0.5 setgray0 0.5 setgray1

Nuclear Physics.

Main Challenges for Next Decade

L.Grigoryan

Yerevan Physics Institute, Yerevan, Armenia

OECD

Global Science Forum

Report on Nuclear Physics.

(OECD - Organisation for Economic Co-operation and Development)

Globally about $2 Billions is spet annually for Nuclear Physics research. Over 13,000 scientists, engineers, and students involved in research carried out primarily at the 90 major accelerator facilities with user programs, but also at a range of smaller, specialized facilities that provide for national needs.

The working group assessment for the next decade is equally bright, with the main challenges summarized in a series of questions:

- **Is QCD the complete theory of the strong interaction?**
- **What is the structure of nuclear matter?**
- **What are the phases of nuclear matter?**
- **What is the role of nuclei in shaping the evolution of the universe?**
- **What physics is there beyond the standard model?**

The Quantum Chromodynamics (QCD).

Characteristics of Quarks						
Quantum number	Quark type					
	d	u	s	c	b	t
Q - electric charge	-1/3	+2/3	-1/3	+2/3	-1/3	+2/3
B - baryon number	1/3	1/3	1/3	1/3	1/3	1/3
J - Spin	1/2	1/2	1/2	1/2	1/2	1/2
P - parity	+1	+1	+1	+1	+1	+1
I - isospin I	1/2	1/2	0	0	0	0
I_z - z-component	-1/2	+1/2	0	0	0	0
S - strangeness	0	0	-1	0	0	0
C - charm	0	0	0	+1	0	0
B - bottomness	0	0	0	0	-1	0
T - Topness	0	0	0	0	0	+1
Const. mass, GeV	0.31	0.31	0.51	1.8	5	180
Current mass, GeV	0.006	0.003	0.08-0.15	1.1-1.4	4.1-4.9	174

The Lagrangian of QCD:

$$L_{QCD} = \bar{\psi}_i(i\gamma^\mu \partial_\mu - m)\psi_i - gG^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

where ψ_i is the quark field, G^a_μ are the gluon fields, T^a_{ij} are the generators, connecting the fundamental, antifundamental and adjoint representations of the SU(3) gauge group.

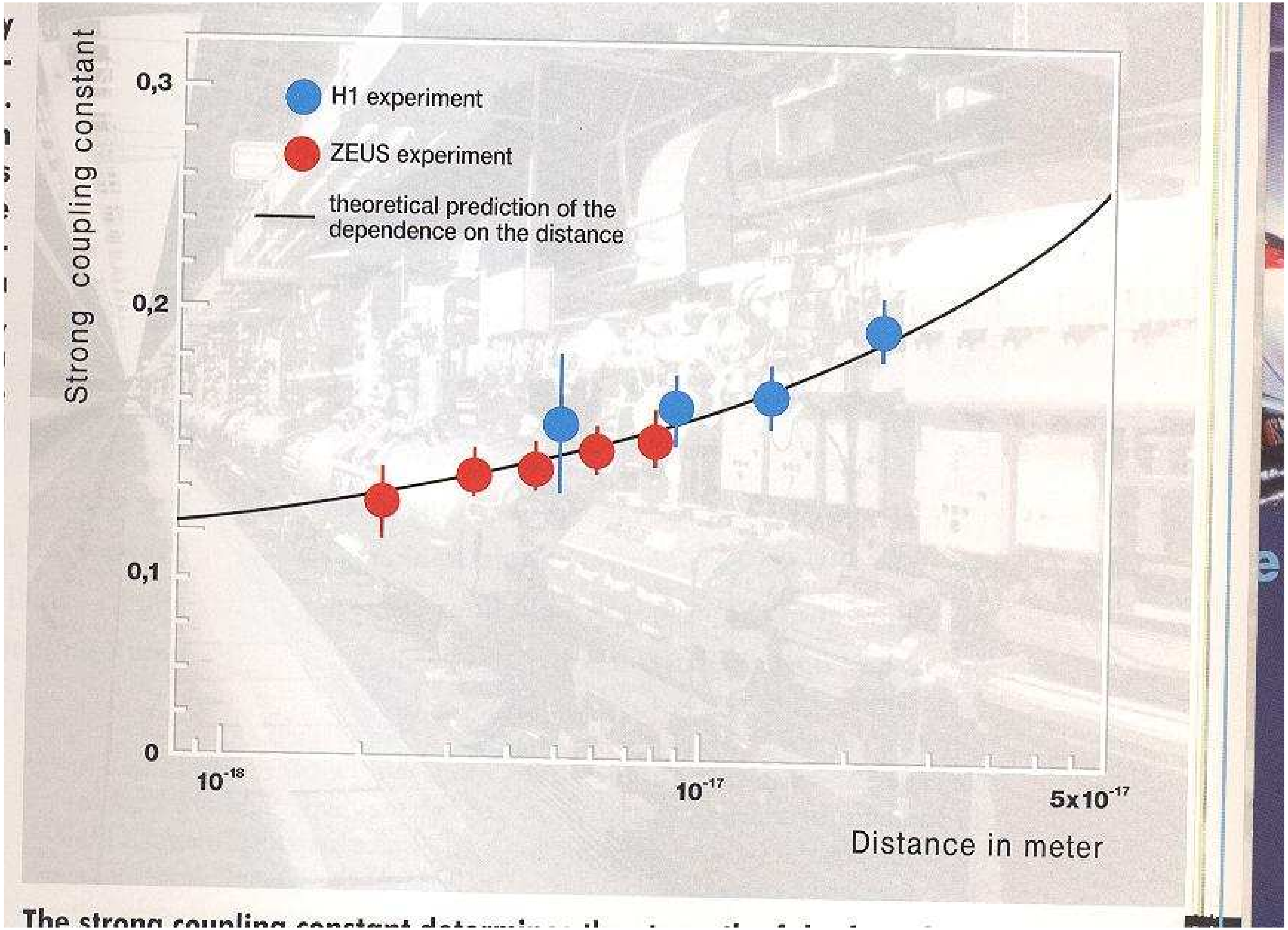
$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g f^{abc} G^b_\mu G^c_\nu$$

where f^{abc} are the structure constants of SU(3).

The QCD coupling constant:

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f) ln(Q^2/\Lambda^2)} \left(1 - \frac{6(153 - 19n_f) ln[ln(Q^2/\Lambda^2)]}{(33 - 2n_f)^2 ln(Q^2/\Lambda^2)} \right)$$

R.Gupta, "Introduction to lattice QCD" (arXiv: hep-lat/9807028 11 Jul 1998).



- **The QCD coupling constant α_s as a function of distance r**

Phenomenological Functions.

When QCD factorization theorem takes place, then:

$q(x, Q^2)$ **- parton distribution functions;** $x = \frac{Q^2}{2m_p\nu}$

$D_q^h(z, Q^2)$ **- fragmentation functions;** $z = \frac{h\cdot p}{q\cdot p}$

$\Delta q(x) = [q^{\downarrow\uparrow}(x) + \bar{q}^{\downarrow\uparrow}(x)] - [q^{\uparrow\uparrow}(x) + \bar{q}^{\uparrow\uparrow}(x)]$ **- polarized parton distribution functions.**

When QCD factorization theorem does not take place, then:

$M_{p,h}^j(x, z, Q^2)$ **- fracture functions.**

Generalized Parton Distributions (GPDs).

Hard exclusive reactions in terms of universal GPDs. Denoted by $H, \widetilde{H}, E, \widetilde{E}$ **which depend upon 3 variables:** x, ξ **and** t**. The light-cone momentum fraction** x **is defined by** $k^+ = x\bar{P}^+$**, where** k **is the quark loop momentum and** $\bar{P}$ **is the average nucleon momentum** $\bar{P} = (p + p')/2$**, where** $p(p')$ **are the initial (final) nucleon 4-momenta respectively). The skewedness** ξ **is defined by** $\Delta^+ = -2\xi\bar{P}^+$**, where** $\Delta = p' - p$ **is overal momentum transfer in the process.** $t = \Delta^2$ **is the total squared momentum transfer to the nucleon.**

The "Spin Crisis".

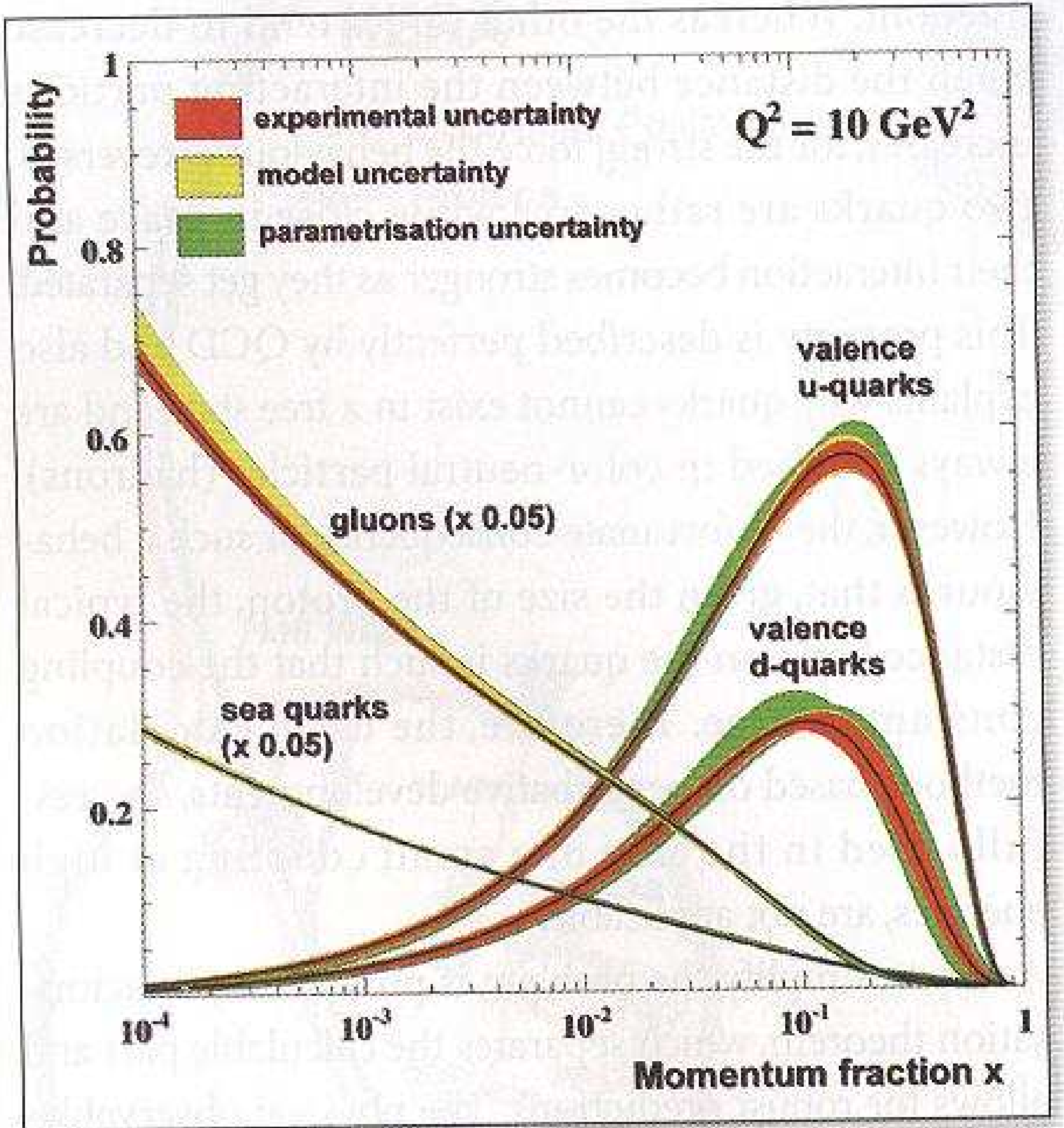
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G,$$

where $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ is contribution of quarks to spin of nucleon. ΔG is polarized gluon distribution function, $L_q(L_G)$ are possible contributions from quarks and gluons angular momenta.

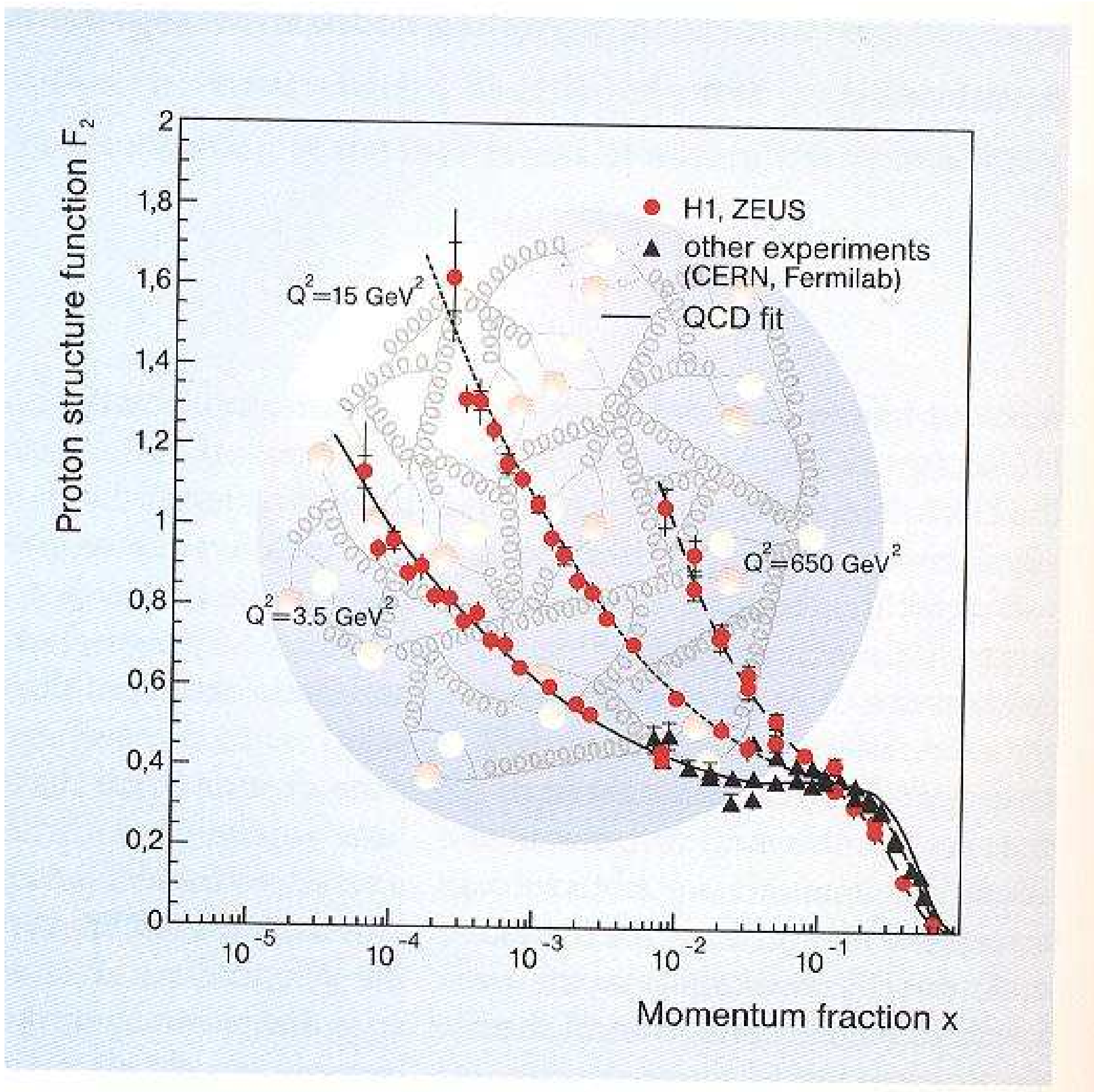
In the simple quark model 3 valence quarks are in an S-state, so $L_q = 0$. No gluons, $\Delta G = 0$ and $L_G = 0$, thus $\Delta\Sigma = 1$. EMC first result is very small: $\Delta\Sigma = 0.12 \pm 0.09(stat) \pm 0.14(syst)$.

Is the Nucleon Spin Puzzle Solved?

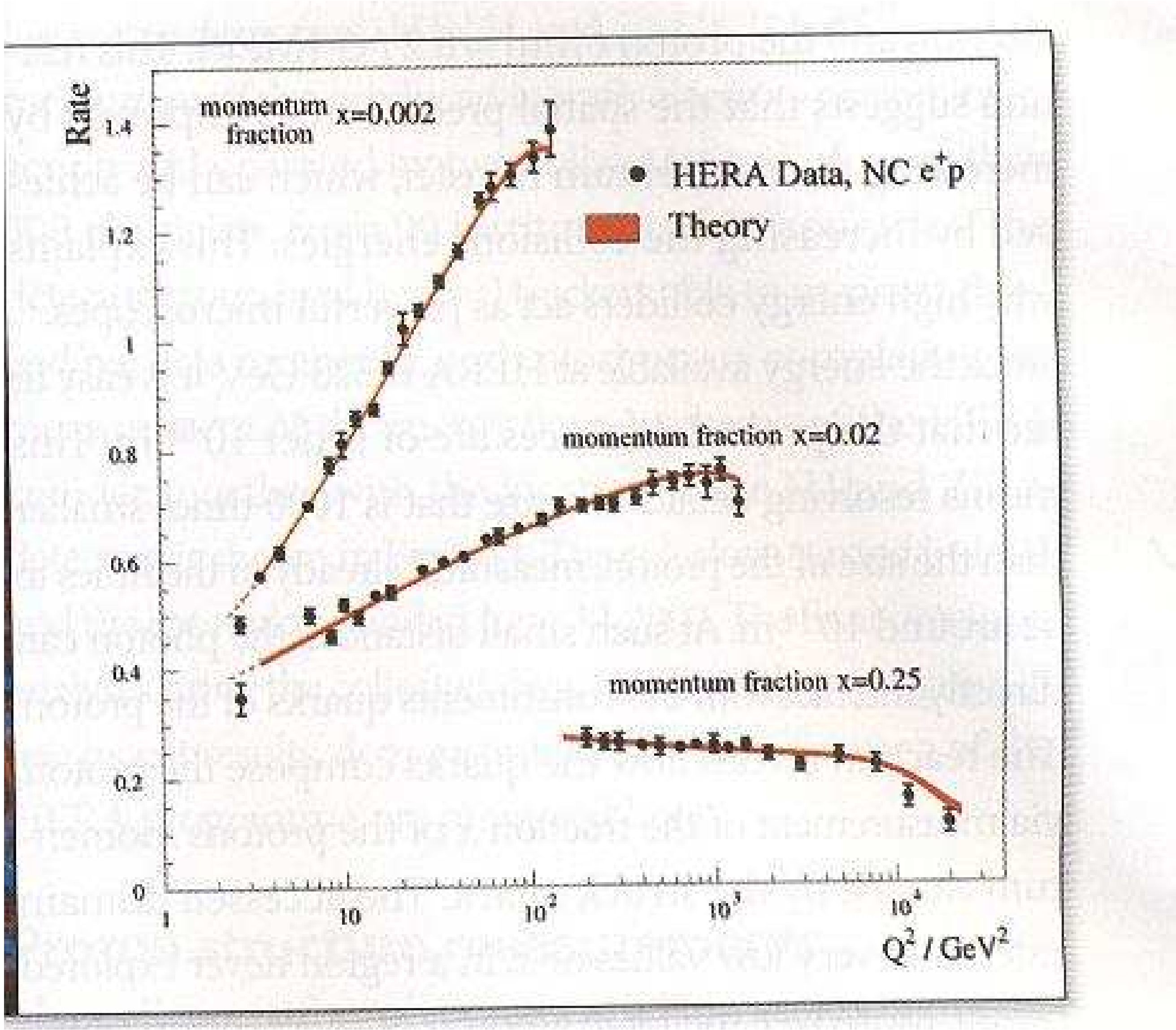
(i) Last experiments give $\Delta\Sigma = 0.3$; (ii) Comparison with the static quark model was misleading. The Melosh rotation, which gives connection between spin states in rest frame and in infinite momentum frame, introduces a nontrivial spin structure and correlations between quark spin and quark angular momentum; (iii) Last measurements give $\Delta G \approx 0$; (iv) New possibilities to understand spin structure through transverse spin effects.



