MeV)	V (MeV)$_{\text{Biot-Savart}}$
P-P	3.93	$4.2688 \cdot 10^{-3}$
N-N	1.84	$4.2688 \cdot 10^{-3}$
N-P	2.69	$4.2688 \cdot 10^{-3}$

Average value = 2.82 MeV

Properties and order of magnitude

Yukawa form with quadrupole features:

(1) Attractive/repulsive for first/second neighbors, according to the antiferromagnetic arrangement.

(2) Short range (as a result of dephasing with distance)

(3) Right order of magnitude ~ 1-10 MeV

(4) Higher order terms $O(y^{-3})$ small at the normal level of the magnetic force < 100keV

Properties Explained by the Nuclear Models

Nuclear Property	LDM	IPM	Cluster	FCC Lattice
Saturation of nuclear force	yes	no	no	yes
Dependence of nuclear radius on A	yes	no	no	yes
Short mean-free-path of nucleons	yes	no	no	yes
Constant nuclear density	yes	no	no	yes
Energetics of fission	yes	no	no	yes
Nuclear shells/subshells	no	yes	no	yes
Nuclear spin/parity	no	yes	no	yes
Magnetic and quadrupole moments	no	yes	no	yes
Diffuse nuclear surface	no	yes	no	yes
Alphas on nuclear surface	no	no	yes	yes
Alpha clustering in nuclear interior	no	no	yes	yes
Alpha-particle decay	no	no	yes	yes
Asymmetrical fission fragments	no	no	no	yes

Properties Explained by the Nuclear Models

Nuclear Property	LDM	IPM	Cluster	FCC Lattice
Saturation of nuclear force	yes	no	no	yes
Dependence of nuclear radius on A	yes	no	no	yes
Short mean-free-path of nucleons	[illegible]	[illegible]	[illegible]	[illegible]
Constant nuclear density	yes	no	no	yes
Energetics of fission	yes	no	no	yes
Nuclear shells/subshells	no	yes	no	yes
Nuclear spin/parit…	[illegible]	[illegible]	[illegible]	[illegible]
Magnetic and quadrupole…	[illegible]	[illegible]	[illegible]	[illegible]
Diffuse nuclear surface	no	yes	no	yes
Alphas on nuclear surface	no	no	yes	yes
Alpha clustering in nuclear interior	[illegible]	[illegible]	[illegible]	[illegible]
Alpha-particle decay	no	no	yes	yes
Asymmetrical fission fragments	no	no	no	yes

Local Nucleon Interactions

Discrete Energy States of Nucleons

Tetrahedral Nucleon Grouping

Properties Explained by the Nuclear Models

Nuclear Property	LDM	IPM	Cluster	FCC Lattice
Saturation of nuclear force	yes	no	no	yes
Dependence of nuclear radius on A	yes	no	no	yes
Short mean-free-path of nucleons	[illegible]	[illegible]	[illegible]	[illegible]
Constant nuclear density	yes	no	no	yes
Energetics of fission	yes	no	no	yes
Nuclear shells/subshells	no	yes	no	yes
Nuclear spin/parit	[illegible]	[illegible]	[illegible]	[illegible]
Magnetic and quadrupole	no	yes	no	yes
Diffuse nuclear surface	no	yes	no	yes
Alphas on nuclear surface	no	no	yes	yes
Alpha clustering in nuclear interior	[illegible]	[illegible]	[illegible]	[illegible]
Alpha-particle decay	no	no	yes	yes
Asymmetrical fission fragments	no	no	no	yes

Local Nucleon Interactions

Discrete Energy States of Nucleons

Tetrahedral Nucleon Grouping

Finally, the lattice model also explains two sets of "anomalous" data.

(1) The <u>asymmetrical</u> fission fragments produced by thermal fission of Uranium, Plutonium, etc.

("Asymmetric fission along nuclear lattice planes," *Proceedings of the St. Andrews Conference on Fission,* World Scientific, pp. 217-226, 1999)

(2) The <u>symmetrical</u> fission fragments produced by low-energy fission of Palladium.

(Poster ICCF15)

Thank you for your attention.

Further details on the FCC nuclear model can be found in:
N.D. Cook, ***Models of the Atomic Nucleus***, Springer, 2006

The nuclear visualization software (NVS) is available as freeware at: http://www.res.kutc.kansai-u.ac.jp/~cook/nvsDownload.html