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Neutrino Geology

1983: A.K. Drukier (AKD), L. Stodolsky - patent

1984: L. Krauss, S. Glashow , D. Schram - paper

2013- AKD *et al*, Nano-explosive detector

2014: AKD, series of patents

Challenges

It is a very difficult project. New application request new detectors, Interdisciplinarity will not make it easier.

1) Spatial resolution requirements => emission tomography => mobile detector => 1-10 ton coherent scattering detector;
2) Classical sources of background ;
3) Solar neutrino background 10^{10} neutrino/(cm^{2}xsec); Geo-neutrinos using average 10^{8} neutrino/cm^{2}xsec).
4) Need to understand geology, *i.e.* correlations between K, Th, U and economically important minerals.

We did necessary analysis. On paper it works.

Que sera, sera.

Two Stories –
New Neutrino Geology + New Detectors

1) GEOLOGY

Presence of K^{40}, Th^{232}, U^{235}, U^{238} => geo-neutrinos;

U, Th have very high dynamic range in upper crust;

K, Th, U strongly correlates with other “high economic value” minerals;

High U => presence of petroleum/gas in black shales;

High U, Th => IOCG deposits;

High U, Th => 15 different types of deposits.

To be useful neutrino geology must have spatial resolution of about 1 km ;

Emission tomography of Earth is possible only with mobile neutrino detectors based on coherent scattering .

Current Neutrino Detectors

Current neutrino detectors are huge (millions kg) *ergo* can not be moved ;

Coherent scattering => factor 10,000 improvement but:

- NaI detectors have too high E_{th} and too low mass;
- Cryogenic bolometers are too low mass, require dilution
- refrigerators and have slightly too high E_{th} ;
- Liquid Xe-detectors are difficult to move and have too high E_{th}.

=> Need for new classe(s) of detectors

The nano-explosive detectors

AKD *et al.* - 2013 and 2014.

1) *C_v= 10^{-5} keV/(nm^{3}xK) => C_v (grain) << 1 eV ;*
2) *1 keV will flip a grain , but single grain is not detectable;*
3) *If the grain is made from explosive, it acts as chemical amplifier; ca. 2 Mev per grain is released;*
4) *Nano-grains are sensitive only for dE/dx > 100 eV/nm, i.e. only to nuclear recoil;*
5) *Background is rejected because single charged particles energy deposition < 0.1 eV per grain;*
6) *One can achieve the directionality;*
7) *Read-out is simple.*

"Post-Industrial" reality

- What? How? WHY?
- Industry of mining (including petroleum/gas) are 15-25% of BNP;
- Between 20 largest corporations world-wide are 9 mining Companies.
- Two types of minerals:

- commodities (Al, Fe, Cu, Zn etc) (> 100 ppm in crust);

- *present at very low abundance (REE, PtGE, Au, some other):*

Two types of mining operations:

- classical: very high abundance, one mineral only, deep, high cost , marginal profitability.

- modern : open pit; lower abundance but polymetals, low cost, very profitable.

"Laws of diminished return".

TOWARDS PENURIES

1) Peak of minerals discovery:

1960 - Europe

1970 - US

1980 - Canada, Australia, Soviet Union

1990 - Asia (!!!China!!!), South America

2000 – Africa

1) Total for world – *ca.* 1985; now about two-fold below the peak.

2) Consumption : 2-3 times higher today than in 1980

Que Vadis Geology

Increased importance of geophysical methods (seismography, magnetic, gravity)

Increased cost of drilling (manpower, “crazy” and “politically unstable” places, under the water)

General timing:

Understanding the “territory” geology (10-20 years);
Exploration geology (5-10 years);
Discovery confirmation and evaluation (5-10 years);
Resources development (5-10 years)

- ***Cost scale : 1 : 2: 4 : 6***

MINING and RESERVES DEPLATION

Initial mining - 1-5 Years
Best Years – 6-15 Years
Economic Deplation -15-20 years
Physical Deplation - 20-30 years

Attention : in 20-30% the mine life-time may be extended by discovery of another reserves close (5-10 km) to initial mining zone.