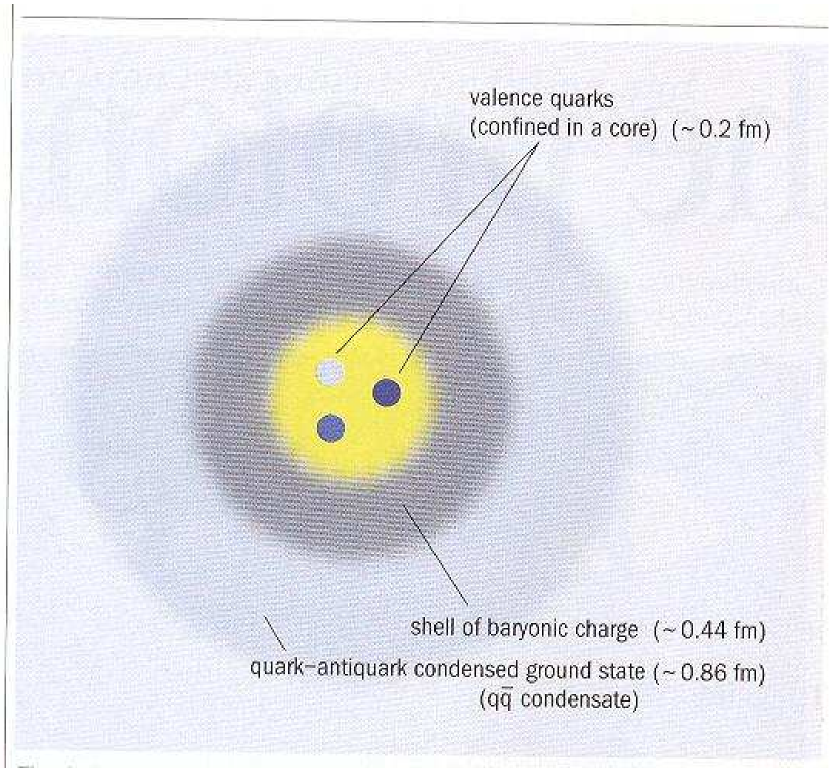
▲ FIG. 4: Distribution of quarks and gluons in the proton as a



H1 and ZEUS show that the number of quarks and gluons in the proton increases dramatically when the momentum fraction is small (at various resolutions Q^2).



Rates of neutral boson exchange (NC). Evolution as a function of Q^2 is described by theory and is clear sign of gluon contributions to the proton structure.



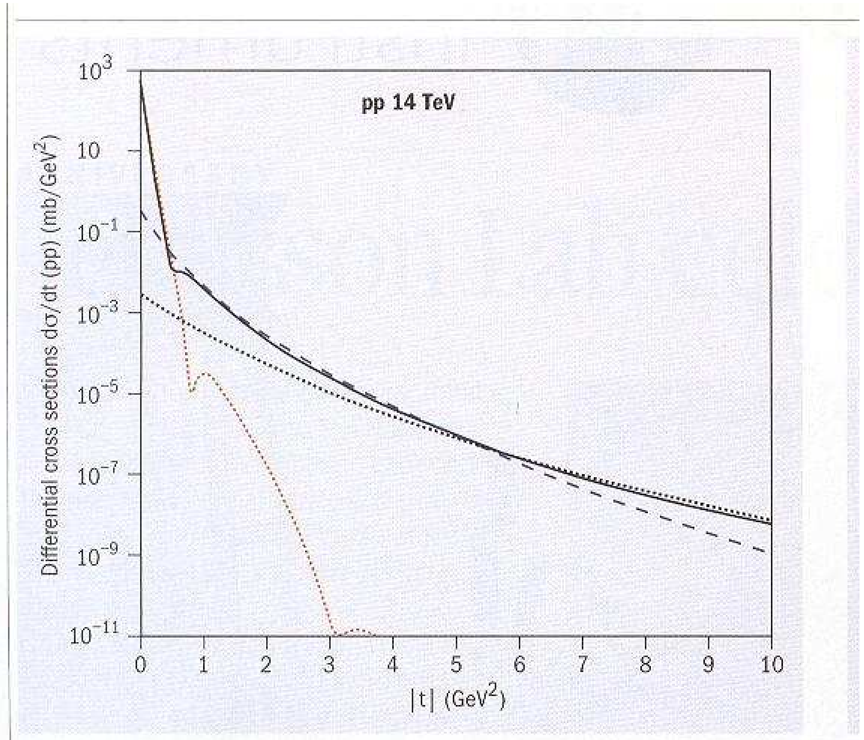


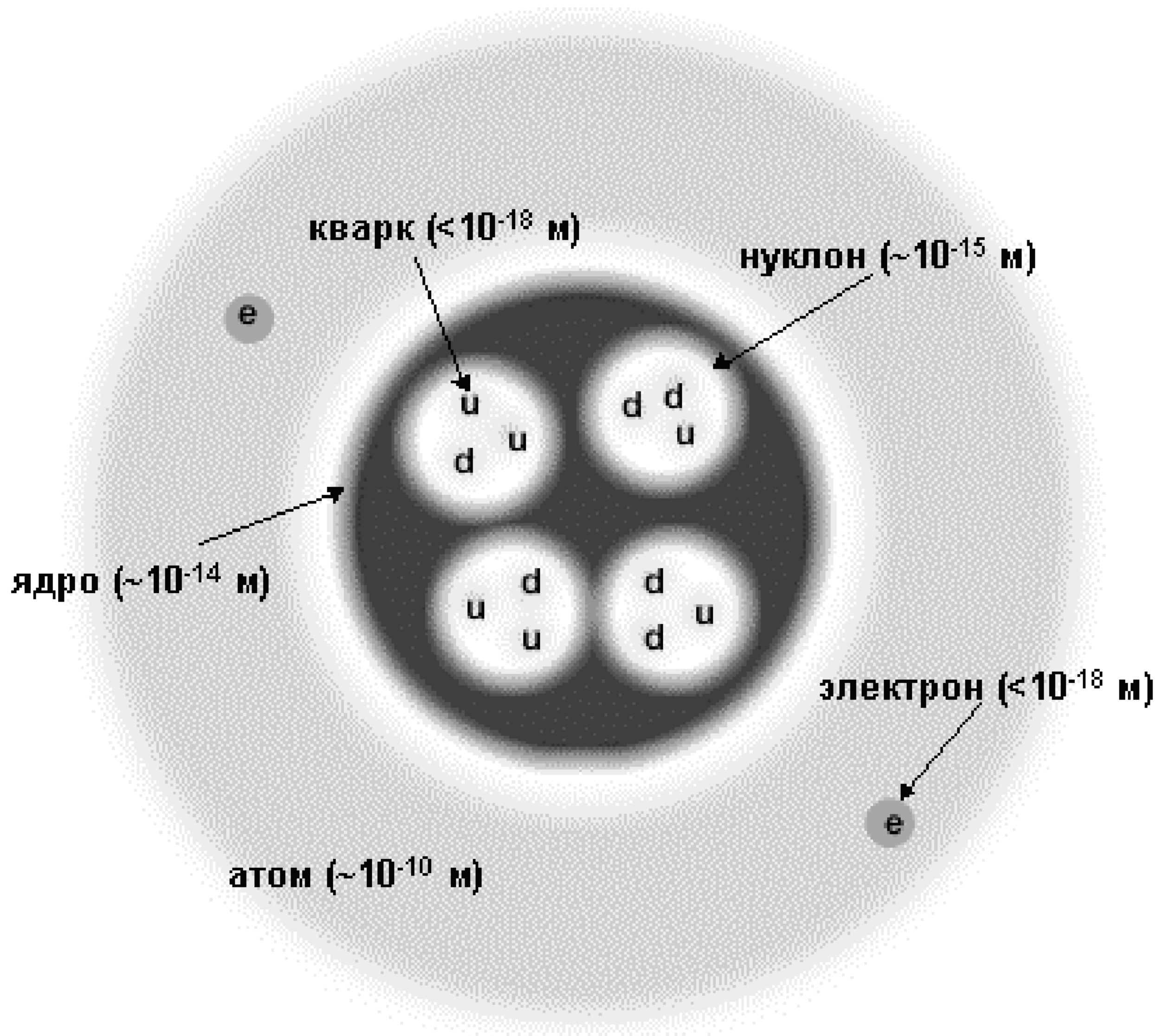
Fig.5. The solid curve shows our predicted differential cross-section at

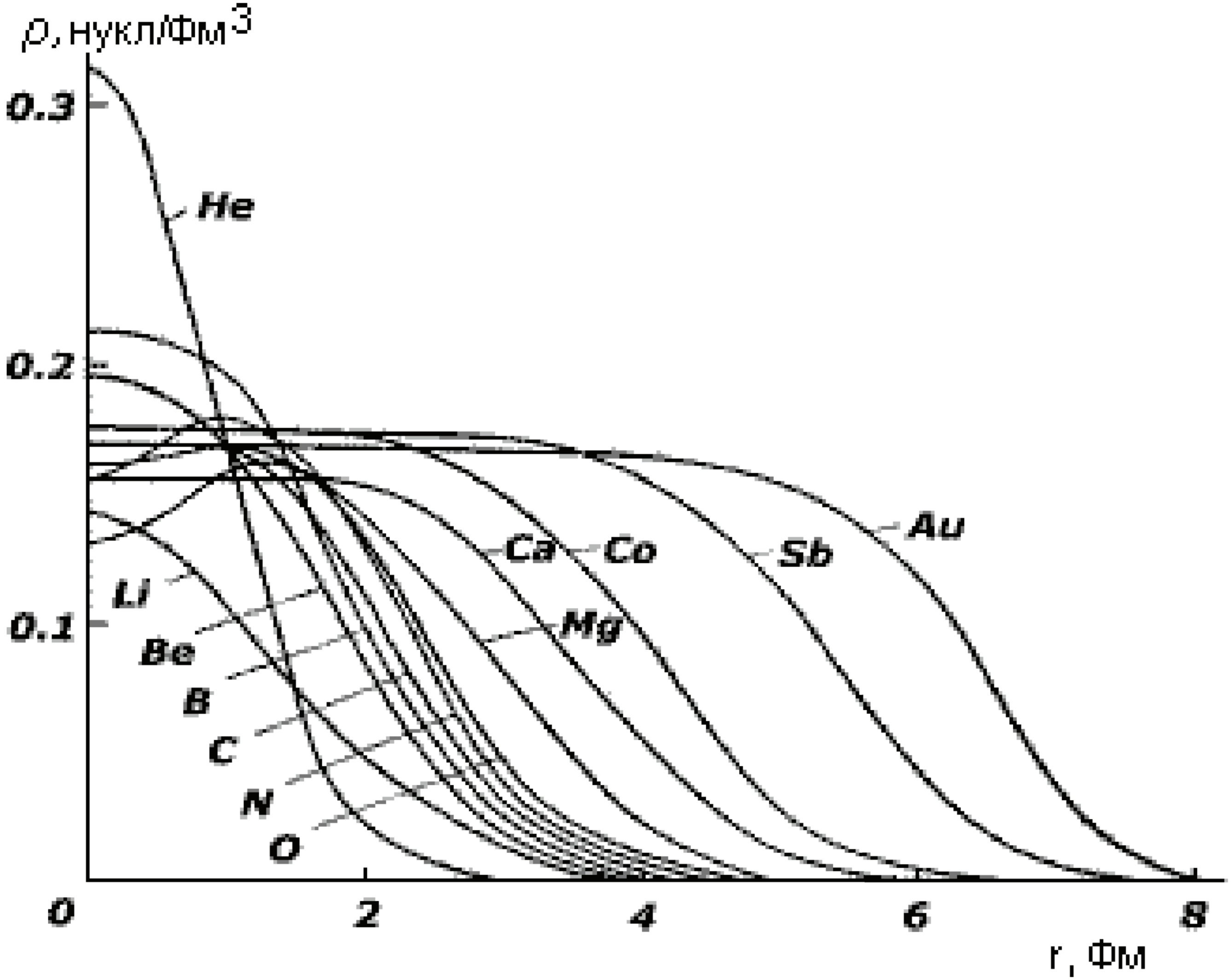
- **Contents of proton**

- **Differential cross sections $d\sigma/dt(pp)(mb/GeV^2)$ as a function of $|t|$.**

What is the structure of nuclear matter?

General parameters of atomic nuclei: radius $R = r_0 A^{1/3}$, where A is number of nucleons, $r_0 = 1.2 - 1.3 fm$; maximal kinetic energy (speed) of nucleon $T_N^{max} \sim 30 MeV$ ($\sim c/4$).





In inner regions of middle and heavy nuclei density is constant $\rho_0 = 0.17 - 0.18 nucl/fm^3$**.**

Radioactive decay modes:

α**-decay H.Becquerel 1896;**

β^- **decay(emit electron and anti-neutrino) H.Becquerel 1896;**

γ **decay(re-arrangement of the nucleons in nucleus) P.Villard 1900;**

β^+ **decay Irene and Frederic Joliot-Curie 1934;**

fission(two medium mass A **of the order of 70-170 are created) O.Hahn and F.Strassmann 1938;**

double-β **decay(emission of 2 electrons and 2 anti-neutrinos) Moe and Lowenthal 1980;**

one-proton radioactivity(proton-rich nuclei with odd number of protons) Hofmann et al. and Klepper et al.(GSI, Germany) 1982;

cluster radioactivity(heavy nucleus emits a nucleus of mass $A \sim 14 - 34$**) Rose and Jones 1984;**

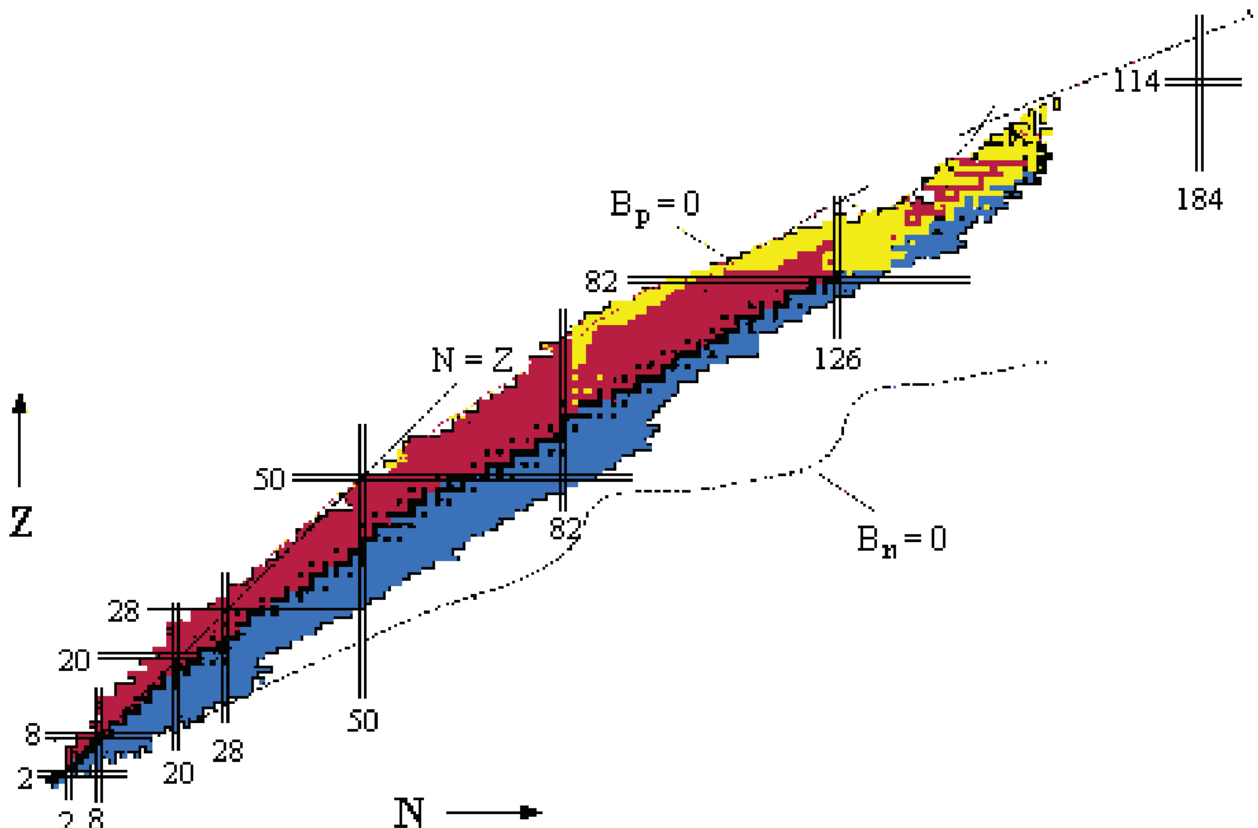
two-proton radioactivity(proton-rich nuclei with even number of protons due to pairing effect, emit pair of protons) GANIL and GSI 2002;

Stable nuclei are grouped near valley of stability:

$$Z = \frac{A}{1.98 + 0.015A^{2/3}}.$$

The very heavy stable isotopes are Lead isotopes (Z=82) and Bismuth isotopes (Z=83). Heavy nuclei together with β^+ and β^- decays subject to α-decay and spontaneous fission, which become their basic channels of decay.

