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CONFERENCE ON FUNDAMENTAL SYMMETRIES AND FUNDAMENTAL CONSTANTS

15 - 18 September 2004

EXPERIMENTAL CHECK OF THE PAULI EXCLUSION PRINCIPLE - THE VIP EXPERIMENT

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Experimental check of the Pauli exclusion principle: the VIP experiment

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LNF – INFN

for the VIP experiment

Conference on Fundamental Symmetries
and Fundamental Constants
15 - 18 September, ICTP Trieste

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6. *The VIP experiment*
7. *Plan of the measurements*
8. *Instead of Conclusions*

1. From DEAR to VIP….or how everything started

DEAR = DAFNE Exotic Atom Research Experiment at LNF – INFN, Frascati 1996 - 2002

The scientific aim of DEAR

the determination of the ***isospin dependent*** $\bar{K}N$ ***scattering lengths*** through a

~ eV measurement of the shift

and a

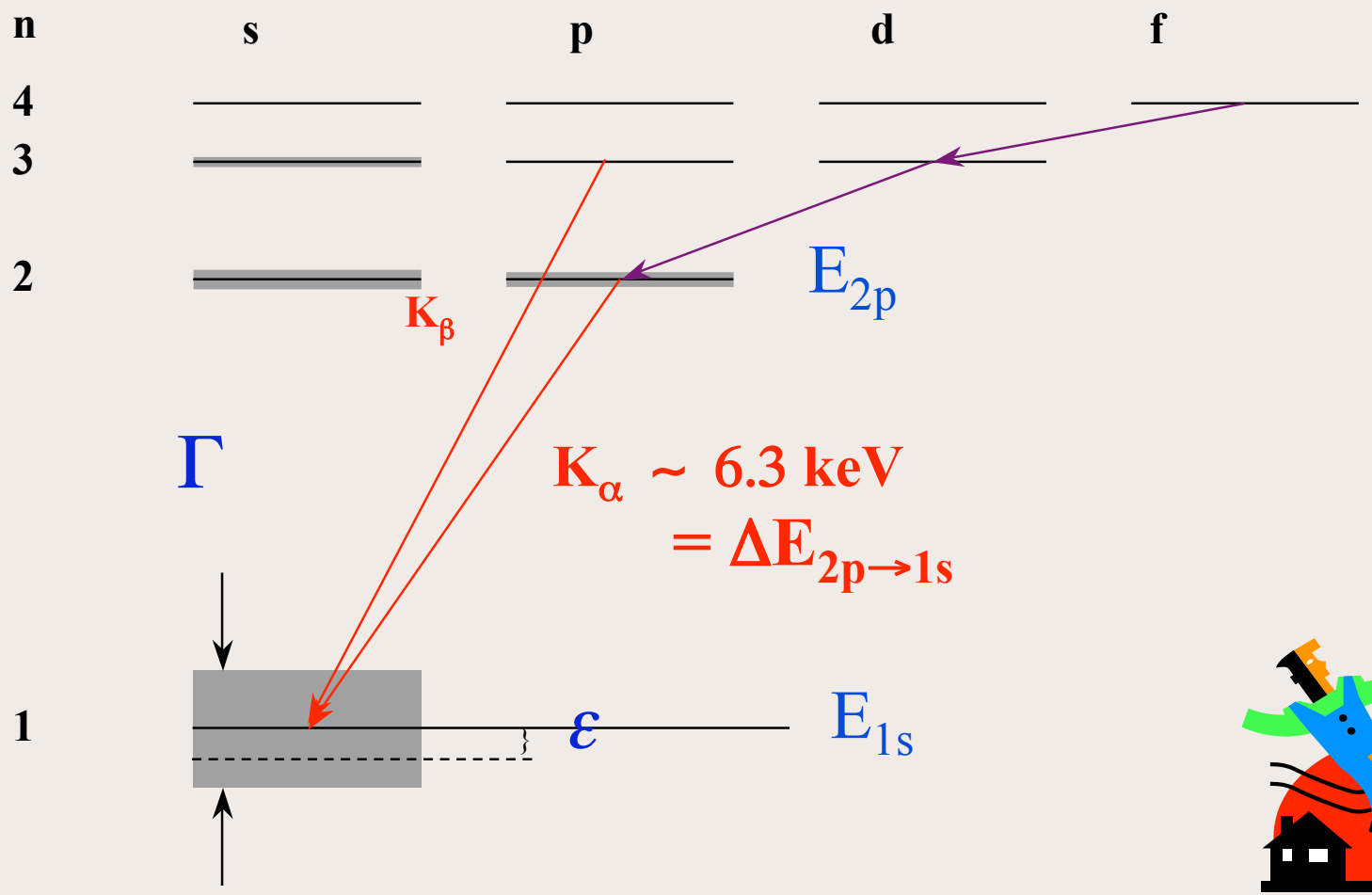
few percent measurement of the width

of the K_α line of **kaonic hydrogen**

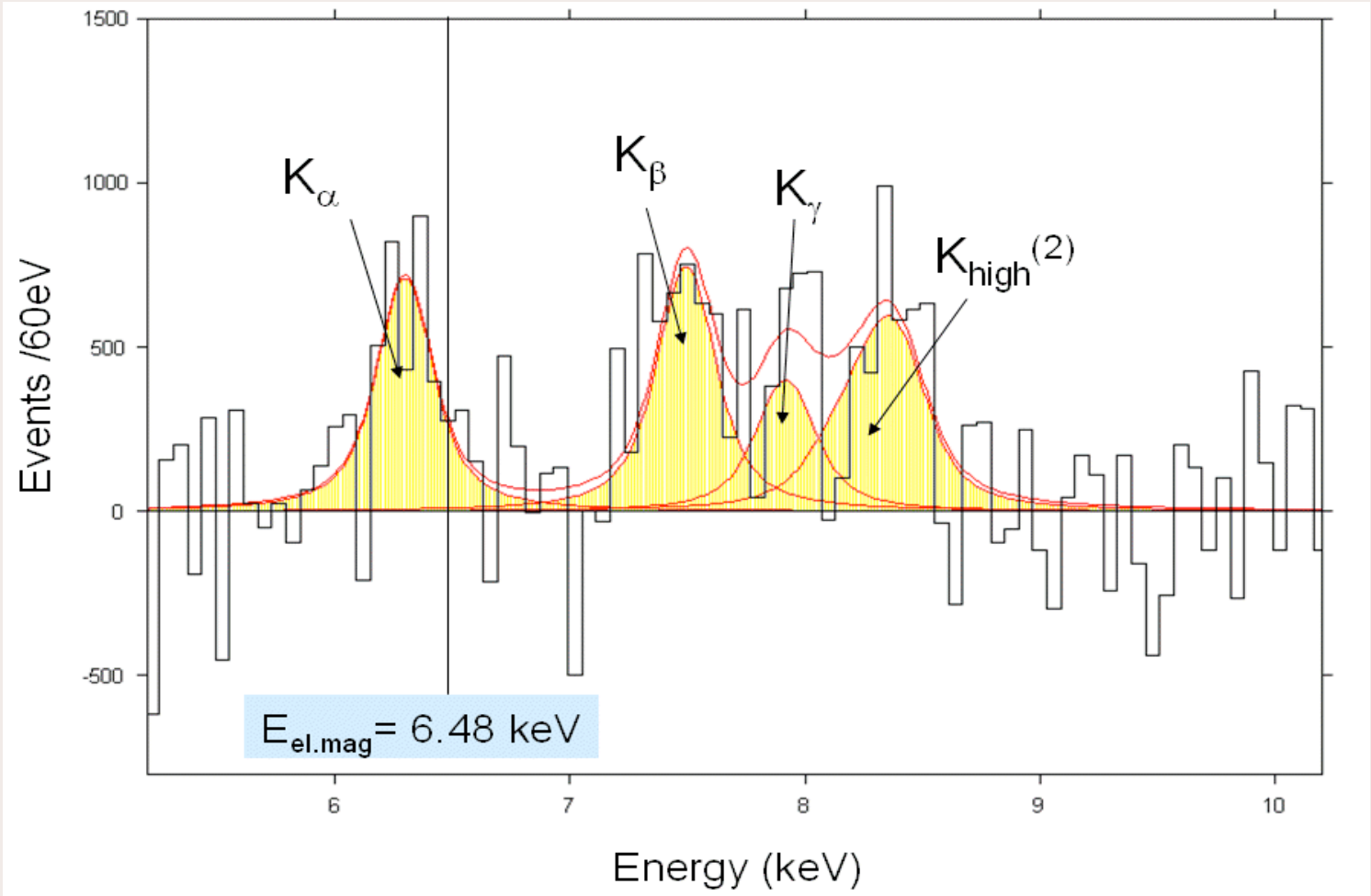
and

the ***first measurement*** of **kaonic deuterium**

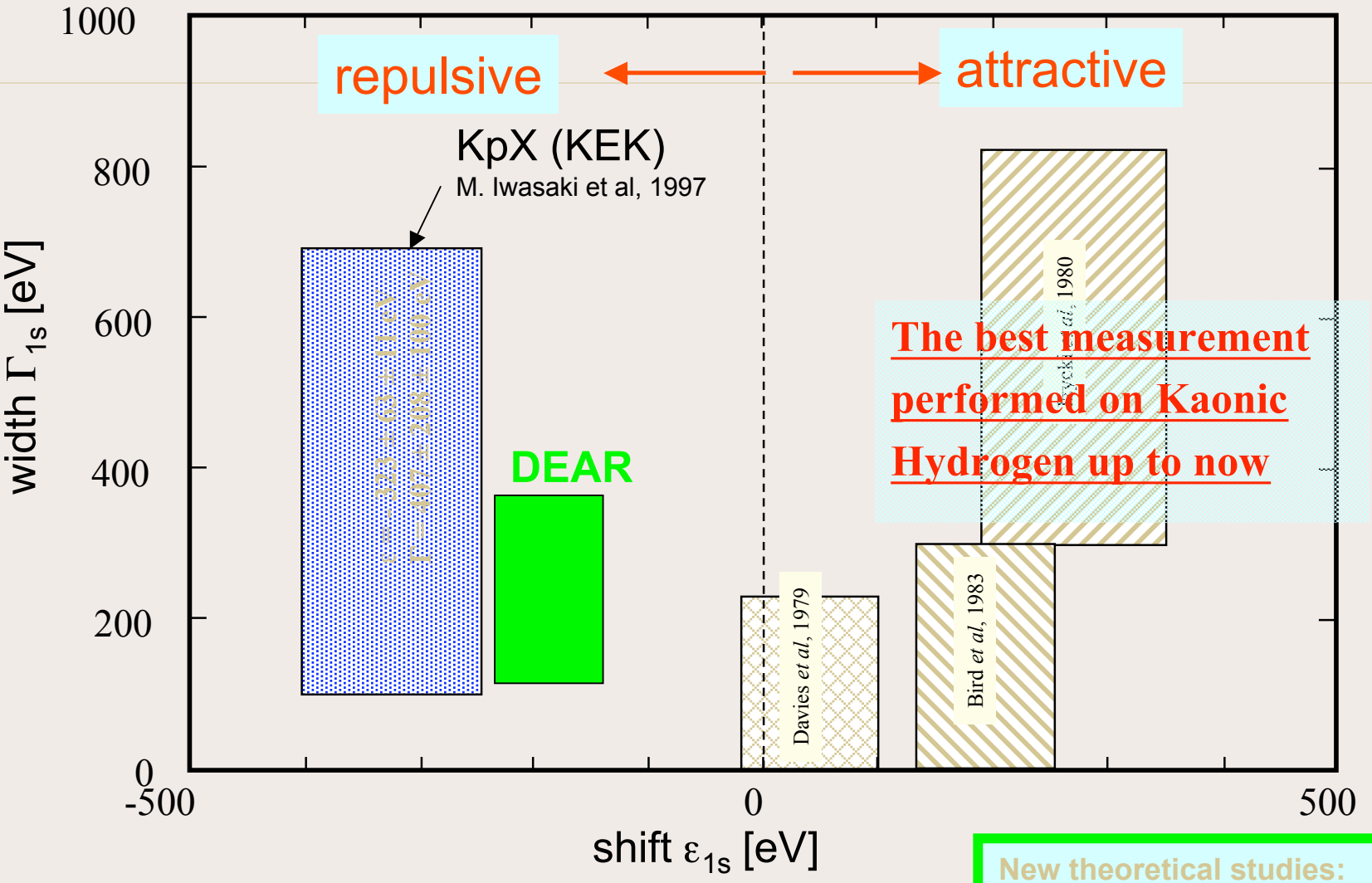
Kaonic cascade and the strong interaction



Resulting K^-p Spectrum (2002)
(all background fit-components subtracted)



DEAR Results on Kaonic Hydrogen

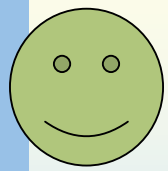


The best measurement performed on Kaonic Hydrogen up to now

New theoretical studies:
Ivanov *et al.* 2003 / 2004
Meißner, Raha, Rusetsky 2004

2003 - DEAR is finished
(->SIDDHARTA continues scientific line)

We are left with an excellent X-ray detector (CCD)



Idea: search around for other types of exotic X-ray transitions, in the region of few keV and rare events:
VIP is getting born!

2. The scientific case

Disclaimer:

By no means complete

Represents more an invitation to this very present community for a future fruitful collaboration!!!

"Class, I've got a lot of material to cover, so to save time I won't be using vowels today. Nw lts bgn, pls trn t pg 122."

The spin-statistics connection

Commutators lead to symmetric wavefunctions and symmetric wavefunctions lead to the Bose-Einstein Statistics

Anticommutators lead to antisymmetric wavefunctions and antisymmetric wavefunctions lead to the Fermi-Dirac statistics