Conclusion :

Process of discovery and building mine takes longer than " development and coming under production ".

Geology of K, Th, U

There are large, *ca.* 100 yrs of use, known reserves of K.

At current needs of atomic energy, the known reserves of U and Th are significant, *ca*. 50 yrs.

At 75% fraction of electricity from atom (France) worldwide reserves are < 20 yrs.

K^{40} – 1 beta , E_{max} = 1.4 MeV

Th^{232}- 4 beta, 2 have E_{max} > 3 MeV

U^{235}- 5 beta, 3 have E_{max} > 3 MeV, U^{238}- 5 beta, 3 have E_{max} > 3 MeV

Geology of K, Th, U

Th and U are moving up
Th and U range is 6 logs in upper crust
Th and U are localized- gradient may be a few ppm / m

Example of U: **Upper crest => X(U) = 5 ppm**
Lower crust =>X(U) = 2 ppm
Mantle => X(U)= 0.5 ppm
Core =>X(U)= 0.05 ppm

How many ???	5- 10 %	> 10^2
	1- 5%	> 10^3
	0.1- 1 %	> 10^4
	0.01%- 0.1%	> 10^5

Geology of K, Th, U

Table : The grade of U_3O_8 in eight Canadian U-mines.

Site	Method	Reserve(T)	Grade (%)	XX
Cigar Lake	UG	234	22.3	34,400
Mc Arthur River	UG	465	21.4	33,000
Kay Lake	OP	67.5	0.5	771
Rabbit Lake	OP	43	0.29	447
Crow Butte	ISR	928	0.11	169
Smith Ranch	ISR	1,100	0.10	154
North Butte	ISR	925.	0.09	139
Inkai	ISR	1,947	0.08	123

wherein XX = Abundance (deposit)/Abundance (crust).

UG = Underground mining, depth > 500 m
OP = Open pit; depth 100-500 m
ISR = in situ recovery, depth 10-50 m.

Th and U correlates with important minerals

There are about 5,000 distinguishable geologic structures (GS) on landmasses.

There are 25 GS which produce >80% of minerals mined.

A IOCG discovered only 30 yrs ago, accounts for 10 % of value of minerals mined

Almost all these 25 GS have high abundance of U/Th:

- *10 have 100 X(U) > abundance > 50 X(U)*
- *5 have 50 X(U) > abundance > 10 X(U)*

  3 have 10 X(U) > abundance > 5 X(U)

Only two types of bauxite deposits have abundance lower than X(U)

Oil/Gas Exploration*

Two types of hydrocarbons deposits; classical and in Black Shales.

– **Classical deposits:**

Extremely low level of U/Th ca. 1 ppb;
Very good contrast (1 ppb vs. 5 ppm)
Good example of "cold spot" emission tomography
=> requires S/B > 10
Both "count rate" and especially S/B challenges
=> 2nd Generation NG

– ** analyzed by AKD and L. Stodolsky in 1983/84*

Oil/Gas in Black Shales

Geological Mechanism for Black Shales deposits:

Oil/Gas present if Total Organic Carbon (TOC) is high (> 4 %);
For TOC > 3% , a spongy layer of bitumate is created;
Uranium and Thorium from magmatic activity drifts up;
It is stopped in spongy layer in Black Shales.

=>

High level of U and Th ca. 100- 500 ppm;
Great contrast (100-500 ppm vs. 5 ppm);
Good example of "hot spot" emission tomography => S/B = O(1)
May be shallow – at 300-500 m depth.