Characteristic nuclear time ($\sim 10^{-23}$c).



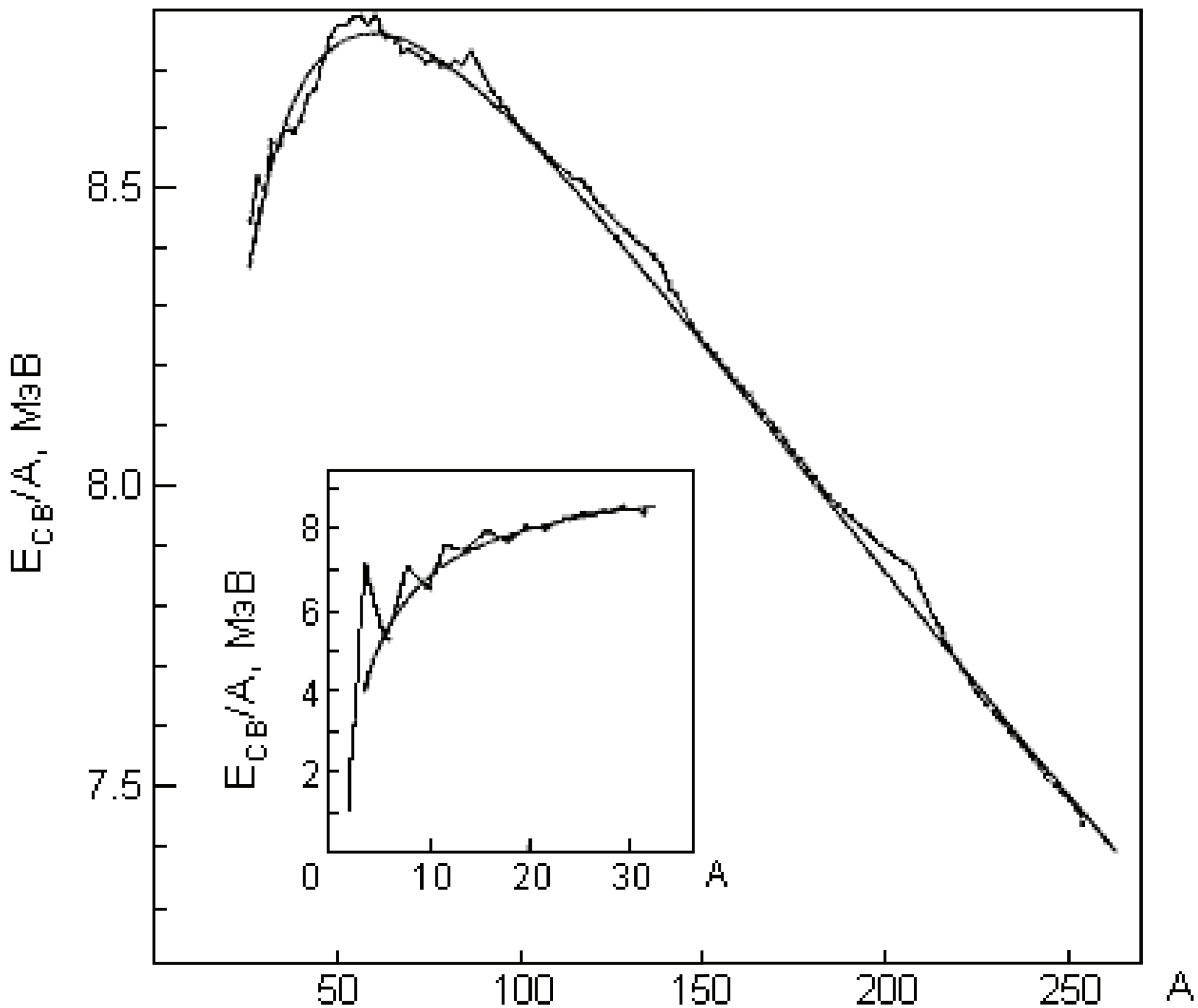
There are 80 elements which have at least one stable isotope (defined as isotopes never observed to decay).
There are about 256 such stable isotopes.
Theoretical models predict ∼6000 radionuclides.
Nearly 3000 have been generates and characterized in the laboratory.
Very little information could be obtained on these unstable nuclei.
For example, the first excited state of only about 550 nuclear species has been observed.

Droplet model (first collective model)

Binding energy:

$$E_{bin} = a_1 A - a_2 A^{2/3} - a_3 Z^2/A^{1/3} - a_4(A/2 - Z)^2/A + a_5 A^{-3/4}$$

where coefficients a_1, a_2, a_3, a_4, a_5 are estimated from exp. data on nuclear binding energy. Their values are:
$a_1 = 15.75 MeV; a_2 = 17.8 MeV; a_3 = 0.71 MeV; a_4 = 94.8 MeV;$
$a_5 = +34 MeV$ **for even-even nuclei;** 0 **for odd nuclei;** $-34 MeV$ **vor odd-odd nuclei. Decreasing of E_{bin} in region of small A connected with surface energy term (per nucleon) $-a_2 A^{-1/3}$. On other side gradual decreasing in region of heavy nuclei connected with Coulombe forces (per nucleon) $-a_3 Z^2/A^{4/3}$.**



A dependence of binding energy per nucleon.
Experimental data are shown by breaking line. Smooth curve is result of calculation by semiempiric formula of Weizsacker.

Nuclear Shell Model

Basic hypotheses:

(i) The atomic nucleus is a quantum n-body system.

(ii) The nucleus is not a relativistic object. The equation of motion giving the system wave function is the Schroedinger equation (which is non-relativistic).

(iii) The nucleons interact via 2-body interaction. It is a practical consequence of the Pauli exclusion principle: the mean free path of a nucleon being large with respect to the nucleus size, the probability that three nucleons interact simultaneously is considered as very small.

(iv) Spin-orbital interactions are taken into account.

(v) Nucleons are considered to be pointlike.

Nuclear Potential and effective interaction.
Square Well Potential; Harmonic Oscillator Potential; Woods-Saxon Potential.

Choice of Potential.
Direct nuclear reactions at low energies. Optical model.

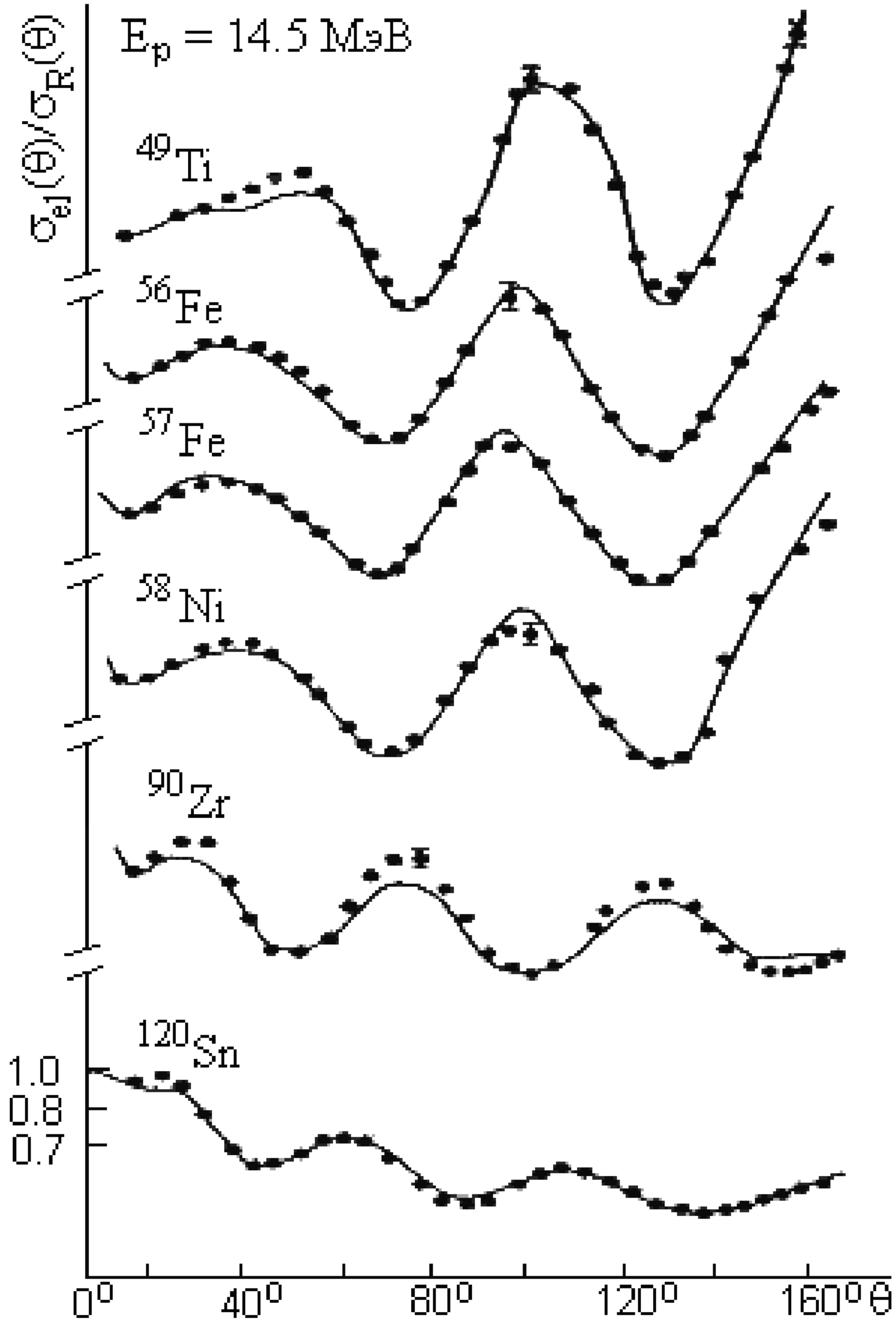
Elastic scattering of protons(hadrons) with kinetic energy of tens MeV on atomic nucleus. The nucleus as complex potential well:

$$U(r) = V(r) + iW(r).$$

$V(r)$ **describes scattering. It is used as average nuclear potential.**

$W(r)$ **describes absorption of beam particles. Small value of** $W(r) \approx fewMeV$**, which was obtained from experiment, point out on large enough length of free motion in nucleus.**

Large probability, that interacting nucleon encounters with one nucleon of nucleus, and one of these nucleons leave nucleus.


$E_p = 14.5$ МэВ
$\sigma_{el}(\Theta)/\sigma_R(\Theta)$
^{49}Ti
^{56}Fe
^{57}Fe
^{58}Ni
^{90}Zr
^{120}Sn
1.0
0.8
0.7
0°
40°
80°
120°
160°
θ

Woods-Saxon Potential. Central and spin-orbital terms.

A mean field potential for the nucleons inside nucleus. Approximately describe the forces applied on each nucleon, in the shell model.

Central Potential.

As a function of the distance r from the center of nucleus, is:

$$V(r) = -\frac{V_0^{N,Z}}{1 + exp\left(\frac{r-R}{a}\right)}$$

where $V_0^N = V_0\left[1 - 0.63\frac{N-Z}{A}\right]$, $V_0^Z = V_0\left[1 + 0.63\frac{N-Z}{A}\right]$, a is a length representing the "surface thickness" of the nucleus, and $R = r_0 A^{1/3}$ is the nuclear radius where $r_0 = 1.24 fm$.
Typical values for the parameters are: $V_0 = 53 MeV$, $a = 0.63 fm$.

Spin-orbital Potential.

$$V_{ls}(r) = -b\frac{1}{r}\frac{dV(r)}{dr}(\mathbf{ls}),$$

where $b = 0.263\left(1 + 2\frac{N-Z}{A}\right) fm^2.$

****

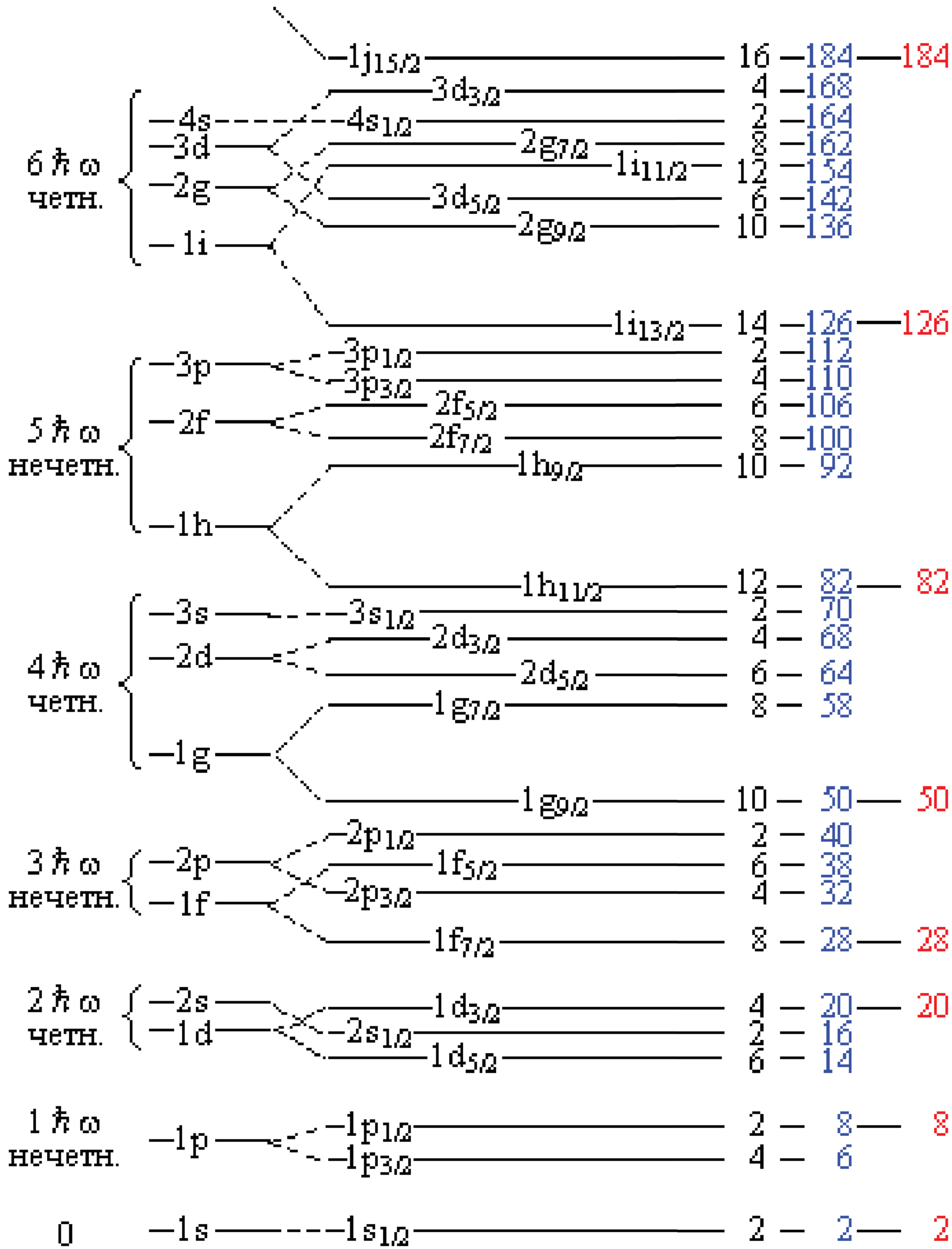
It is need to stress that convincing theoretical basis for introduction of spin-orbital potential is absent.

****

However hypothesis about existence of comparatively large spin-orbital part in average field potential is confirmed by sequence of experimental facts. In case of electron shells spin-orbital potential is not essential.

For large A **Woods-Saxon potential is similar to a potential well.**

The Schroedinger equation to find the energy levels of nucleons subjected to the Woods-Saxon potential cannot be solved analytically, and must be treated numerically.