The spin-statistics connection

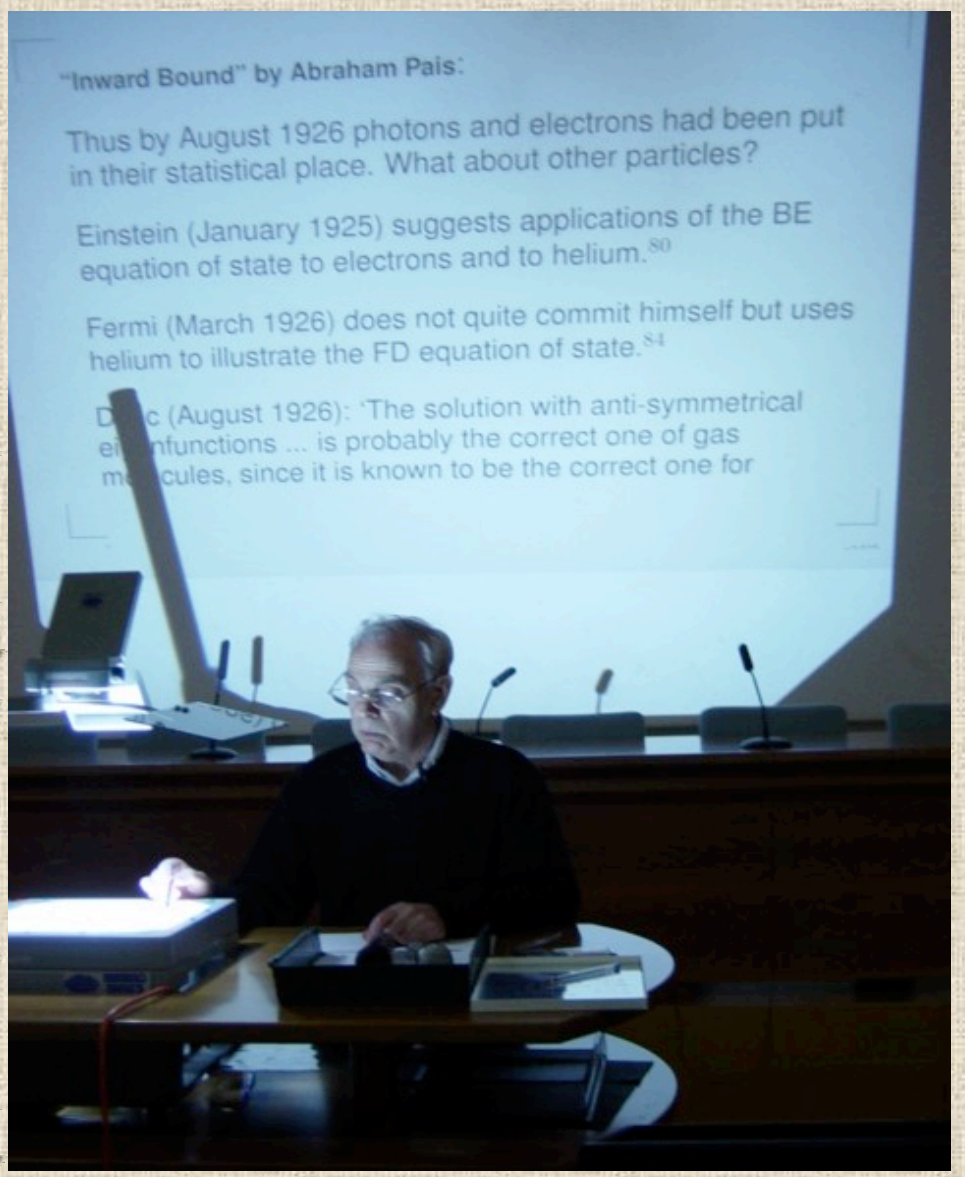
Particles with integer spin obey the Bose-Einstein statistics

Particles with half-integer spin obey the Fermi-Dirac statistics

(W. Pauli, Phys. Rev. **58** (1940) 716)

Consequences of Pauli Exclusion Principle (PEP) and spin-statistics connection

- No two fermions in the same quantum state
- Two or more bosons may share the same quantum state
- Explanation of periodic table of the elements
- Solid state theory (e.g. conduction in metals)
- Degeneracy pressure maintains stability of white dwarfs (electrons) and neutron stars (neutrons)
- ...