"Count rate" and S/B compatible with 1st Generation NG

Oil/Gas in Black Shales

Properties of some gas black shales (all in feet)

Site	Barnett	Ohio	Antrium	N. Albany
Depth	6,800-8,500	2,000-3,000	500-2,000	500-2,000
Thickness	200-300	30-100	70-120	50-100
TOC(%)	4.5	0-7.5	1.0-20.0	1.0-25.0
Porosity (%)	4.0-5.0	4.7	9,0	10.-14
Gas (%)	2.5	2.0	4.0	5.0

Attention : Black shales in Europe tend to be deeper than in US

Oil/Gas in Black Shales

Uranium in six Canadian tar sands

Site	1	2	3	4	5	6
U(ppm)	88.8	9.420	30.5	331	62,800	809
XX	33	3,500	11.3	122	23,200	300

Attention : in Canada average U= 2.5 ppm

Correlation between U (ppm) and TOC(%) in US black shales

U(ppm)	N_{total}	min [TOC]	max[TOC]	<TOC>
[200,600]	7	2.0%	7.5%	4.6%
[50,200]	20	0.3%	6.2%	2.3%
[25,50]	8	0.2%	2.5%	1.1%
< 25%	37	0.0%	1.5%	0.5%

Oil/Gas in Black Shales

The probability of "hydrogens"hit for different U(ppm) (USA)

U(ppm)	N_{total}	P(>2%)	P(>3%)	P(>4%)
[200,600]	7	100%	86%	57%
[50,200]	20	65%	30%	10%
[25,50]	8	12.5%	0%	0%
< 25%	37	2.7%	0%	0%

Strategy : Seismography tells where are shales (50 km x 50 km)

Neutrino Geology tells where are "true black"shales, say TOC > 3% (say 2 km x 2km).

This improves "hit rate" about 5 to 10 fold .

Iron Oxide, Cooper, Gold (IOCG) deposits

New type of deposits discovered only 30 yrs ago, because they are "invisible " in seismic maps.

Initially discovered in Australia by plane-borne gravity and magnetic surveys. Shows overlapping peaks of increased gravity and small change in magnetization. Needed very extensive drilling compagne to confirm/outline deposits.

In last two decades, many already known deposits were reclassified as IOCG, *e.g.* Kiruna, Magnitogorsk and Bayan-obo.

Australian Olympic Damn is 2 largest value mine in world and 4^{th} largest Uranium mine .

Today accounts for about 10% of all minerals mined. In 2030 expected to account for 20-25% of all minerals production (excluding hydrocarbons).

Iron Oxide, Cooper, Gold (IOCG) deposits

There are known 24 major IOCG Terranes (exc. Russia):
S. America = 7, Australia = 5, USA =4; Canada = 3,
Scandinavia =1, S. Africa = 1, Asia = 1, S. Africa = 1

The IOCG deposits are found in extensive domains. Peru/Chile Cordilliera belt extends about 2,500 km and features about 50 major deposits of which the largest and most important are seven IOCG deposits.

The Candelaria deposit is in a 5 km x 20 km mineralization domain. In both Candalaria and Las Tazas complexes, the monozites are present which accounts to high LREE, Th and U levels.

To establish the characteristics of IOCG deposits one needs large number of drill sites. In Estrellito deposit one drilled about 100 sites, each hole about 1 mln dollars.

Iron Oxide, Cooper, Gold (IOCG) deposits

Almost all Australian - IOCG and about 50% of all IOCG worldwide are very high in uranium. Actually, they are between largest Uranium mines

Uranium in some Australian IOCG

Name	*Size (Mt)*	*Cu(%)*	*Au(ppm)*	*U(ppm)*
Olympic Dam	*3810*	*1.1*	*0.5*	*337*
Mt. Elliot	275	0.6	1.8	> 100
Ernest Henry	167	1.1	0.5	>100
Carrapantera	100 ?	??	??	227

Monakoff 1
? 1.5 0.5 224

Iron Oxide, Cooper, Gold (IOCG) deposits

Almost all S. American IOCG are high in U and also contain large amounts of LREE, ergo high Th.