6 ℏ ω
четн.
—4s
—3d
—2g
— 1i
—1j15/2
—3d3/2
—4s1/2
2g7/2
1i11/2
—3d5/2
2g9/2
1i13/2
16 —184—184
4 —168
2 —164
8 —162
12 —154
6 —142
10 —136
14 —126—126
5 ℏ ω
нечетн.
—3p
—2f
—1h
—3p1/2
—3p3/2
2f5/2
2f7/2
1h9/2
1h11/2
2 —112
4 —110
6 —106
8 —100
10 — 92
12 — 82— 82
4 ℏ ω
четн.
—3s
—2d
—1g
—3s1/2
2d3/2
2d5/2
1g7/2
1g9/2
2 — 70
4 — 68
6 — 64
8 — 58
10 — 50— 50
3 ℏ ω
нечетн.
—2p
—1f
—2p1/2
1f5/2
—2p3/2
1f7/2
2 — 40
6 — 38
4 — 32
8 — 28— 28
2 ℏ ω
четн.
—2s
—1d
1d3/2
—2s1/2
1d5/2
4 — 20— 20
2 — 16
6 — 14
1 ℏ ω
нечетн.
—1p
—1p1/2
—1p3/2
2 — 8— 8
4 — 6
0
—1s
—1s1/2
2 — 2— 2

***Hans Jensen* and *Maria Goeppert-Mayer* shared the Nobel Price for Physics in 1963 for the development of the nuclear shell model, which they published independently in 1949. The model offered the first coherent explanation for the variety of properties and structures of atomic nuclei. In particular, the "magic numbers" of protons and neutrons, which had been determined experimentally from the stability properties and observed abundances of chemical elements, found a natural explanation in terms of the spin-orbit coupling of the nucleons.**

"Magic" numbers for protons and neutrons are:

$$2, \quad 8, \quad 20, \quad 28, \quad 50, \quad 82, \quad 126, \quad 184 \quad neutrons$$

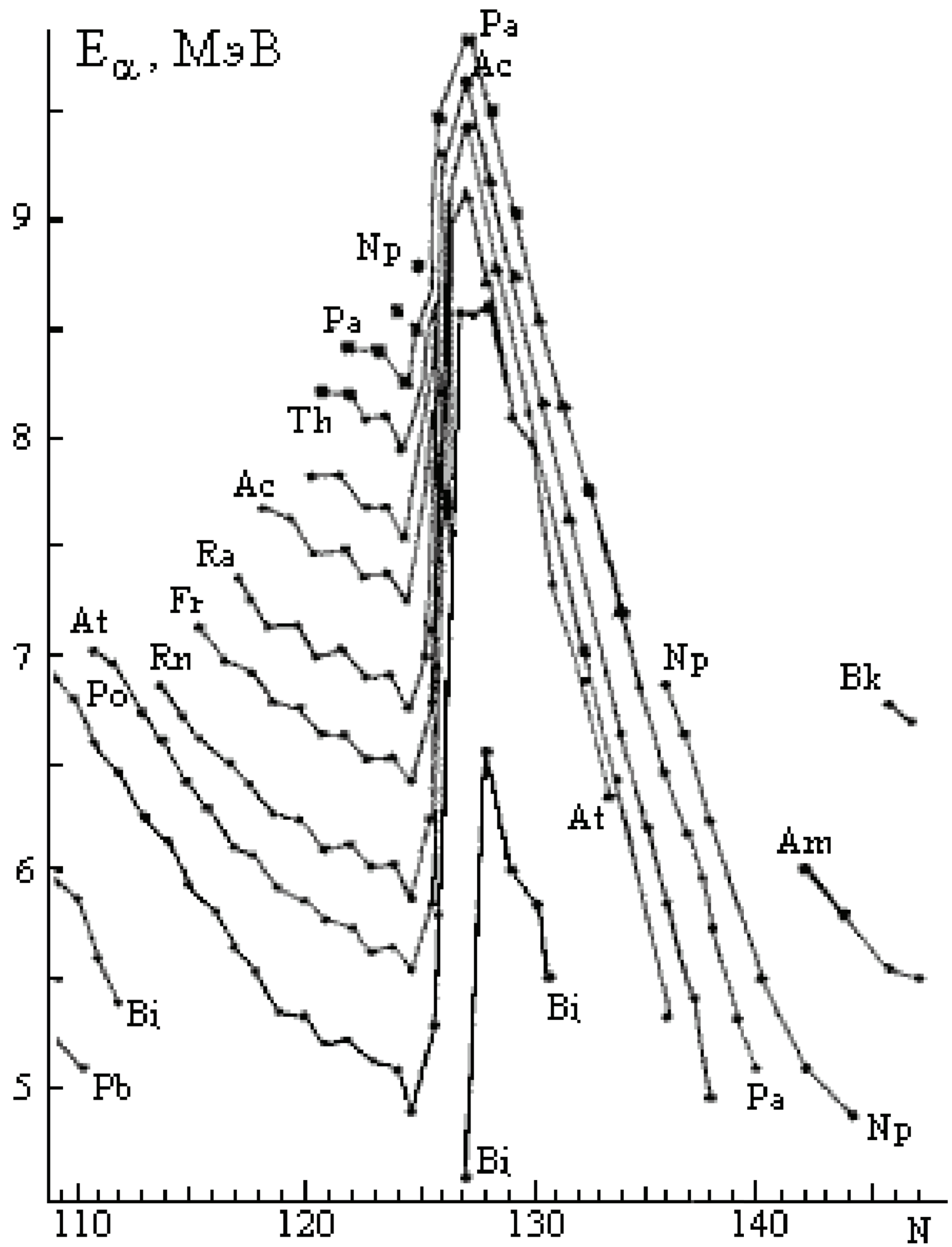
$$2, \quad 8, \quad 20, \quad 28, \quad 50, \quad 82, \quad 114 \quad protons$$

Difference in magic numbers - 126 **(for neutrons) and** 114 **(for protons) connected with Coulomb interaction.**

These numbers play a decisive role in the synthesis of the elements in star, as well as in the artificial synthesis of the heaviest elements at the borderline of the periodic table of elements. The shell model proved to be a surprising solution to the problem of nuclear-energy levels. Based on picture of independent particle motion of protons and neutrons with strong spin-orbit coupling, the model yields the correct sequence of energy levels and explains the magic numbers in terms of energy gaps above full levels.

α-decay of heavy nuclei.

Energies of emitted α-particles. Lines connect data for different isotopes of the same element. Peak at N=128 corresponds most favourable for α-decay case, when forms strongly binding magic nucleus-product (N-2=126).



Eα, МэВ
9
8
7
6
5
110
120
130
140
N
Pa
Ac
Np
Pa
Th
Ac
Ra
Fr
At
Rn
Po
Bi
Pb
Bi
At
Np
Bk
Am
Bi
Pa
Np
Bi

In shell model spin of nucleus sumes up from the sum of spins and orbital momenta individual nucleons. Pauli principle and specific features of the nuclear interaction lead to the fact that *all even-even nuclei have spin equal 0.* Parity of state is determined by multiplication of inner parities of constituent particles on parities of wave functions, describing their motion relative common center of inertia. Inner parity of nucleons is defined as positive. Thus, for *parity of nuclear state* we obtain expression:

$$P = (-1)^{\sum_{i=1}^{A} l_i}$$

where l_i is orbital momentum of i-th nucleon. *Shell model* in many cases satisfactorily *reproduces experimental values of spins and parities, electrical quadrupol and magnetic momenta of atomic nuclei, average time of life of β-active nuclei, describes distribution of isomer nuclei.*

Better foretells shell model gives for nuclei near closed shells, for which self-consistent potential is spherically symmetric.

Collective excitations of nuclei.

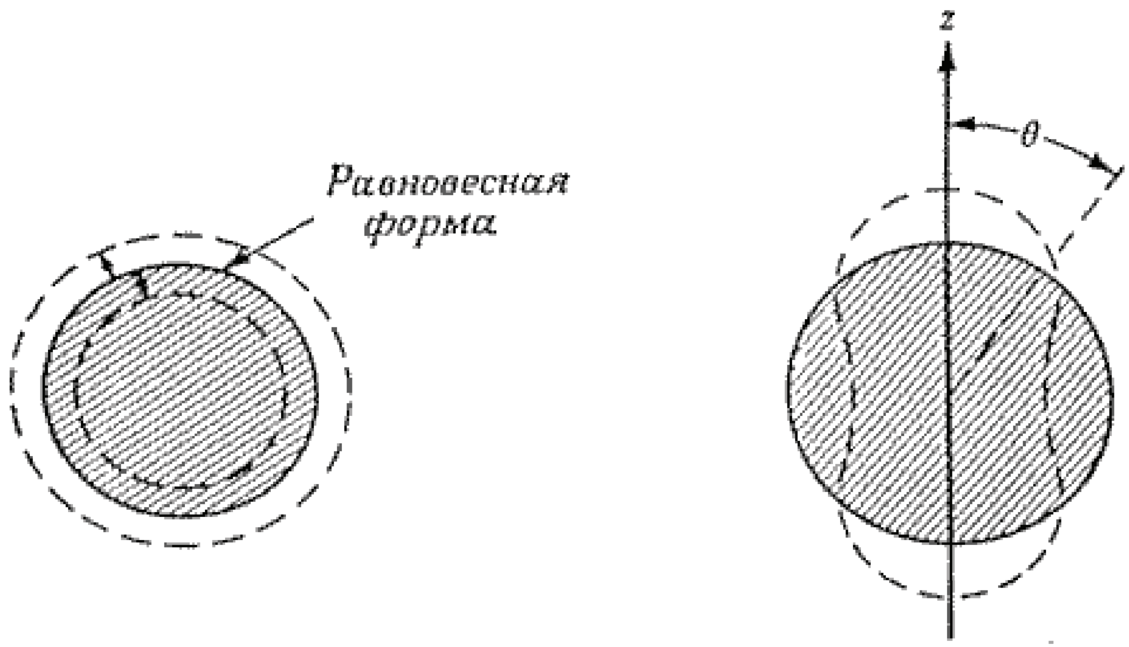
In nuclei are observed collective excitations in which motions of individual nucleons are correlated:

Generalized Model of Nucleus was proposed by D.Reinuoter, O.Bor, B.Mottelson(1952). Equilibrium form of magic nuclei is spherically symmetric. When the number of particles and holes (dirok) in outher shells are grown, the spherical form of nuclei becomes less stable. Residual interaction between outher nucleons lead to correlated motion of particles, in result shape of nucleus become distinguish from form of sphere.

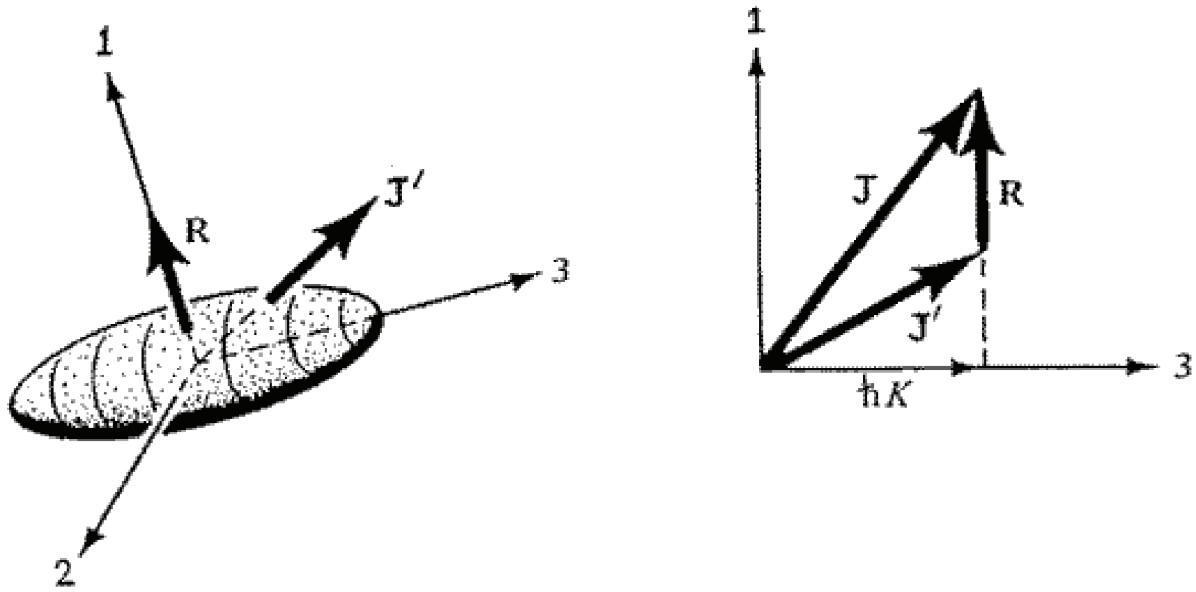
In base of GMN lie two suppositions:

1. Equilibrium form of nuclei being far of magic ones is ellipsoid of rotation.

2. Condition of adiabaticity (adiabatichnosti) is $\omega_{rot} \ll \omega_{vib} \ll \omega_{in}$ **i.e. rotational frequencies are much smaller than vibrational frequencies and these in their queue much smaller than frequencies connected with inner motion of nucleons.**
This condition allows consider these motions separately!



а б


1
R
J′
3
2
1
J
R
J′
ħK
3

Variational principle of Hartry-Fock-Bogolyubov.

General form of model nuclear Hamiltonian:

$$H = H_{av} + H_{pair} + T_{rot} + H_{cor},$$

H_{av} **describes mean field of nucleus;**
H_{pair} **is term describing pair correlation of nucleons supercoducting type (as Cooper pairs of electrons);**
T_{rot} **is term of kinetic energy of rotation;**
H_{cor} **is term of coriolise (koriolisova) interaction which describes connection between rotation and inner motion.**

Pairing

Any attractive interaction between fermions at low temperatures generally leads to fermion pairing analogous to the Cooper pairing of electrons in superconducting metals.

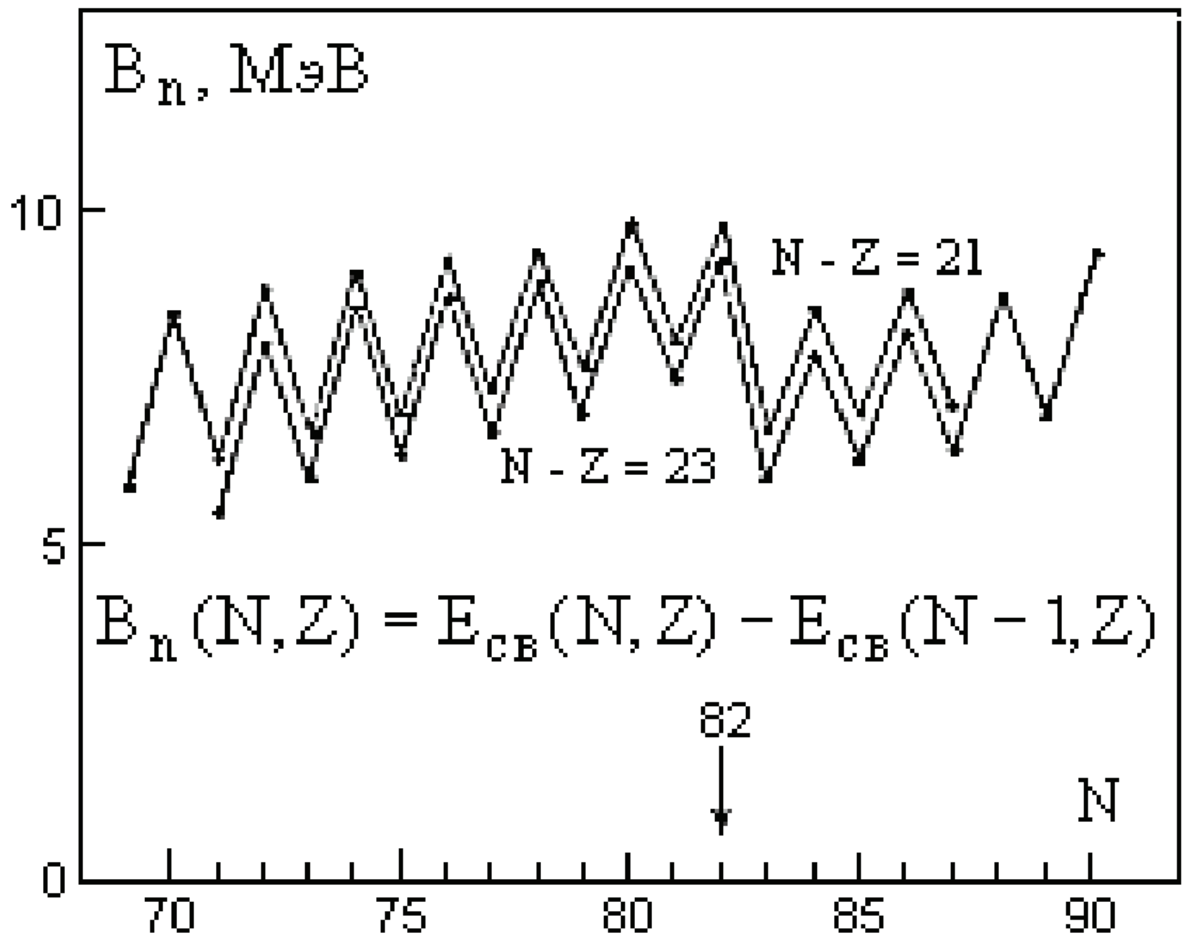
It is present in finite nuclei and in the nuclear matter of neutron stars (nucleonic pairing), and it is believed to exist in the quark-gluon plasma (color superconductivity). The coherence length (the size of the Cooper pair) in atomic nuclei is much larger than the nuclear size.

Pair correlations of superconducting type between protons and neutrons are absent.

Strong correlations there are only if spin $S = 0$ and isospin $T = 1$.

Separation energies of neutrons B_n.

Lines connect data for nuclei with equal neutron excess(izbitok). Observed sharp jumps connected with energy of pairing neutrons in nucleus.



Pairing can determine even the existence of a nucleus. A classic example is the chain of helium isotopes: the N-even nuclei $^4He, ^6He, ^8He$ are bound while the odd-N isotopes $^5He, ^7He$ are not.

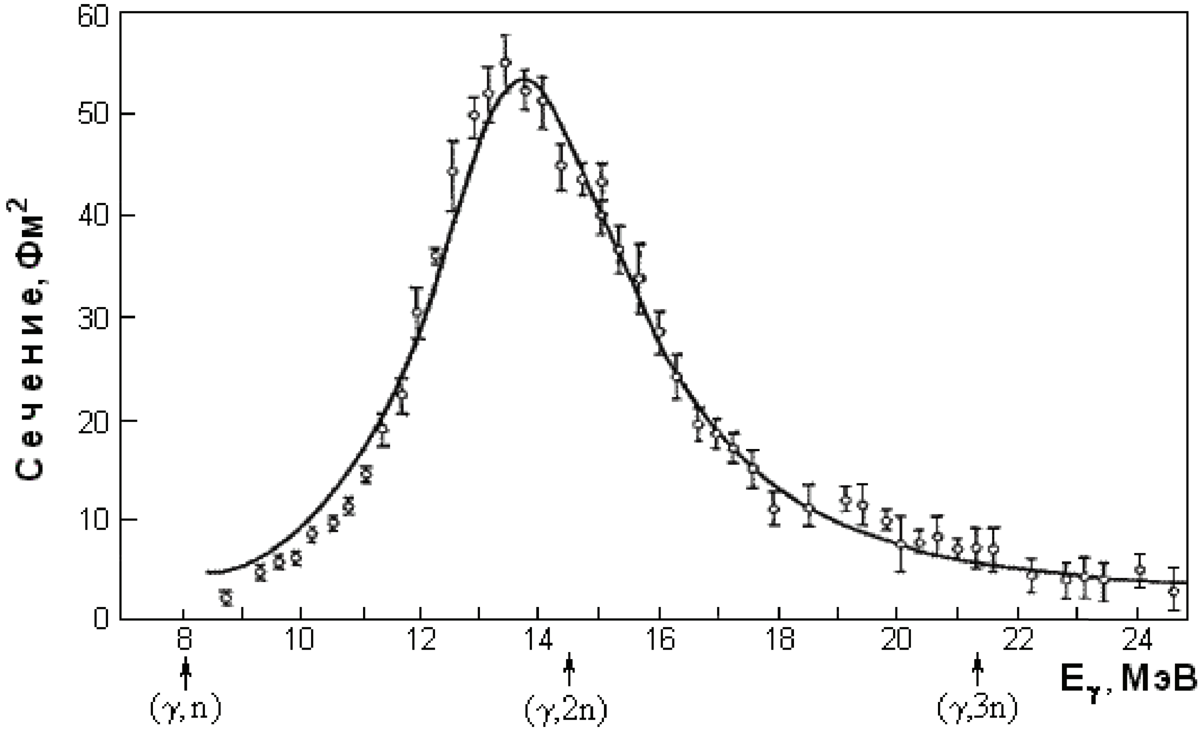
In this model it is supposed strong connection outher relative closed shells nucleons with frame (ostov), which can lead to the stable equilibrium deformation of nucleus. Motion of frame (ostov) is described in hydrodynamic model. One-particle states are calculated in deformed potential. For the first time such calculations for one-particle states with using of deformed axial-symmetric potential were performed by Nilsson(1955).