14 Maggio 2004 , Frascati

Seminario di

L.B. Okun

ITEP, Moscow,

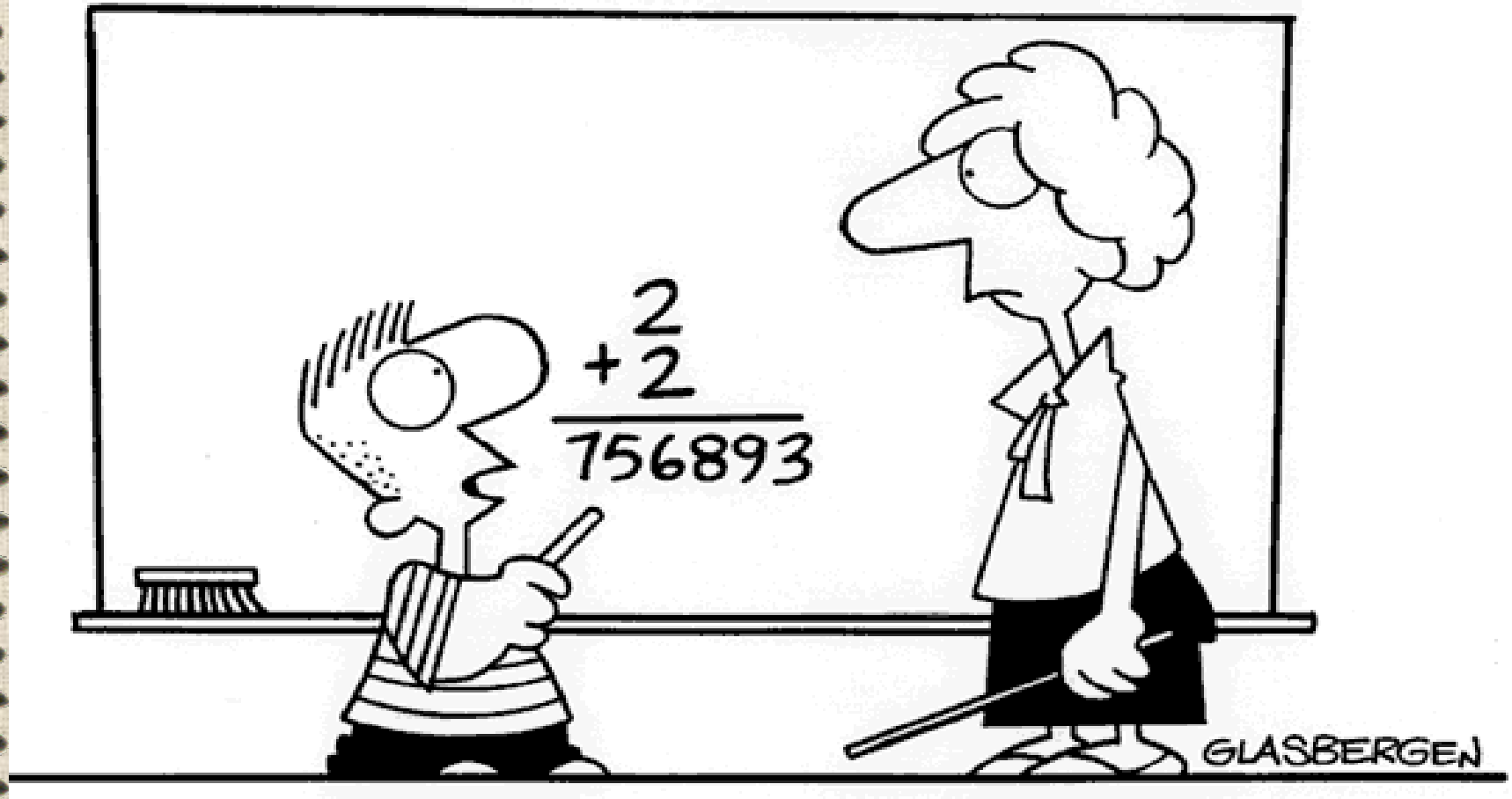
"Testing Pauli Exclusion Principle"

Oh if you knew the way that
poems grow
From bits of rubbish, knowing
no shame
(Anna Akhmatova, "Creation")