Uranium in some S. American IOCG

Name	*Size (Mt)*	*Cu(%)*	*Au(ppm)*	*U(ppm)*
Salabo, Brazil	*789*	*0.96*	*0.52*	*> 100*
Cristalino, Brazil	500	1.0	0.3	high Th
Candelaria, Chili	470	0.95	0.22	high Th
Igarape, Brazil	170	1.5	0.8	>100

Iron Oxide, Cooper, Gold (IOCG) deposits

Other IOCG are not as well described, but most of them have high U and some contain largest amounts of LREE, ergo high Th.

Uranium in some other IOCG

Name	***Size (Mt)***	***Cu(%)***	***Au(ppm)***	***U(ppm)***	***Th(ppm0***
Palaborwa, S. Africa	***850***	***0.5***	***high***	***> 100***	***>100***
Bayan Obu, Chinal	**200 ?**	**??**	**??**	**??**	**> 500**
Sue Diane, Canada	**17**	**0.72**	**??**	**> 100**	**> 100**
Rautuvaara, Finland	**4**	**1.5**	**2.6**	**> 100**	**> 100**
Tjarajaka, Swedenl	**3.2**	**0.9**	**??**	**>100**	**>100**

Because they are invisible in seismic data, IOCG are strongly under-rapported world-wide. New Geology will change it.

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The nano-explosive detectors

Read-out options

Almost 100% energy in kinetic energy of hot gas ;

15-20% of energy in shock waves => sonic boums;

1-5% of energy in optical photons.

Efficient detection of hot gas is difficult in large volumes

=> select the second best and look for sonic - boom ;

Microphones are not single phonon devices wherein QDE of light sensors close to 100%

=> accoustic and light detection may be of similar sensitivity

Magnetic Read-out Option

How much energy available:

1) From neutrino scatter 0.1-1 keV;

2) Chemical energy in a R= 5 nm grain is about 2 MeV;

3) Energy in 1 micron micro-ball = 100 TeV;

4) Energy available in 1 mm^3 = 10^8 TeV

We had been wrong: energy of hot gas is easy to detect. It is called a gun. In well designed a gun, bullet takes up to 90% of energy of gas. We implemented the system with magnetic bullets; small Nd magnets.

Progress in last month:

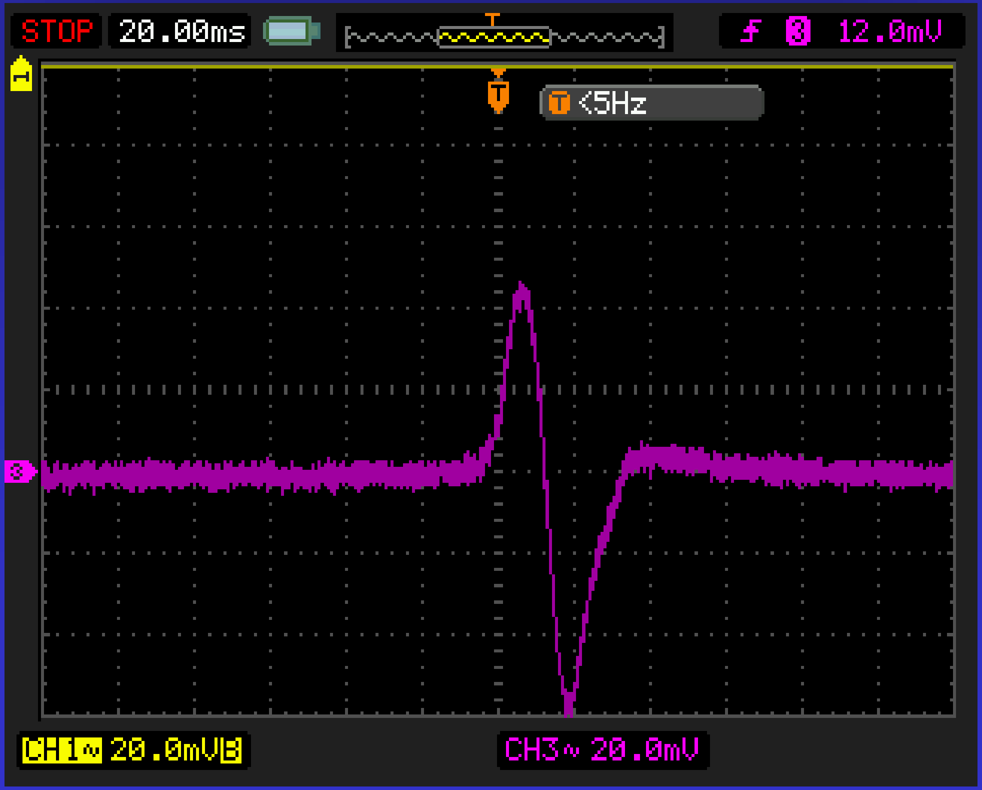
Rods : (R= 2 mm, l= 10 mm) => (R=1.5 mm, l = 8 mm);