The apparent contradictions with the collective properties of nucleons in nuclei (evident from the rotational spectra) as well as with the chaotic properties of nuclei (evident in Niels Bohr's compound nucleus picture) only found their explanations much later. Today, shell-model calculations in large configuration spaces can indeed explain rotational spectra, and within individual shells consistency with the random nuclear properties appears once the residual interaction is considered. However, a derivation of the shell model from the basic nucleon-nucleon interaction is still missing.

Vibration of nuclear surface.

Two-component model of nuclear liquid.
In this model neutrons and protons are considered as two liquids regularly distributed inside nucleus. Electromagnetic field disturbs this equilibrium distribution, therefore in result of absorption of γ-quanta are arised vibrations (oscillations) of densities of neutron and proton liquids (polarization vibrations (oscillations)) which in experiment are observed as wide peaks in cross sections of photonuclear reactions.
Coherent oscillations(vibrations) of protons relative neutrons. They called giant resonances. Better studied giant resonance is giant dipole resonance. It is observed in all nuclei.

Phenomenological theory of oscillating(vibrational) states of atomic nuclei was developed by O.Bor(1952).


Сечение, Фм^2
60
50
40
30
20
10
0
8
10
12
14
16
18
20
22
24
Eγ, МэВ
(γ,n)
(γ,2n)
(γ,3n)

Theoretical models using for prediction of drip lines.

The finite-range droplet model (FRDM).

FRDM uses a semi-classical description of the macroscopic contributions to the nuclear binding energy, which is augmented with microscopic corrections arising from local single-particle shell structure and the pairing of nucleons (P.Moeller et al.,1995 At. Data Nucl. Data Tables 59 185).

The Hartree-Fock-Bogolyubov model (HFB-8).

HFB-8 is a state-of-the-art quantum-mechanical calculation that puts the nucleons into a mean-field with a Skyrme interaction with pairing (M.Samyn et al., 2004 Phys. Rev. C70 044309).

The neutron drip line (NDL)

Although models predict location of NDL, they cannot account interplay of valence protons and neutrons, even among the oxygen and fluorine isotopes. The discrepancies in magnesium and silicon region!

At NSCL (2007) discovered isotopes at NDL: ^{44}Si (Z=14,N=30), ^{40}Mg (Z=12,N=28), ^{42}Al (Z=13,N=29) and ^{43}Al (Z=13,N=30).

The strange NEW result

Al isotopes gain stability from an unpaired proton, which narrows normal gaps between shells and provides opportunity to bind many more neutrons.
Feature established in 2002 by difference between heaviest isotopes of oxygen (^{24}O (Z=8,N=16)) and fluorine (^{31}F (Z=9,N=22)).
It is strange, since in stable nuclei, attractive pairing interaction generally enhances stability of "even-even" isotopes.
More important than observation of ^{40}Mg is discovery of odd-odd ^{42}Al, which two models predicted to be unbound.

The proton drip line

The proton drip line is relatively well established for most of elements because the Coulomb repulsion among protons has a dramatic destabilizing effect on nuclei with significantly fewer neutrons than protons.

The neutron-binding energy only gradually approaches zero as the neutron number increases. Subtle quantum-mechanical effects such as neutron pairing and energy-level bunching end up determining the stability of the heaviest isotope of each element. The weak binding of the most neutron-rich nuclei leads to the phenomena of neutron "skins" and "halos", which give these nuclei some unusual properties.

Current knowledge of the neutron drip line is limited to only the lightest nuclei.

Researchers have made observations in different regions of the isotopic landscape by examining the nuclear structure of ^{64}Ge **(Z=32,N=32) and** ^{36}Mg **(Z=12,N=24).**

Change of Shape

Nuclei with equal proton (Z) and neutron (N) numbers are important in unraveling nuclear structure, in particular in the context of the shell model.

Between ^{56}Ni(Z=28,N=28) and ^{100}Sn(Z=50,N=50) they exhibit a variety of shapes, evolving from spherical to prolate (cigar-shaped) to oblate (pancace-shaped) as the mass increases.

Studies of transition rates between excited states and ground states in these nuclei provide important information to test shell-model predictions.

One such experiment at NSCL has studied ^{64}Ge(Z=32,N=32), making use of the recoil distance method (RDM) to measure the lifetime of two excited states. The results agree well with large-scale shell-model calculations for the two excited states studied, and show the promise of the techniques used.

Island of inversion

Exotic nuclei far from N=Z, with too many neutrons, offer other possibilities for testing shell-model predictions. One area of interest is the "island of inversion" where around a dozen neutron-rich isotopes should exhibit shell orderings that differ from standard theoretical predictions.

Studies of magnesium isotopes have already placed $^{31-34}Mg$(Z=12, N=19-22) in the island. Now at NSCL has examined the shell structure of ^{36}Mg which has as many as 24 neutrons. In this case, a secondary beam of ^{38}Si collided with a berilium target to create ^{36}Mg on rare occasions: only 1 in 400 000 ^{38}Si nuclei yielded the desired ^{36}Mg. Spectroscopic measurements of the first excited state confirmed shell-model predictions, placing ^{36}Mg in the island of inversion as expected.

Heaviest elements

GSI in Darmstadt synthesed heaviest elements using cold fusion (only one neutron emitted) up to and beyond roentgenium, symbol Rg and atomic number Z=111. The relative stability of these elements, with mean lifetimes in the order of milliseconds to seconds, is a consequence of shell effects. Without these they would not exist. The element Z=112, synthesized at GSI in 1996.

Yuri Oganessian's group at the Flerov Laboratory at JINR, Dubna, used radioactive targets in hot-fusion reactions with emission of up to five neutrons, to create synthetically element 114, 116 and 118 (now experiment for synthesis of element 117).

Kosuke Morita and co-workers at RIKEN in Japan made element 113 in 2004.

Relativistic mean-field calculations indicate that the closed shell should occur at Z=120 (number of protons), with magic neutron number of 184, as had appeared in the book of Jensen and Goeppert-Mayer. This doubly magic superheavy nucleus should have 304 nucleons.

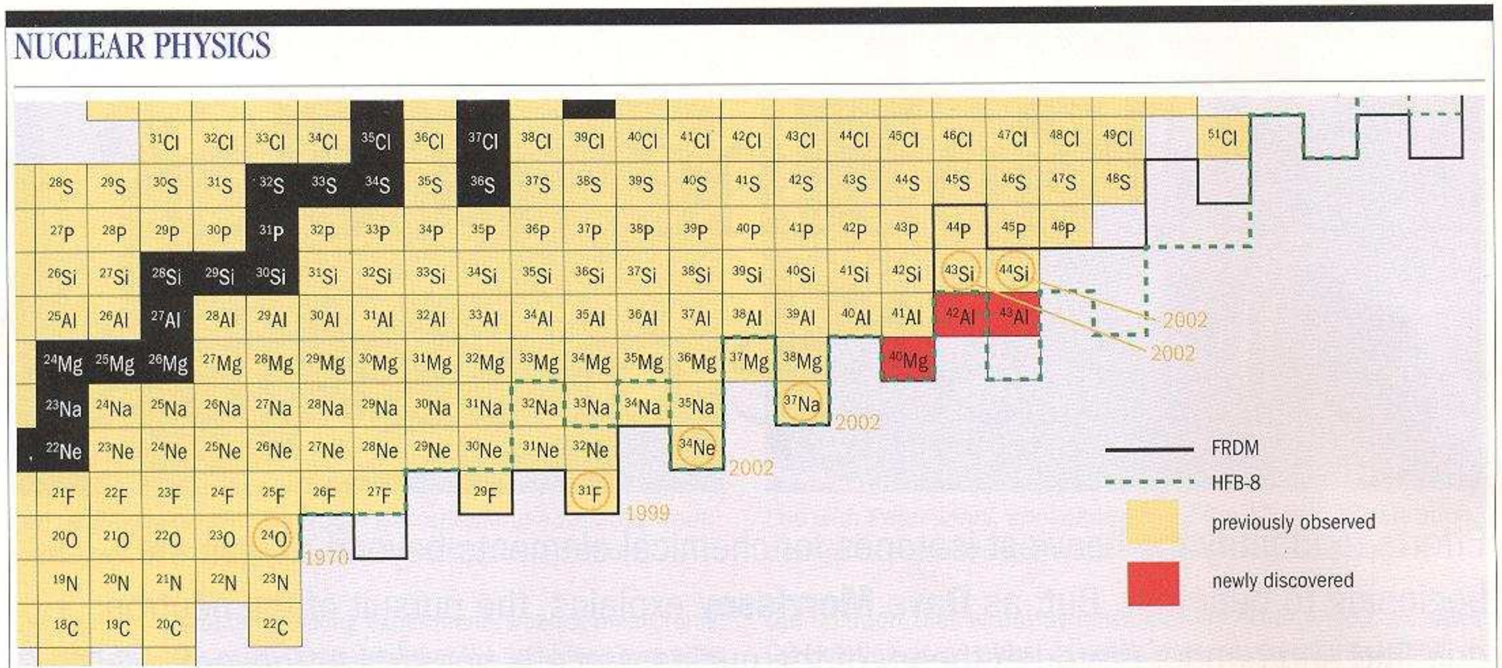


Fig. 2. A section of the chart of nuclides for light, neutron-rich nuclei in which the proton number increases vertically and the

Supernovae and the shell model.

In Type 1a supernovae there is a high and almost identical fraction of nickel-56(Z=28,N=28). This doubly magic nucleus is not stable (its half-life is six days) and its decay through cobalt-56(Z=27,N=29) to iron-56(Z=26,N=30) is what makes these supernovae shine. Hence, the brightness of the supernova is proportional to the produced mass of nickel-56.

Core-collapse supernovae (Type II), such as SN1987A in the Large Magellanic Cloud, where a blue supergiant exploded in several seconds, allow the direct test of ideas about the synthesis of heavy elements. For example, observations of the characteristic gamma rays indicate the presence of the corresponding isotopes synthesized in the particular star of during the explosion. Elements beyond iron are, in particular, produced in a sequence of rapid neutron captures known as the r-process. It turns out that the element abundances are mainly determined by nuclear structure, and hence, by shell model.

NSCL facility.

Michigan State University's National Superconducting Cyclotron Laboratory (NSCL) was founded in the 1980s. NSCL facility is based on two coupled superconducting cyclotrons and can produce intense energetic beams of primary heavy ions from hydrogen to uranium. Maximum beam energies of 200 MeV per nucleon for lighter elements and 90 MeV per nucleon for uranium are achieved after final acceleration. A high-acceptance fragment separator allows efficient production and the in-flight separation of a broad range of secondary rare-isotope beams produced by projectile fragmentation or fission reactions. These beams are sent to various experimental devices that serve a community of researchers from the US and abroad.

ISOLDE results

In nature, relatively few nuclei have a spherical shape in their ground state. Examples are ^{16}O (Z=8,N=8), ^{40}Ca (Z=20,N=20), ^{48}Ca (Z=20,N=28) and ^{208}Pb (Z=82,N=126), which are "doubly magic".

By moving away from the closed shells and increasing the number of valence nucleons, both protons and neutrons, these nuclei can eventually acquire a permanent deformation in their ground state.

Experiments reveal that sometimes-due to the complex interplay of single-particle and collective degrees of freedom-both a spherical and deformed shape occur in the same nucleus at low excitation energies. In the region around lead in the 1970 first observed this "shape co-existence", using optical spectroscopy at the ISOLDE facility at CERN. Since then, an extensive amount of data has been collected throughout the chart of nuclei.

GSI results.

Nuclear physics gets a stepping stone to the "island of stability" Their new technique will provide experimentalists with much better understanding of the superheavy elements, and it may even provide a stepping stone to the fabled "island of stability"- a hypothesized group of superheavy elements with much longer half-lives than uranium.

The element in question is nobelium (No), defined by its 102 protons, which the researchers produce by firing isotopes of calcium at a lead target. By fusion, this process produces one isotope every second of either ^{252}No(Z=102,N=150), ^{253}No or ^{254}No.

A major challenge that faced the researchers was to find a way of slowing down the energetic young nobelium ions to get them under control for their weigh-in. This was achieved by guiding them through a cloud of neutral helium atoms, which forced the sprightly ions to shed much of their energy through a series of collisions.

Methods of investigation:

in flight fragmentation

The use of a heavy-ion linac allows in-flight separation of ions and provides a path to reaccelerated beams that overcomes some of the chemical limitations of traditional ISOL techniques. Stopping, extracting and reaccelerating rare-isotope beams leads to intensity losses, the full extent of which is not yet known.

Ion Separation On-Line (ISOL)

In this techniques isotopes are produced at rest in a thick target. Stopped beams are important for precision measurements with ion or atom traps or for collinear laser spectroscopy.

Reaccelerated beams provide the opportunity to measure important nuclear-reaction rates relevant to nuclear astrophysics and to employ the well proven techniques of nuclear-structure physics to a host of new nuclei.

Reaccelerated beams allow investigation of fusion reactions, which will lead to production of new neutron-rich isotopes of very heavy elements.

Experimental Facilities.

NSCL at Michigan State University
ISOLDE at CERN
ISAC(I and II) at TRIUMF
SPIRAL1@GANIL in Gaen, France
JINR in Dubna
GSI in Darmstadt

The near-future facilities

RIKEN in Japan
SPES in Italy
GSI-FAIR in Germany
SPIRAL2@GANIL in France.

Still in the planning stage

EURISOL in Europe
Rare Isotope Beam Facility in the USA.

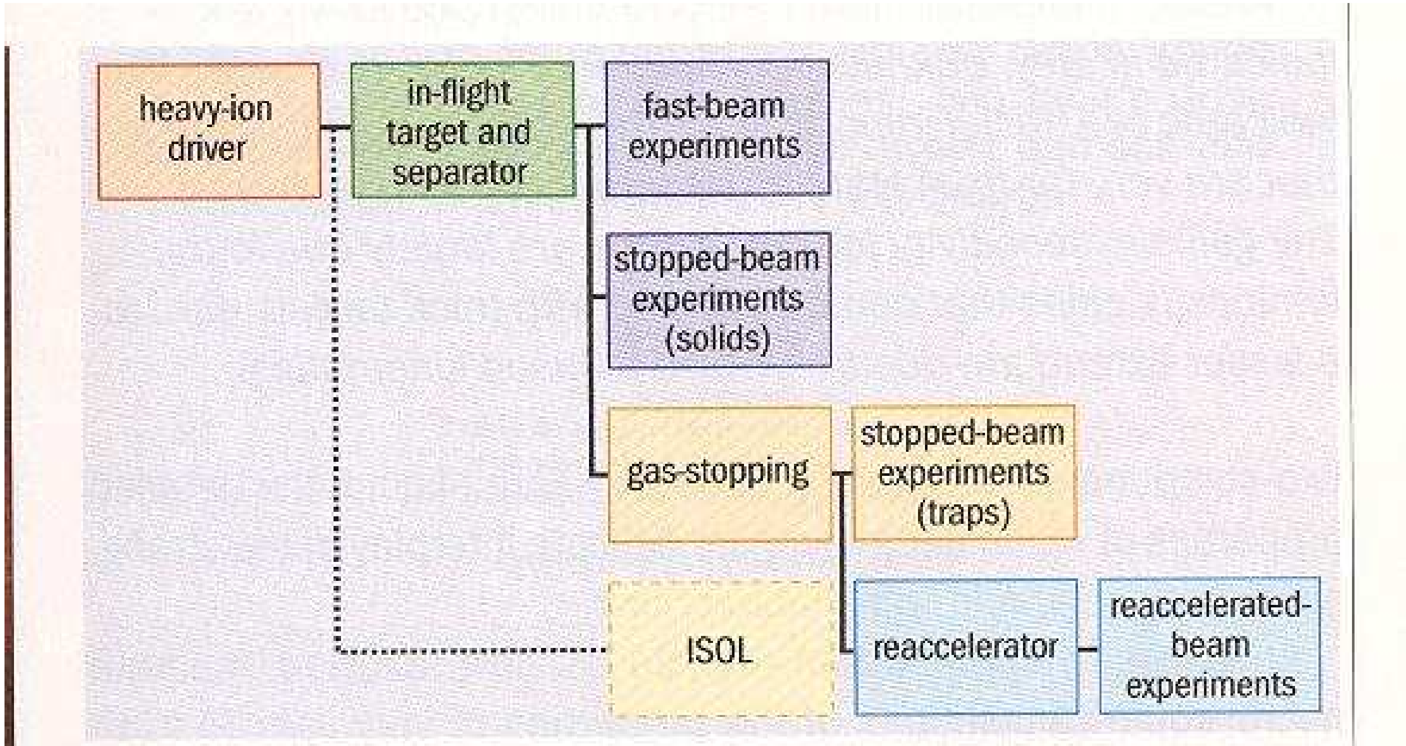


Fig. 1. Building blocks of an isotope-science facility based on a

Experimentally determined nuclear structure and decay data for all known nuclei are evaluated and incorporated into the Evaluated Nuclear Structure Data File (ENSDF)

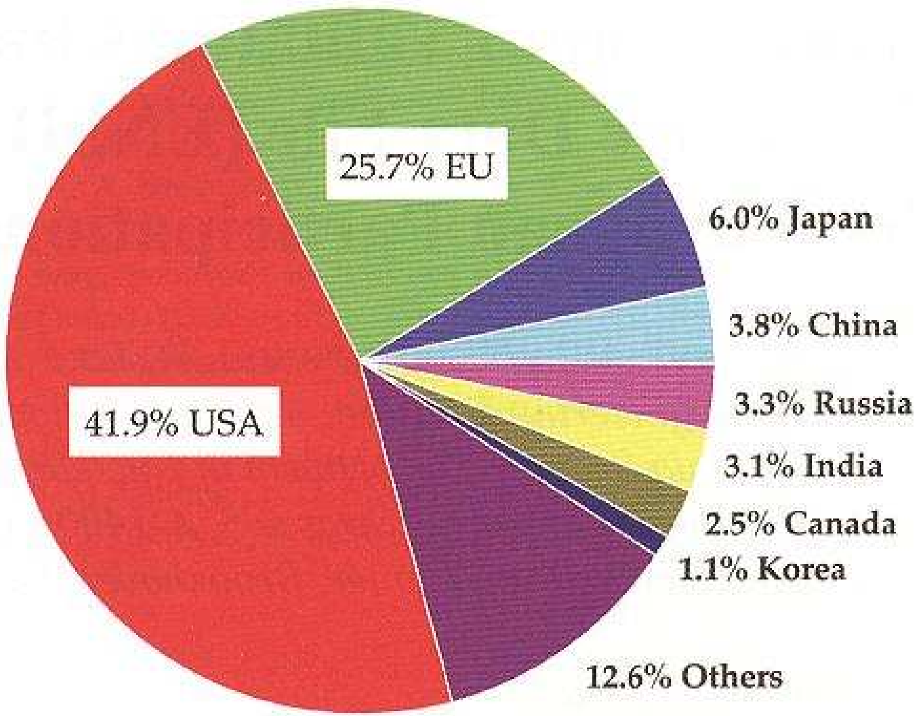


Figure 1. *Geographical usage of the nuclear data services of NNDC, BNL, USA. Data source www.nndc.bnl.gov/usndp.*

- **What are the phases of nuclear matter?**

Nuclear Matter (NM) is an idealized system of interacting nucleons (protons and neutrons) that exists in several phases that yet are not fully established. It is not matter in a nucleus, but hypothetical stuff consisting of a huge number of protons and neutrons interacting by only nuclear forces and no Coulomb forces. Volume and particle number are infinite, but ratio is finite. Infinite volume implies no surface effects and translational invariance. A common idealization is symmetric nuclear matter, which consists of equal numbers of protons and neutrons, with no electrons.