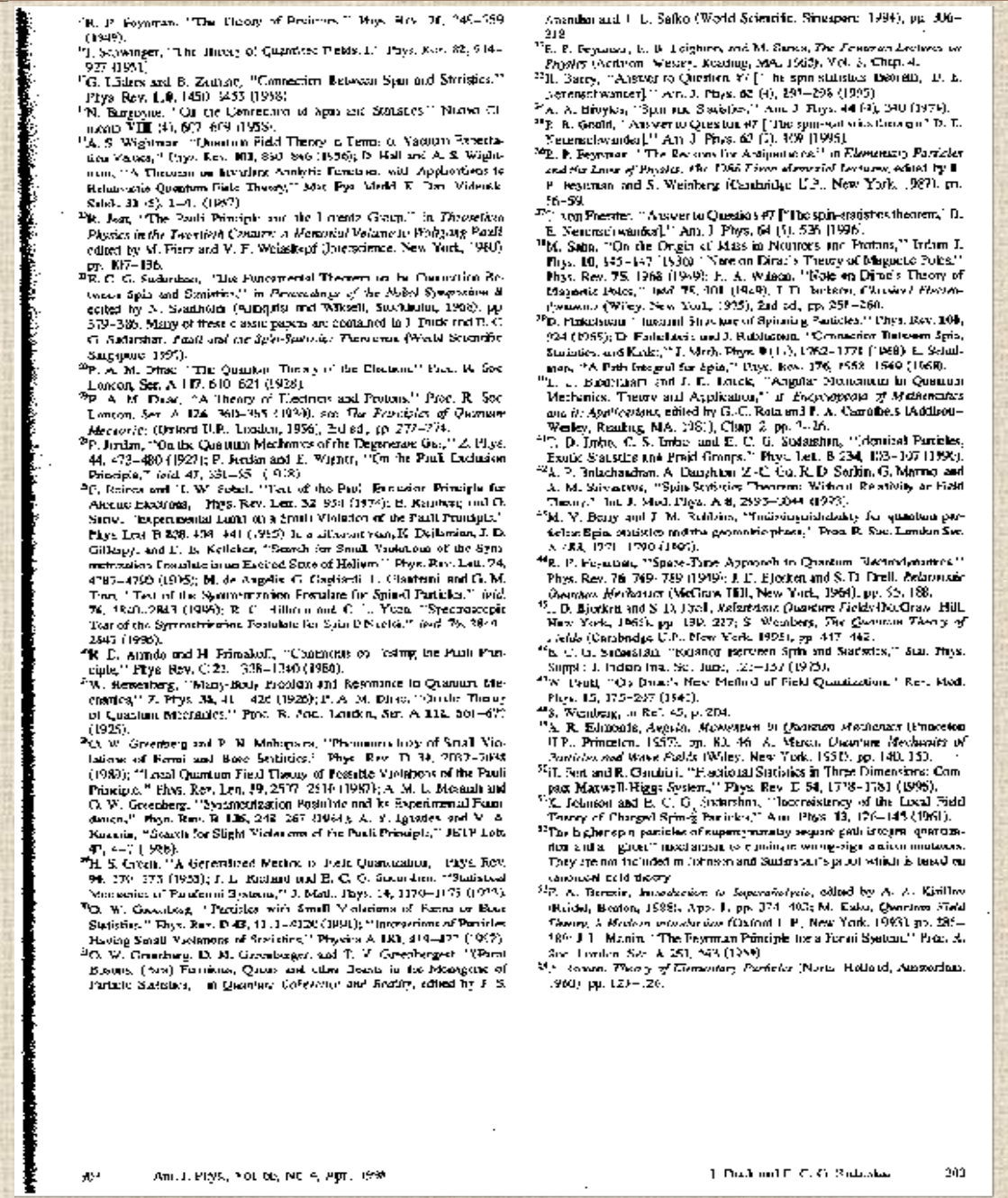
From Lev Okun's slides

Spin-statistics connection for elementary particles

- PEP, Lorentz group and CPT: Luders (1954), Pauli (1955);
- SSC in QFT: Pauli (1940, 1950), Luders and Zumino (1958), Wightman (1956 – 1964), Schwinger (1958 – 1961)
- CPT, commuting bosons, anticommuting fermions have positive energy, antiparticles without Dirac sea. Started with Pauli-Weisskopf 1934;
- Greenberg (2004): Lorentz covariance of vacuum matrix elements of time ordered products of fields implies local commutativity.
- **All these basic symmetries are questioned at present**



"In an increasingly complex world, sometimes old questions require new answers."



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Part of the list of references in

I. Duck and E. C. G. Sudarshan: Towards an understanding of the spin-statistics theorem, Am. J. Phys, 66 (1998) 284.

There are theories which:

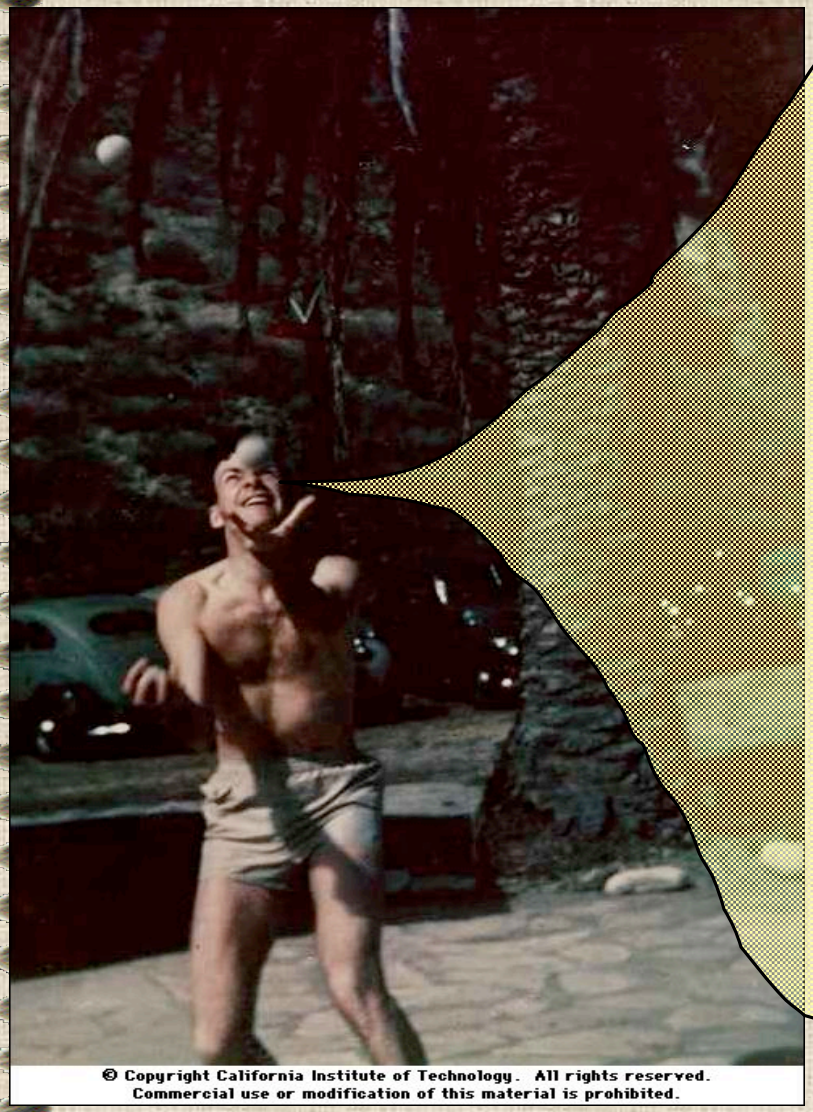
- *Theory: push the limit in the region of 10^{-30} of particular interest: example: the validity of Pauli principle in a higher-dimensional spacetime – small violation in the*