Spheres; (R=2.5 mm) => (R = 1.5 mm) => (R= 1 mm)

Magnetic Read-out Option

Magnetic-bullet = Nd-magnet ball (R= 1.5 mm)

;

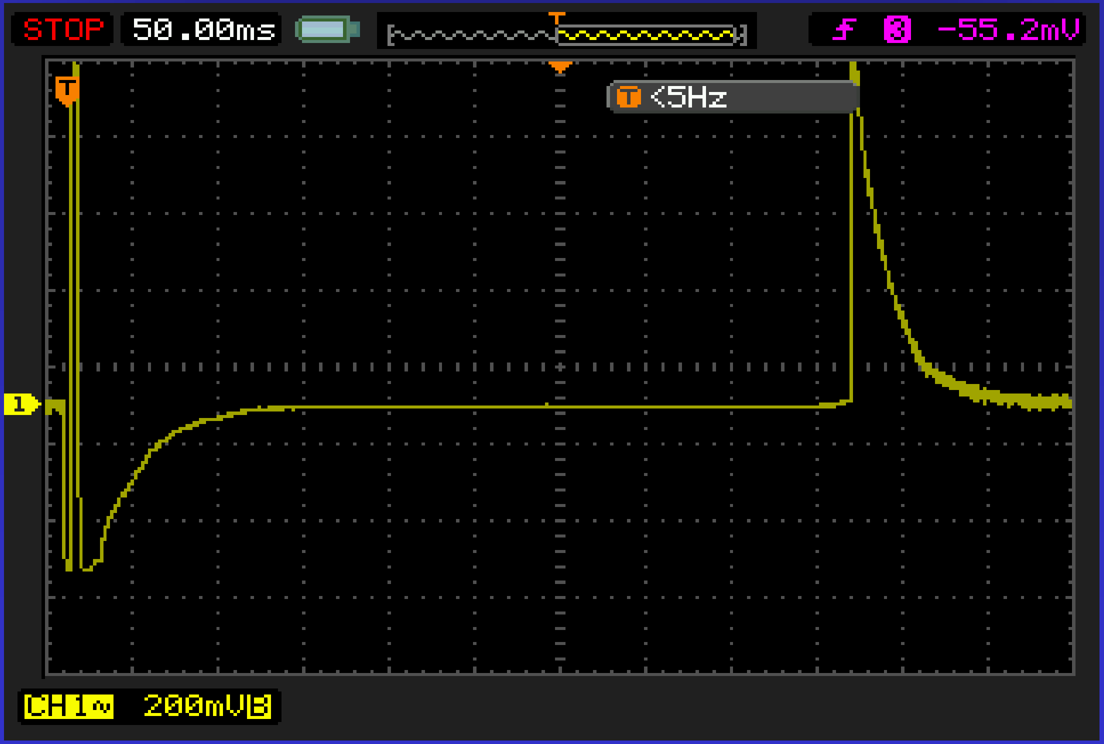


Magnetic Read-out Option

Can recognize small from very small magnets;