Idea about NM arises on basis of experimental fact, that average energy per nucleon in nucleus E_{av}, does not depend from the number of nucleons. Moreover, density of inner regions of middle and heavy nuclei is constant $\rho_0 = 0.17 - 0.18 nucl/fm^3$. For infinite system, in neglecting the Coulomb energy of interaction of protons, at equal number of protons and neutrons $E_{av} = -15.75 MeV$. In theory of NM it is supposed that between nucleons inside NM act the same forces as between pair of free nucleons, and it is shown that NM with such interaction is stable, i.e. energy of system has minimum at values $E_{av} = -15.75 MeV$ and $\rho = \rho_0$. Essential element in theory of NM, is the choice of potential for nucleon-nucleon interaction V, which can be found on basis of experimental data for nucleon-nucleon interaction with energy up to few hundreds MeV.

The choice of potential.

Potential does not fully determined. It consists from short acting [on distances $(0.4 - 0.5) fm$] very strong repulsive core and long acting forces. Long acting forces contain direct and exchange terms, tenzor and spin-orbital terms, which give resulting effect - attraction. They have acting radius $\sim (1.5 - 2.5) fm$, depth of corresponding potential well $30 - 50 MeV$.

When nuclear matter is compressed to sufficiently high density, it is expected, on the basis of the asymptotic freedom of QCD, that it will become quark matter, which is a degenerate Fermi gas of quarks.

The different phases of Nuclear Matter.

The study of hot and dense nuclear matter by means of relativistic heavy ion collisions is nowadays one of the main topics of heavy ion physics. As the incident kinetic energy increases well above the Coulomb barrier, the nuclear shell structure becomes less and less relevant; up to 30A MeV, collective states of nuclei still play an important role. Beyond the Fermi energy, the scenario evolves toward nuclear matter dynamics.

Within such a scenario we try to understand the nuclear matter behavior in terms of an equation of state that, connecting variables such as pressure, temperature, and density could provide an explanation to the multifragmentation of the colliding nuclei as a liquid-gas transition.

At even higher energies, above 1A GeV, a large fraction of the beam energy is transferred into the excitation of nucleon resonances and meson production. This exotic phase of nuclear matter is called hadronic matter.

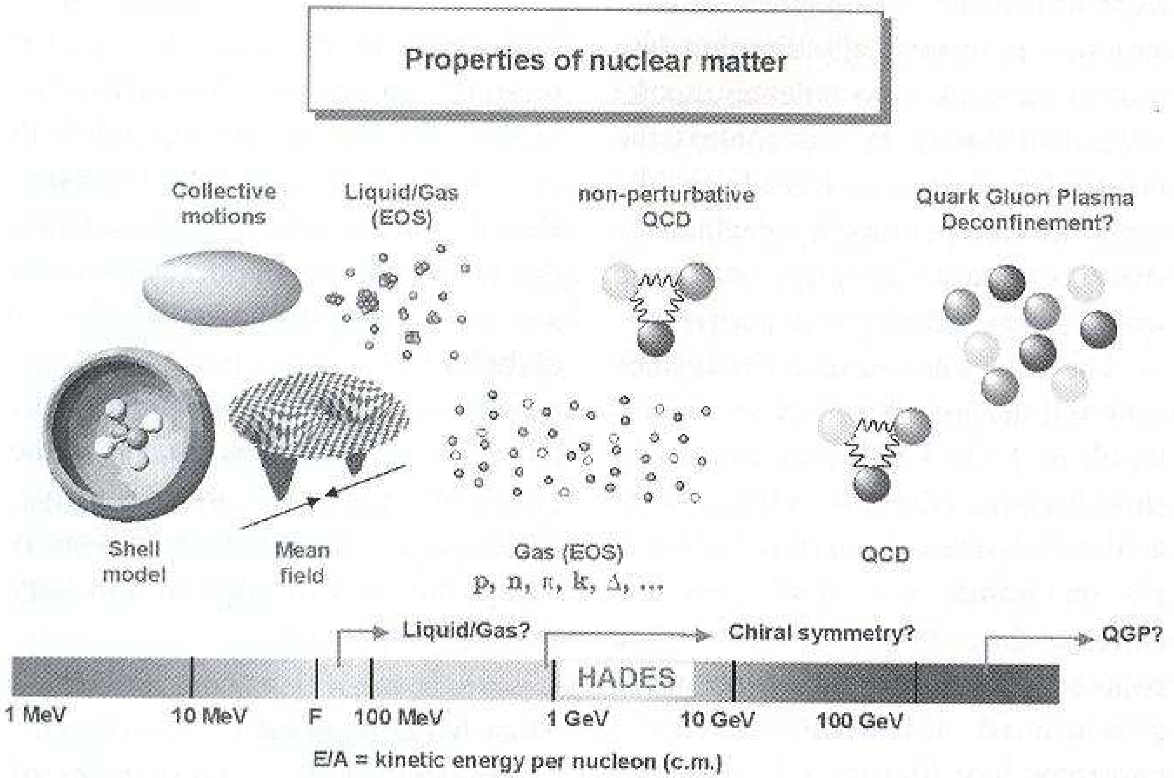
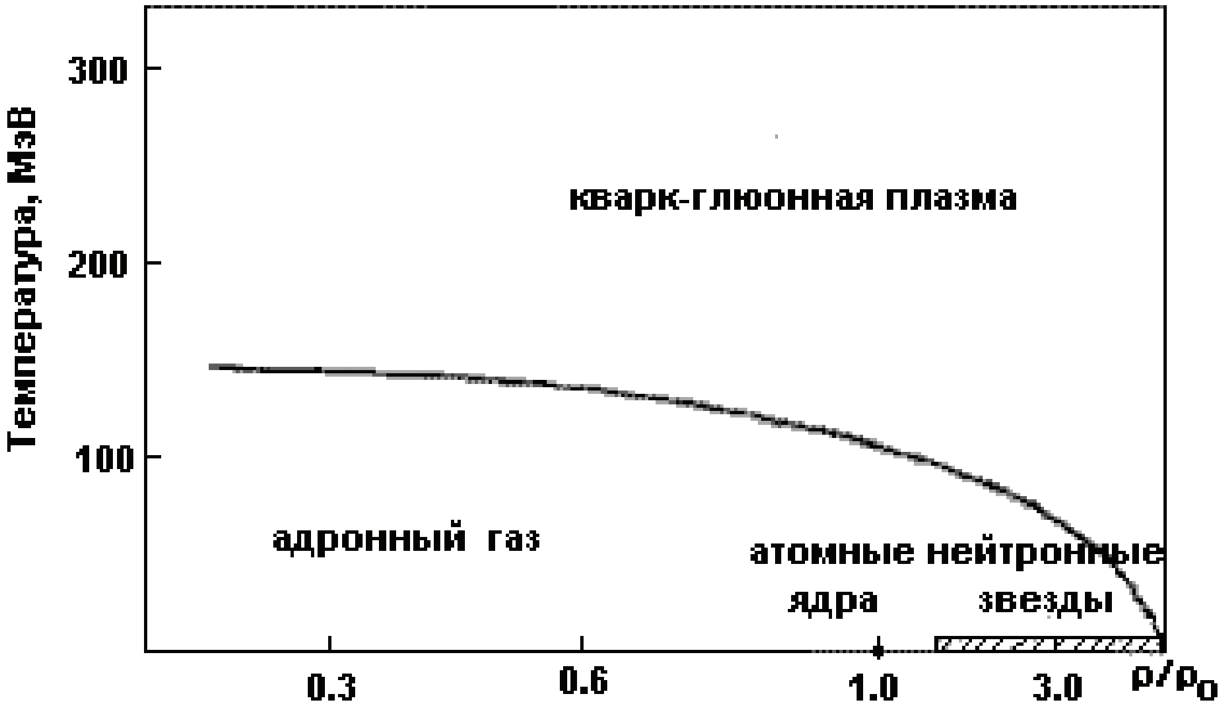


Figure 1. *Properties of nuclear matter as a function of the collision energy*

At even higher densities and temperatures, of the order of $T = 175 MeV$ per particle (temperature $2 \cdot 10^{12}$ kelvin) a new nuclear matter phase characterized by the melting of hadrons into a Plasma of Quarks and Gluons (QGP) is expected to occur. Note that $T = 175 MeV$ is not the energy of the colliding beam. Lead and gold nuclei have been used for such collisions at CERN SPS and BNL RHIC, respectively. The nuclei are accelerated to ultrarelativistic speeds and slammed into each other while Lorentz contracted. They largely pass through each other, but a resulting hot volume called fireball is created after the collision. Once created, this fireball is expected to expand under its own pressure, and cool while expanding. By carefully studying this flow, experimentalists hope to put the theory to test.

The investigation of the nuclear matter phase diagram in such a broad range of temperatures and/or densities offers a unique way to study the strong interaction and its theory, QCD, in a region of transition from hadronic to partonic degrees of freedom.

NICA Project. A team at the Joint Institute for Nuclear Research (JINR) at Dubna has conceived of one such project: the Nuclotron-based Ion Collider fAcility (NICA), a superconducting accelerator complex for colliding beams of heavy ions in the energy range of 4-11 GeV per nucleon in the centre of mass. The aim of NICA is to study an intricate and mysterious phenomenon: the mixed phase of quark-gluon matter. According to modern ideas, quark-gluon matter has a mixed phase- like boiling water that exists simultaneously with vapour. The mixed phase of hadronic matter should include free quarks and gluons simultaneously with protons and neutrons, inside which quarks are already constrained-or "glued"-by gluons. In the phase diagram of temperature and baryon density, the border between the hadronic state and quark-gluon plasma is not a thin line but a domain the size and shape of which is still difficult to determine. It is here in what we call "the Dubna meadow", where the mixed phase of hadron matter should exist.


Температура, МэВ
300
200
100
кварк-глюонная плазма
адронный газ
атомные ядра
нейтронные звезды
0.3
0.6
1.0
3.0
ρ/ρo

One of the most important symmetries of QCD is the chiral symmetry. Chiral symmetry is spontaneously broken by a non trivial feature of the QCD vacuum, namely the existence of long-range quark-quark correlations resulting in the appearance of a quark condensate. "Dressing" of quarks by the quark condensate is responsible for the generation of constituent quark and hence hadron mass. Moreover, the quark constituent masses appear in this picture as dynamical quantities depending on the temperature and/or density of the surrounding nuclear matter.

Several authors have predicted that partial chiral symmetry restoration occurs even at moderate temperatures and nuclear matter densities. Calculations based on the Nambu-Jona-Lasino (NJL) model show a reduction of the "up/down" constituent quark mass as a function of temperature and/or density. The underlying mechanism responsible for this remarkable phenomenon is the melting of the quark condensate in hot and/or dense nuclear matter. This situation is somehow similar to the formation of Cooper pair in a superconductor below the critical temperature and its disappearance at higher temperatures.

Typical behavior of the constituent up quark mass, which at high temperature and/or density approaches zero according to the NJL model.

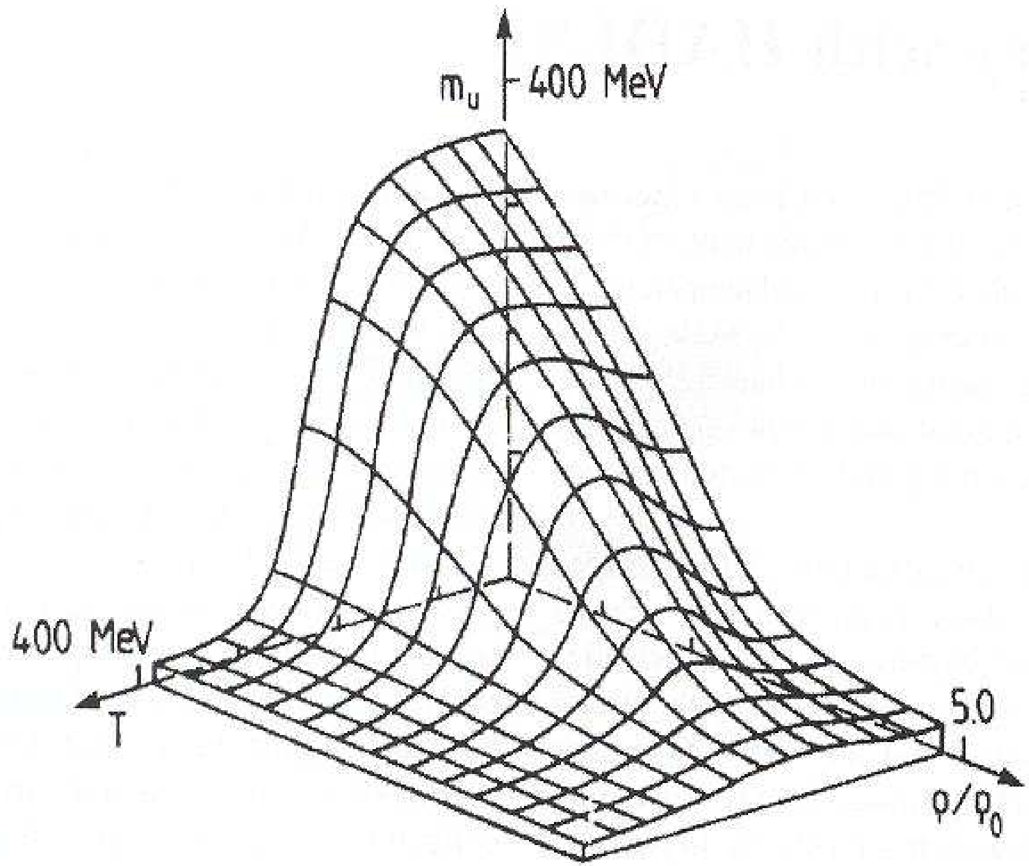


Figure 2. Typical behavior of the constituent up quark mass which at high

Neutron stars are the remnants of core collapse supernovae. They are the most compact stellar objects after black holes. The link between neutron stars and bulk nuclei is made via the nuclear matter. The central density of heavy nuclei is very close to the equilibrium density of nuclear matter, called the saturation density ρ_0. Moreover, the nuclear matter concept can be extended to isospin asymmetries:

$$\delta = (N - Z)/(N + Z).$$

Asymmetric nuclear matter is rather similar to the nuclear matter found in neutron stars. Coulomb potential energy at those densities is usually small compared to kinetic energy and the main interaction between particles is driven by the nuclear force. Recently, more direct relations between neutron-rich nuclei and neutron star matter have been proposed. Some of the exotic neutron-rich nuclei produced in nuclear facilities are also located in the outer crust of neutron stars, while the inner crust is composed by drip-line nuclei immersed in a neutron gas.
About 1500 neutron stars have been identified so far.