3 +1 dimensional; or strings and superstrings etc. – violation of Pauli principle in this range

"More recently … membrane theorists have been speculating on a large compactification radius for one of their eleven dimensions, which could give a ratio (for PEP violation) of 10^{-30}" [1]

[1] I. Duck and E. C. G. Sudarshan: Towards an understanding of the spin-statistics theorem, Am. J. Phys, 66 (1998) 284.

Feynman Lectures on Physics



This brings up an interesting question: Why is it that particles with half-integral spin are Fermi particles (...) whereas particles with integral spin are Bose particles (...)?
We apologize for the fact that we can not give you an elementary explanation.
An explanation has been worked out by Pauli from complicated arguments from quantum field theory and relativity. He has shown that the two must necessarily go together, but we have not been able to find a way to reproduce his arguments on an elementary level. It appears to be one of the few places in physics where there is a rule which can be stated very simply, but for which no one has found a simple and easy explanation. (...)
This probably means that we do not have a complete understanding of the fundamental principle involved. For the moment, you will just have to take it as one of the rules of the world

3. Experimental check of Pauli principle – focussed on electrons (VIP)

Tests of PEP for nucleons

Search for non-paulian transitions in ^{23}Na and ^{127}I

R. Bernabei [a], P. Belli [a], F. Montecchia [a], M. De Sanctis [b], W. Di Nicolantonio [b], A. Incicchitti [b], D. Prosperi [b], C. Bacci [c], C.J. Dai [d], L.K. Ding [d], H.H. Kuang [d], J.M. Ma [d]

[a] *Dip. di Fisica, Universita' di Roma "Tor Vergata" and INFN, sez. Roma2, I-00133 Rome, Italy*
[b] *Dip. di Fisica, Universita' di Roma "La Sapienza" and INFN, sez. Roma, I-00185 Rome, Italy*
[c] *Dip. di Fisica, Universita' di Roma III and INFN, sez. Roma, I-00185 Rome, Italy*
[d] *IHEP, Chinese Academy, P.O. Box 918/3, Beijing 100039, China*

Physics Letters B 408 (1997) 439–444

NEW EXPERIMENTAL LIMITS ON VIOLATIONS OF THE PAULI EXCLUSION PRINCIPLE OBTAINED WITH THE BOREXINO COUNTING TEST FACILITY.

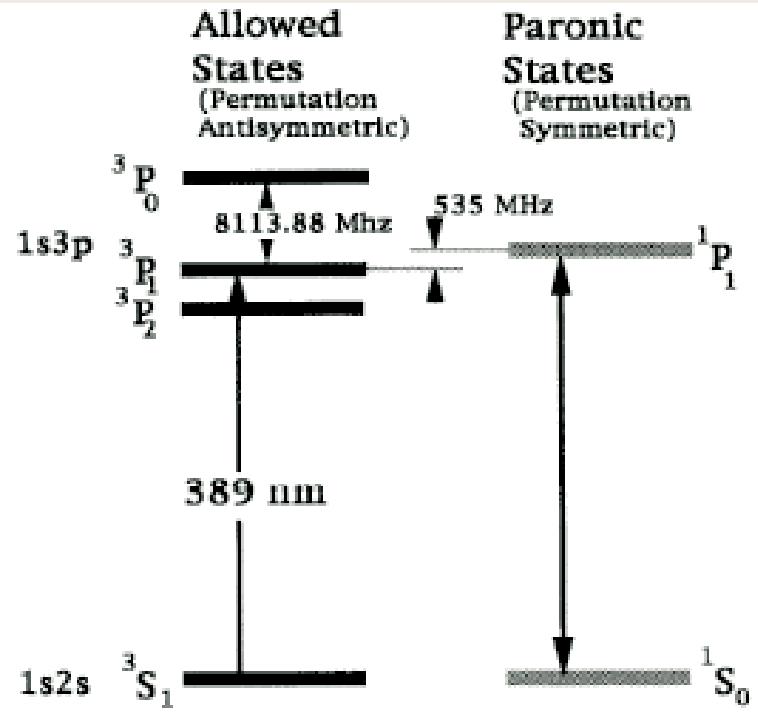
By Borexino Collaboration (H.O. Back *et al.*). Jun 2004. 10pp.
Submitted to Eur.Phys.J.C ;
e-Print Archive: **hep-ph/0406252**