Can recognize shape of the magnets (rods vs. spheres)

Can estimate "magnetic bullet" velocity



Magnetic Read-out Option

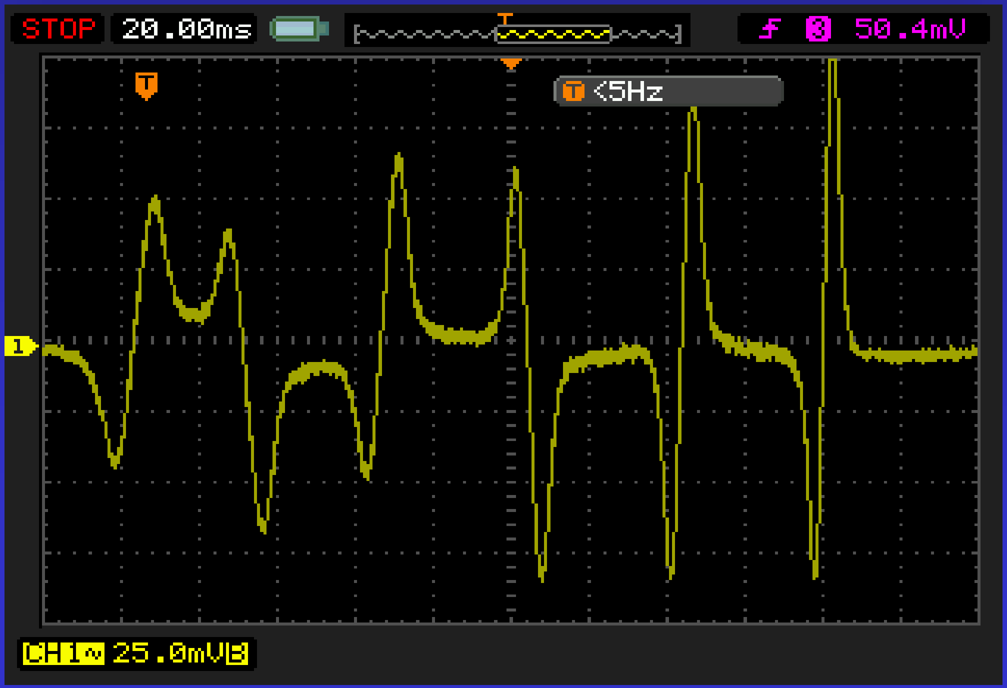
Possibility of magnetic bar-coding. Three parameters :

1) amplitude of peaks;

2) shape of peaks;

3) distance of peaks.

For 4 magnets bar-code, may encode up to 128 distinctive combinations .



Magnetic Read-out + Bar-coding

Optimization of different magnetic sensors:

a) Pick-up loops (simplest, reasonably quantitative, hand-made), ;

b) Reed-relays (lowest cost, senses and encodes up to 128 elements);

c) Hall effect sensors (most sensitive but fragile).

The different bar-coding schemes:

1) *magnetic (128-256 settings);*
2) *multicolor magnets (15 colors, 5 magnets*

   => $15^5 = 7.59 \times 10^5$ settings;
3) *optical QR bar-codes;*
4) *DNA bar codes.*

Optical bar-codes – miniaturized, placed on front face of magnetic bullet.

DNA bar-codes must be placed on "conjugated" Au coated magnetic needles outside of confiment.

Magnetic Read-out + Bar-Coding

Typical detector :

(x-y) plane = > 256 x256 pixels using efficient bar-coding;

z -axis => 512 distinguishable voxels using only 2 channels of electronics.

Total mass: > 1 tonn

Total size = O(1 m^3)

Spatial resolution ca. 1 mm^3

Number of voxels = (256x256)x512 = 3.3 $x10^7$

Cost of electronics parts /channel < \$30;

Total cost of electronics < \$50,000,