Mass and radius are determined by solving hydrostatic equilibrium equation. In the framework of the general relativity the equilibrium of a spherical object is described by the Tolman-Oppenheimer-Volkov equations, and for completeness, the equation of state (EoS) is required. The density increases from $10^6 g/cm^3$ ***at the surface (starting point of the crust), to several times the saturation density (***ρ^0 ***is*** $3 \cdot 10^{14} g/cm^3$***) in the core. The number of neutrons in neutron stars exceeds by far that of protons. The net isospin asymmetry can reach 0.95 (40 times more neutrons than protons) in the interior of the stars.***

Neutron stars are quasi-spherical objects composed of six major regions: the inner and outer cores ($\sim 99\%$ **of the mass) where nuclear matter is homogeneous; the inner and outer crust (1-2 km width) composed of inhomogeneous nuclear matter (nuclei or nuclear clusters), which screens the core from observations (even from neutrinos), and envelope (few meters), which influences transport and release of thermal energy from surface, and atmosphere (few centimeters), which plays an important role in shaping the emergent photon spectrum.**

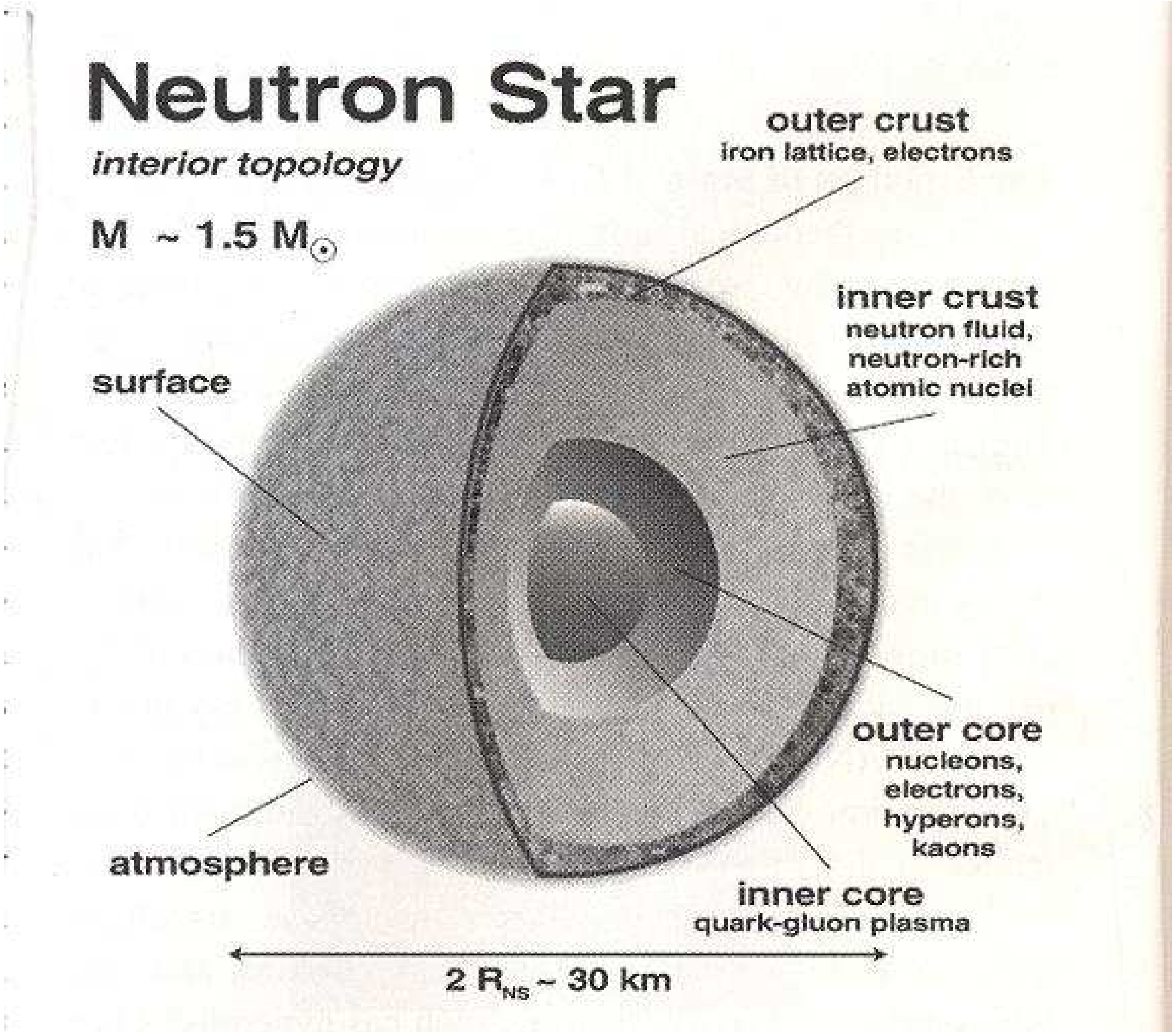


Figure 4. *The basic structure of a neutron star (from G*

- **What is the role of nuclei in shaping the evolution of the universe?**

Primordial nucleosynthesis, nucleosynthesis that occurred during the cooling immediately following the big bang, gave rise to the primordial abundances of H, He, and Li. All other chemical elements in the universe were produced as a result of the nuclear reactions occuring in stars, during supernovae explosions, novae, neutron star mergers, etc. It is another central objective of nuclear physics to explain the origin and abundances of matter in the universe, while nuclear astrophysics must address the many fundamental questions involving nuclear physics issues that remain. The latter include: ***the origin of the elements; the mechanism of core-collapse in supernovae; the structure and cooling of neutron stars and the presence of strange matter;the origin, acceleration, and interactions of the highest energy cosmic rays; and the nature of galactic and extragalactic gamma-ray sources.***

Spreading (rasprostranennost') of elements in universe:

1. Matter in universe in principal consists from **hydrogen** $\sim 90\%$ all atoms.
2. Second place occupies **helium** $\sim 10\%$ **from** number of **hydrogen** atoms.
3. Exist deep minimum of spreading corresponding to **lithium, beryllium and boron**.
4. At once after this deep minimum follows maximum connected with high spreading of **carbon and oxygen**.
5. After oxygen maximum follows jumplike fall of spreading of elements up to **scandium (Z=21,N=24)**.
6. It is observed sharp rise of spreading of elements in region of **iron "iron peak"**.
7. After $A > 60$ fall of spreading happens more even.
8. Observed a marked difference between elements with even and odd Z. As a rule elements with even Z are more spreading.
9. Some nuclei, so called avoided nuclei - ^{74}Se **(Z=34,N=40)**, ^{78}Kr **(Z=36,N=42)**, ^{92}Mo **(Z=42,N=50)**, ^{96}Ru **(Z=44,N=52), and other** have spreading on two order smaller than neighbour nuclei.

Formation of atomic nuclei.

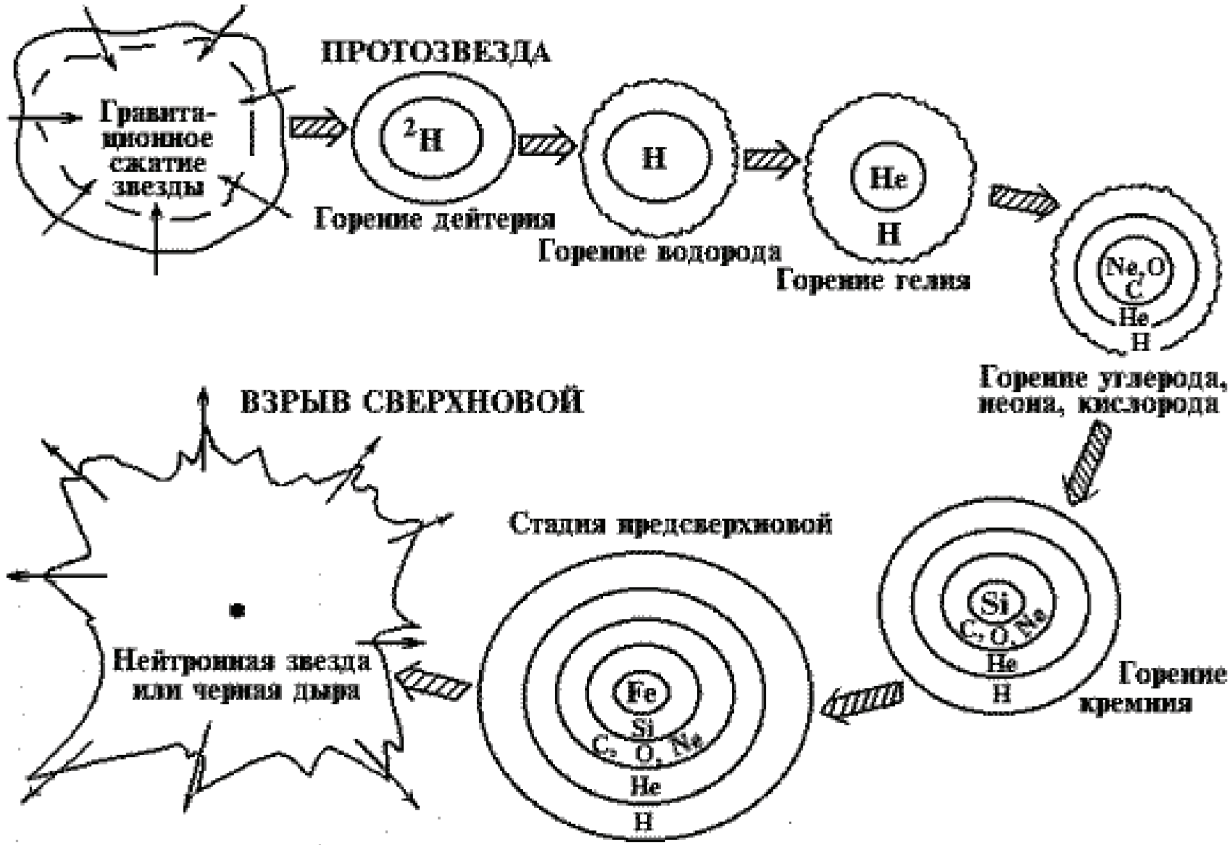
Main process on Sun:

$$p + p + p + p \longrightarrow {}^4He + 2e^+ + 2\nu_e$$

H.Bete and C.-F. Weizsacker proposed CNO-cycle as possible way to create helium in stars. Sequence of processes is:

$$\begin{aligned} {}^{12}C + p \longrightarrow {}^{13}N + \gamma \\ {}^{13}N \longrightarrow {}^{13}C + e^+ + \nu_e \\ {}^{13}C + p \longrightarrow {}^{14}N + \gamma \\ {}^{14}N + p \longrightarrow {}^{15}O + \gamma \\ {}^{15}O \longrightarrow {}^{15}N + e^+ + \nu_e \\ {}^{15}N + p \longrightarrow {}^{12}C + {}^4He. \end{aligned}$$

${}^{12}C$ **in this cycle plays role of katalizator for synthesis of** ${}^4He$**.**



ПРОТОЗВЕЗДА
Гравита-
ционное
сжатие
звезды
^{2}H
Горение дейтерия
H
Горение водорода
He
H
Горение гелия
Ne,O
C
He
H
Горение углерода,
неона, кислорода
Si
C, O, Ne
He
H
Горение
кремния
Стадия предсверхновой
Fe
Si
C, O, Ne
He
H
ВЗРЫВ СВЕРХНОВОЙ
Нейтронная звезда
или черная дыра

M.Burbidge, H.Burbidge, V.Fauler, F.Hoile (1957)

Description of basic processes of evolution of stars, in which happen formation of atomic nuclei. They are:

1. Burning of hydrogen, in result of this process are formed nuclei ^4He.

2. Burning of helium. In result of process $^4He + {}^4He + {}^4He \to {}^{12}C + \gamma$ are formed nuclei ^{12}C.

3. α-process. In result of sequence capture α-particles are formed nuclei ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si ...

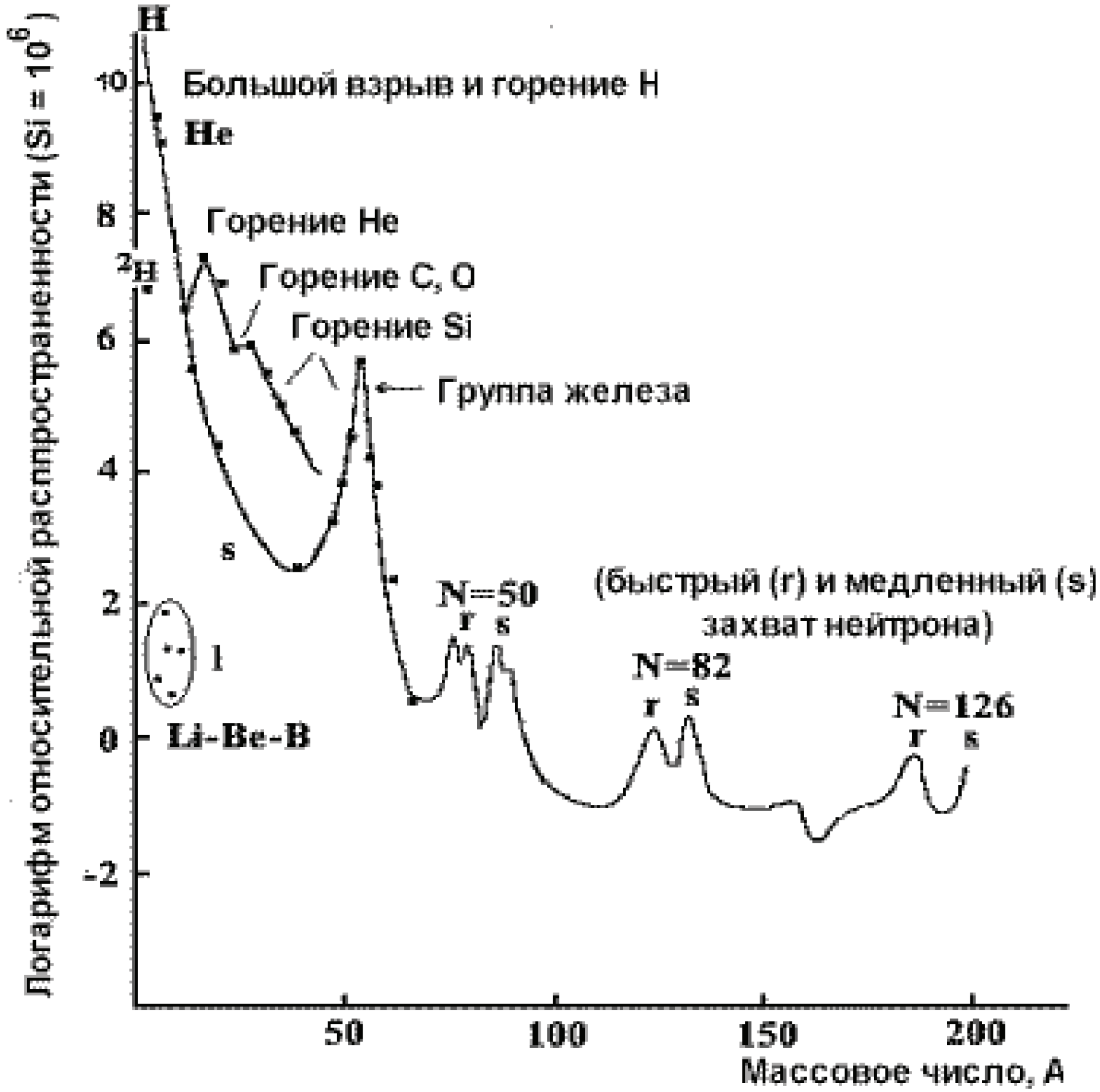
4. e-process. When reaches temperature $5 \cdot 10^9$K in stars, in case of thermodynamic equilibrium take place large quantity of variety reactions, in result are formed nuclei up to Fe and Ni. Nuclei with $A \sim 60$ are most strong bind atomic nuclei. On these nuclei end chain of synthesis nuclear reactions, accompanied by release of energy.

5. s-process. Nuclei heavier than Fe are formed in reactions of sequence capture of neutrons. Then take place β^--decay, which raises Z of formed nuclei. Time interval between sequence capture of neutron larger than period of β^--decay.

6. r-process. When the speed of sequence capture of neutrons much larger the speed of β^--decay, nucleus has time to capture many quantity of neutrons and then, in result of sequence of chains of β^--decay turn in stable nucleus. Now it is consider, that r-processes happen in result of explosions of Supernovae.

7. P-process. Some stable neutrondeficite nuclei (so called avoided nuclei) are formed in reactions of capture of protons, in reactions (β^-,n) or in reactions proceeding under action neutrino.

8. X-process. Mechanism of formation of light nuclei Li, Be, B in that time was unknown. After creation in star these nuclei must destroy in result of interaction with protons. Today is considered, that these nuclei are formed in result of interaction of cosmic rays with cosmic dust. (Light nuclei are formed also before star formation stage).



H
Большой взрыв и горение H
He
Горение He
^{2}H
Горение C, O
Горение Si
Группа железа
s
(быстрый (r) и медленный (s)
захват нейтрона)
N=50
r s
N=82
r s
N=126
r s
1
Li-Be-B
Логарифм относительной расппространенности (Si = 10^6)
10
8
6
4
2
0
-2
50
100
150
200
Массовое число, A

What physics is there beyond the standard model?

The Standard Model is one of the better tested theories in physics, but still it is considered to be incomplete.

Challenges of SM:

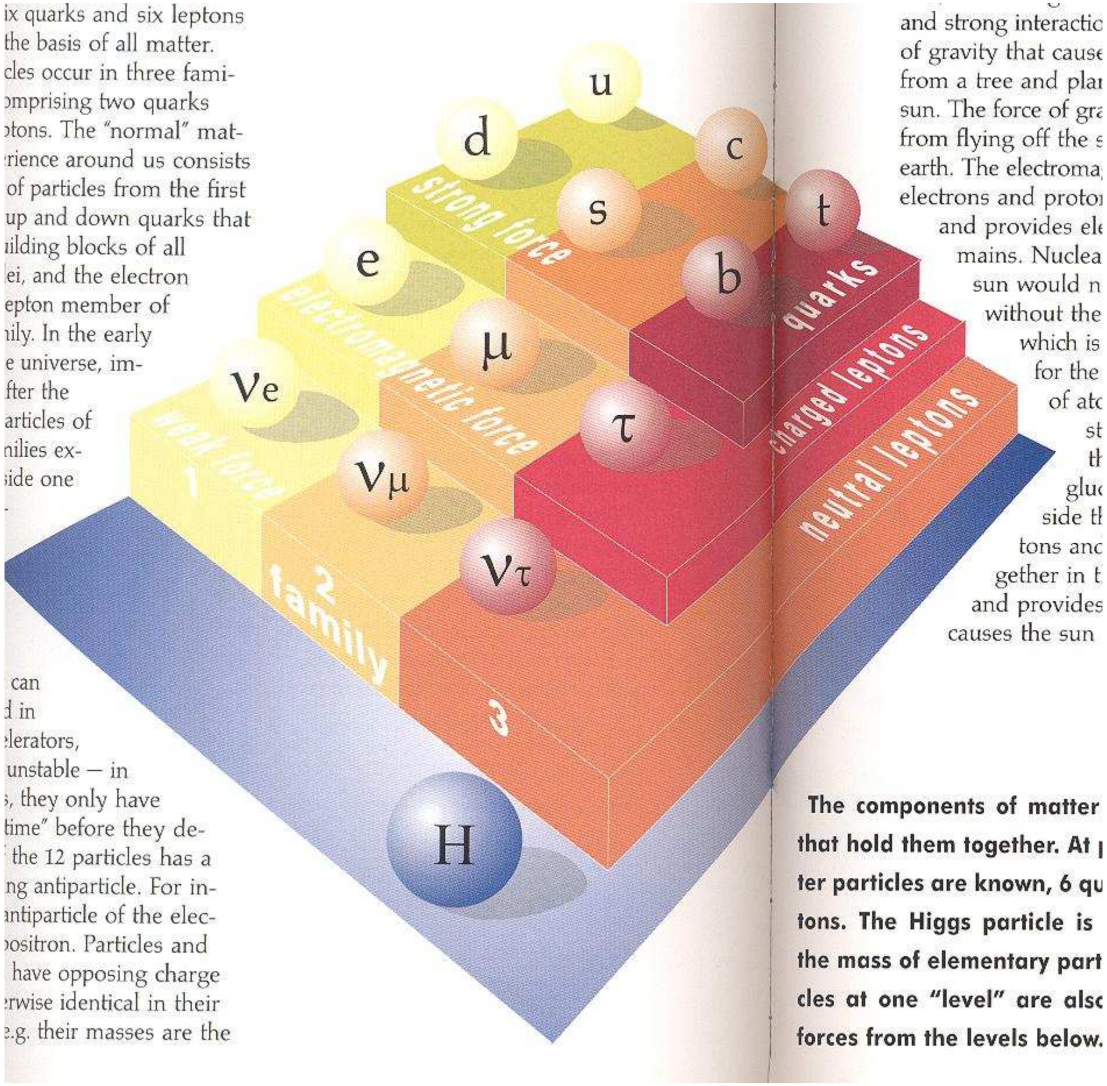
i. The universe has an obvious imbalance between matter and antimatter which the SM is unable to explain. Possible solution is the presence of new interactions which violate time-reversal-invariance (TRI) and charge conjugation/parity inversion (CP) (if one assumes CPT invariance). Probing of TRI violation in the properties of mesons, neutrons, and atoms.

ii. Another key question is the nature of the "superweak" forces which disappeared from view when the universe cooled. Experiments are searching for indications of additional forces that were present in the initial moments after big bang. High-energy experiments will probe the TeV scale directly, but high precision experiments at lower energies probe mass scales not accessible at the high-energy accelerator facilities.

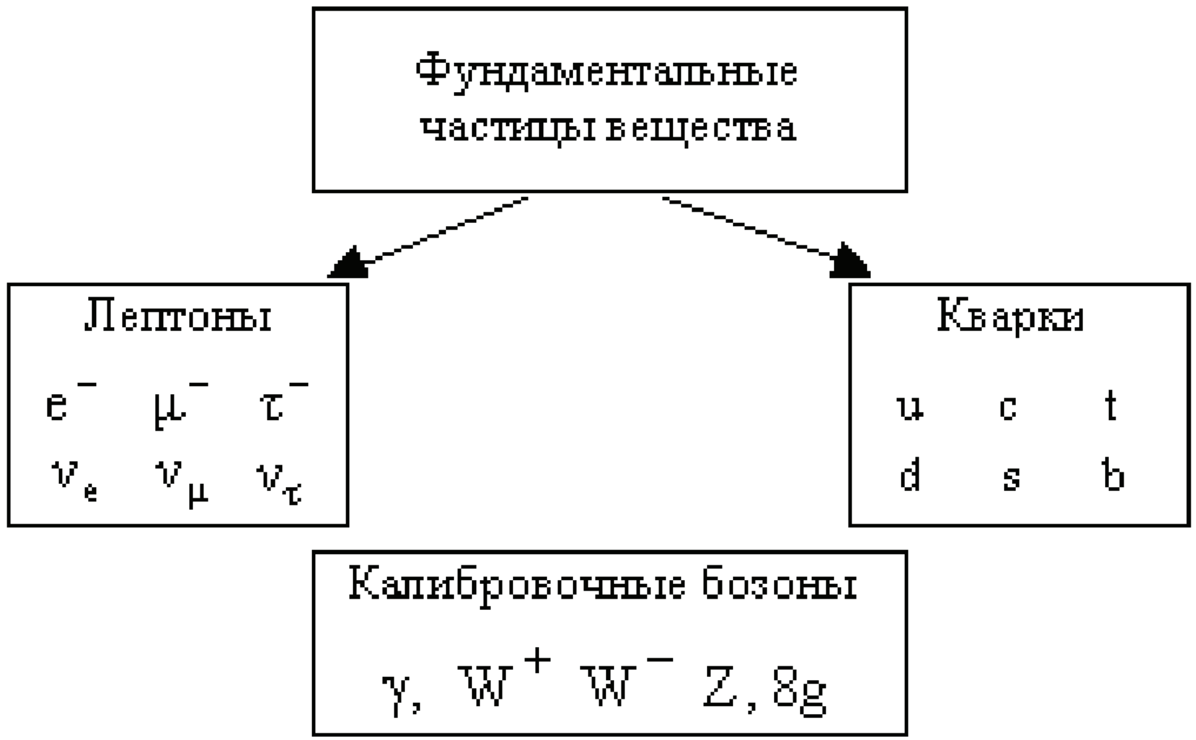
iii. Resolution of solar and atmospheric neutrino puzzles has opened up the possibilities for exciting discoveries in the neutrino sector, like CP violation.

It is general consensus that baryon asymmetry is the result of only one extra matter particle per billion matter-anti-matter particle pairs imbalance in the production or survival-rate of matter over anti-matter particles in the early stage of the development of the universe.

The apparent asymmetry of matter and anti-matter is one of the most challenging problems in physics. Whether regions made entirely out of anti-matter exist is unknown. From our present knowledge it's very unlikely since annihilation radiation that should be emitted from the boundary between matter and anti-matter galaxies is not observed.



The components of matter and forces. At present 12 matter particles are known, 6 quarks and 6 leptons. The Higgs particle is responsible for mass of elementary particles. The particles at one "level" are also subject to the forces from the levels below.


Фундаментальные частицы вещества
Лептоны
e^- μ^- τ^-
ν_e ν_μ ν_τ
Кварки
u c t
d s b
Калибровочные бозоны
γ, W^+ W^- Z, 8g

Standard Model

Fundamental particles of Standard Model are 6 leptons (e^-, μ^-, $\tau^-, \nu_e, \nu_\mu, \nu_\tau$) and 6 quarks (u, d, c, s, t, b). Each from 6 types of quarks can be in three color states (for example, red, green, blue). Quarks and leptons are fermions and have spin 1/2. 12 fundamental fermions correspond 12 fundamental antifermions.

Fundamental fermions interact by means of exchange of interaction carriers - fundamental (or gauge) bosons.

Interaction of particles, having electric charge, happens by means of exchange of quants of electromagnetic field - photons or γ-quants. Photon is electrically neutral.

Strong interaction realizes by means of exchange of gluons g - electrically neutral massless carriers of strong interaction. Gluons carry color charge.

In weak interaction participate all leptons and all quarks. Carriers of weak interaction are massive W- and Z-bosons. Positive W^+-bosons and negative W^--bosons are mutual antiparticles. Z-boson is electrically neutral.

Gravitational interaction does not enter in Standard Model.

Gravitational interaction force has shape:

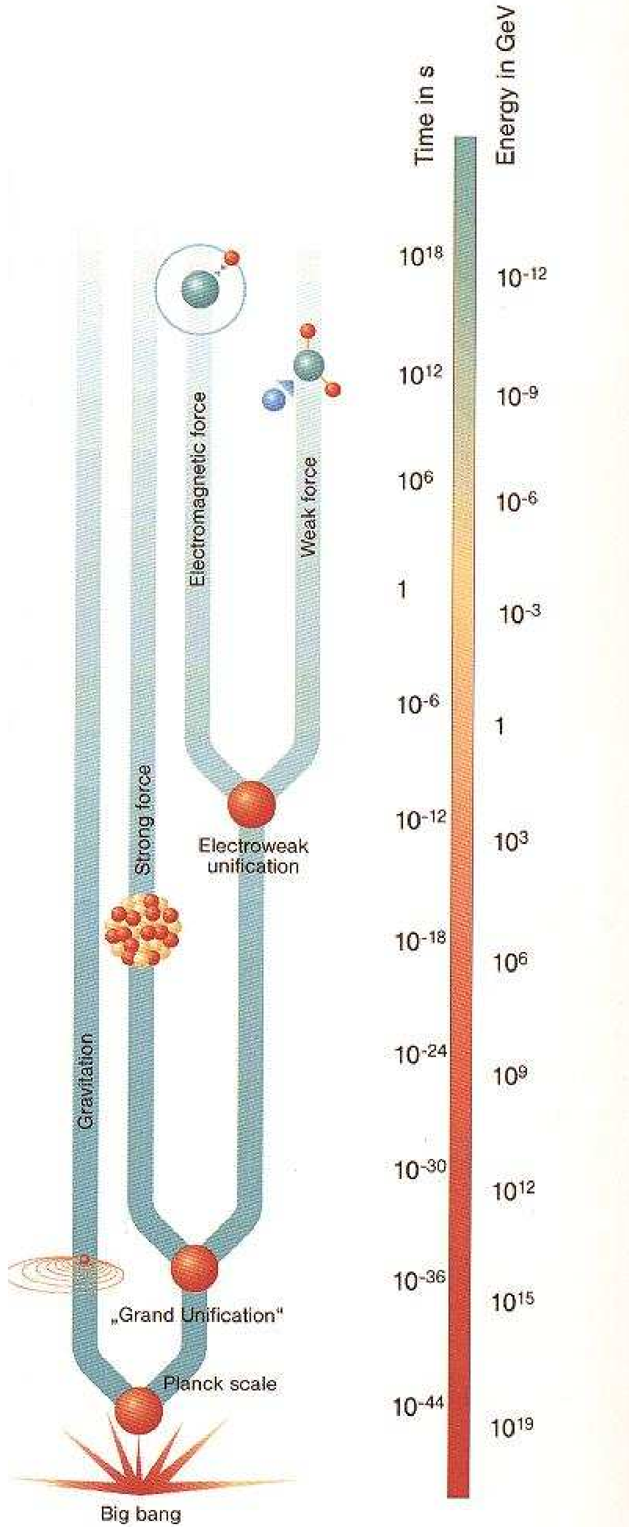
$$F = G\frac{m_1 m_2}{r^2},$$

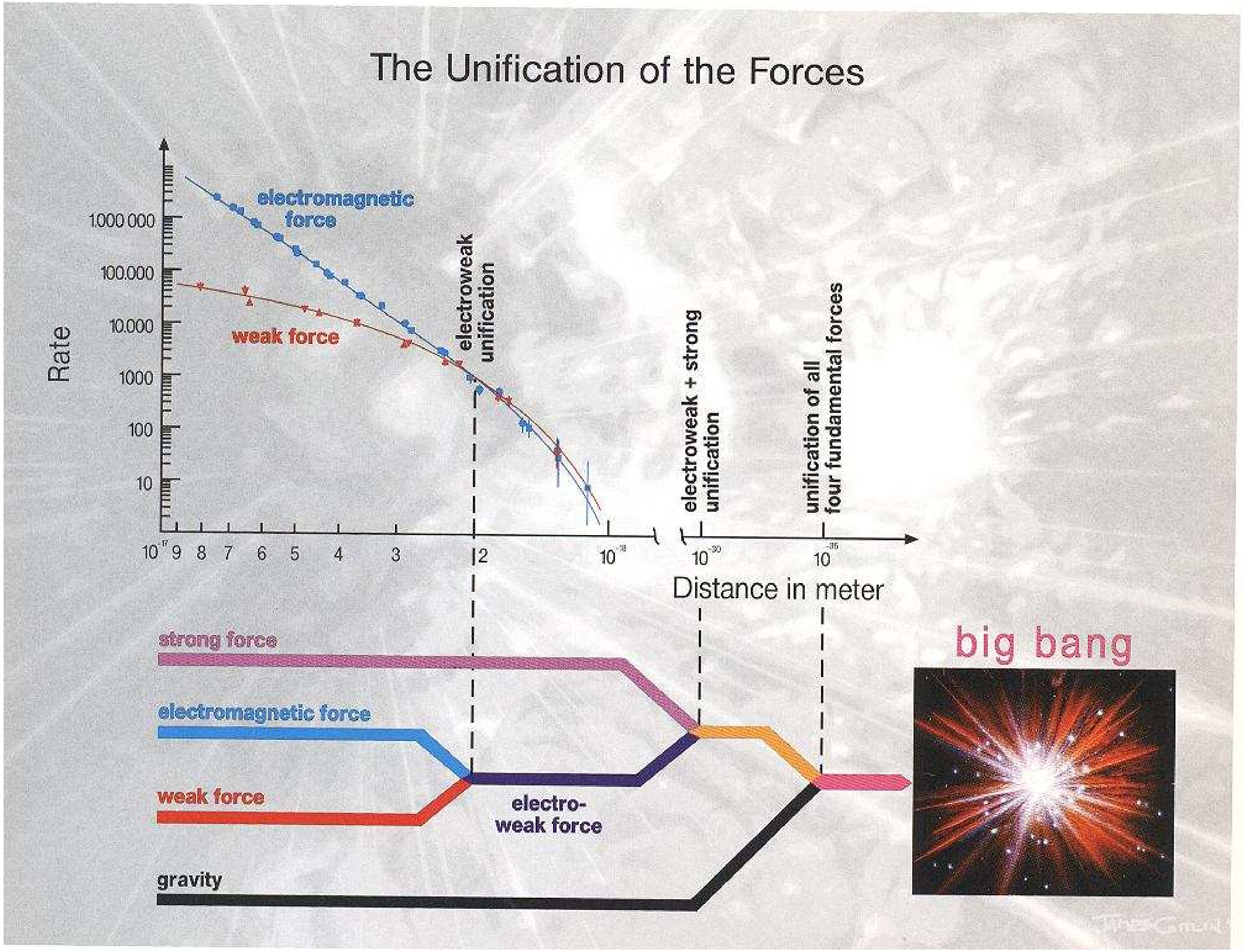
$G = 6.67 \cdot 10^{-11} m^3 kg^{-1} c^{-2}$**. In gravitational interaction participate all particles. Gravitational interaction carrier is graviton, massless particle with spin** $J = 2$**.**

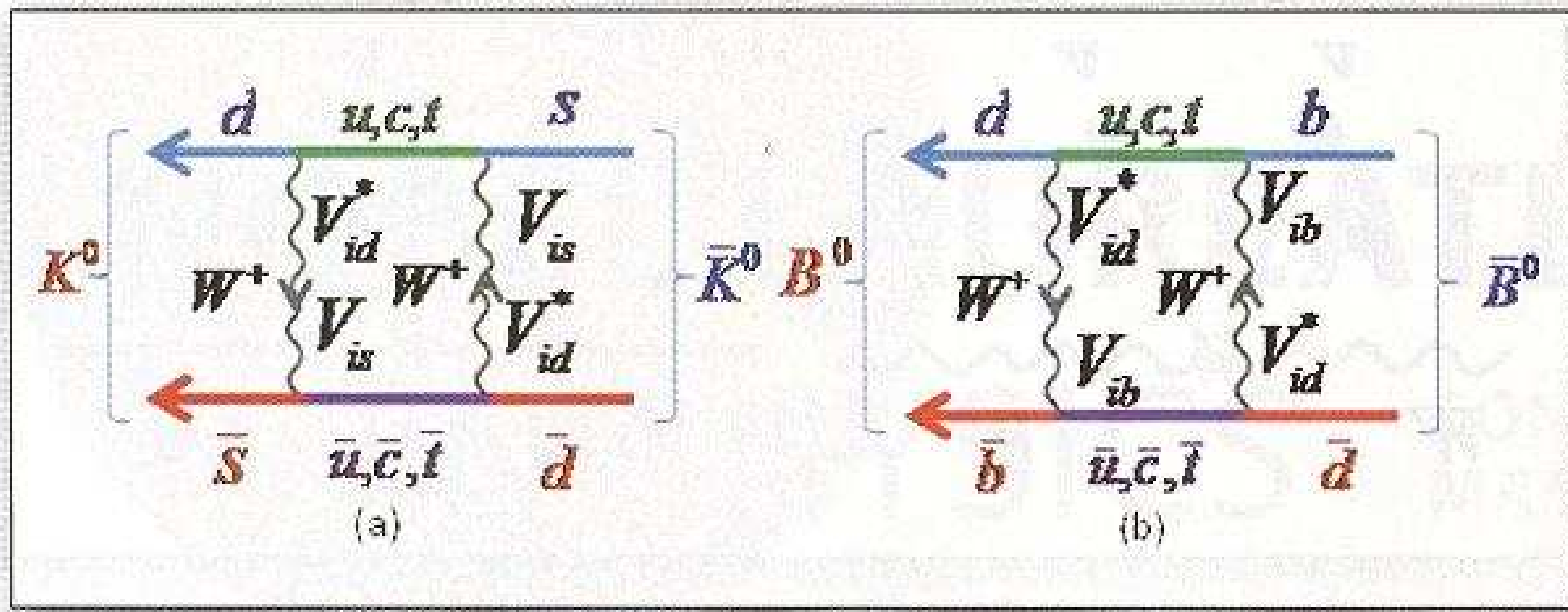
Comparison of gravitational and electromagnetic interactions of two protons being on distance $\sim 10^{-13}$ **cm leads to the ratio:**

$$\frac{F_{grav}}{F_{el.magn}} \sim 10^{-36}.$$

Gauge Bosons				
Interaction	**Characteristic coupling constant of interaction**	**Quants (gauge bosons)**	**Mass of quanta (GeV)**	**Character. scales (cm)**
Strong	**1**	**g(gluon)**	**0**	$\sim 10^{-13}$
El.-mag.	10^{-2}	γ	$< 2 \cdot 10^{-16}$	∞
Weak	10^{-6}	W^-, W^+ **Z**	**80.39** **91.19**	10^{-16}
Gravitation	10^{-38}	**graviton**	**0**	∞


Time in s
Energy in GeV
10^18
10^-12
10^12
10^-9
10^6
10^-6
1
10^-3
10^-6
1
10^-12
10^3
10^-18
10^6
10^-24
10^9
10^-30
10^12
10^-36
10^15
10^-44
10^19
Electromagnetic force
Weak force
Strong force
Electroweak unification
Gravitation
„Grand Unification"
Planck scale
Big bang


The Unification of the Forces
Rate
1.000 000
100.000
10.000
1000
100
10
electromagnetic force
weak force
electroweak unification
electroweak + strong unification
unification of all four fundamental forces
Distance in meter
strong force
electromagnetic force
weak force
gravity
electro-weak force
big bang



A diagrams responsible for CP violation in K and B decays.

K^0 **meson can transform into** $\bar{K}^0$ **through any combination of (**u, c, t**), and (**$\bar{u}, \bar{c}, \bar{t}$**). Amplitude which contains** t **or** $\bar{t}$ **quark is proportional to** $V_{ts}V_{td}^*$ **which is complex, i.e. it will cause CP violation. Diagram for** $B^0 - \bar{B}^0$ **if replace** s **quark with** b **quark. CP violation in** B^0 **decay because** $V_{tb}V_{td}^*$ **has a phase.**

$\sim$ **100% CP violation in** B **decays, and only 0.2% for** K **decays.**