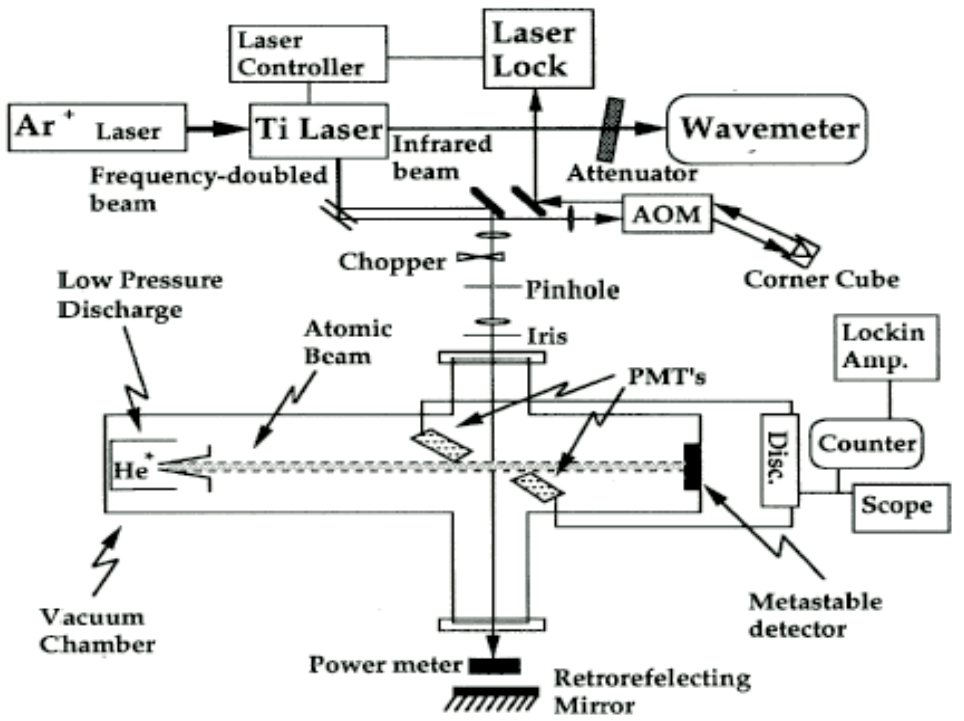
Tests of PEP for electrons

1. Search for non-Paulian atoms, e.g. anomalous Ne or anomalous He (paronic helium)

2. Search for anomalous X-rays (they signal transitions to “anomalous” states)

Search for paronic helium
(Deilamian et al., PRL **74** (1995) 4787
calculation in Drake, PRA **39** (1989) 897)

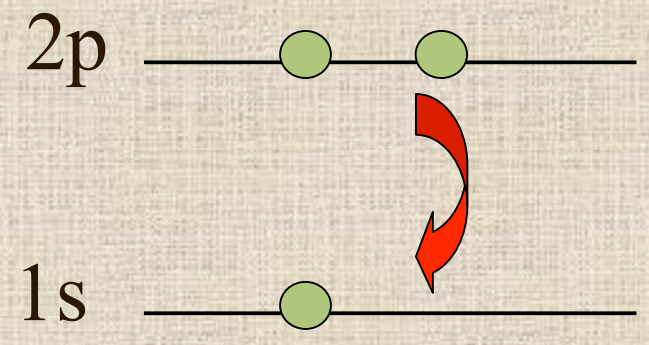




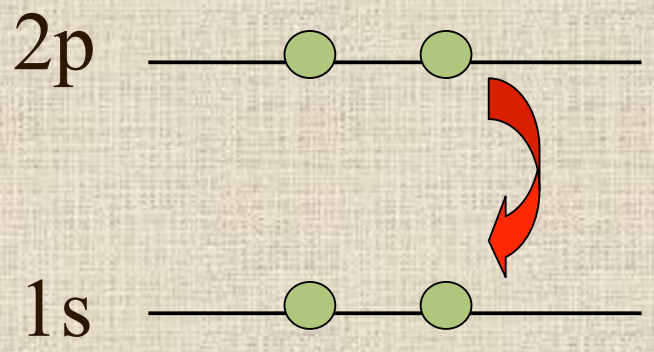
DEAR experience:

CCDs = excellent detectors for X rays

Search for anomalous X-rays

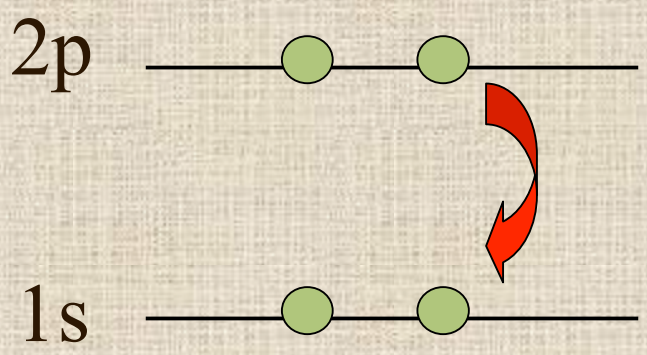


Normal 2p –>1s transition



2p –>1s transition violating Pauli principle

Experimental signature of the anomalous X-rays

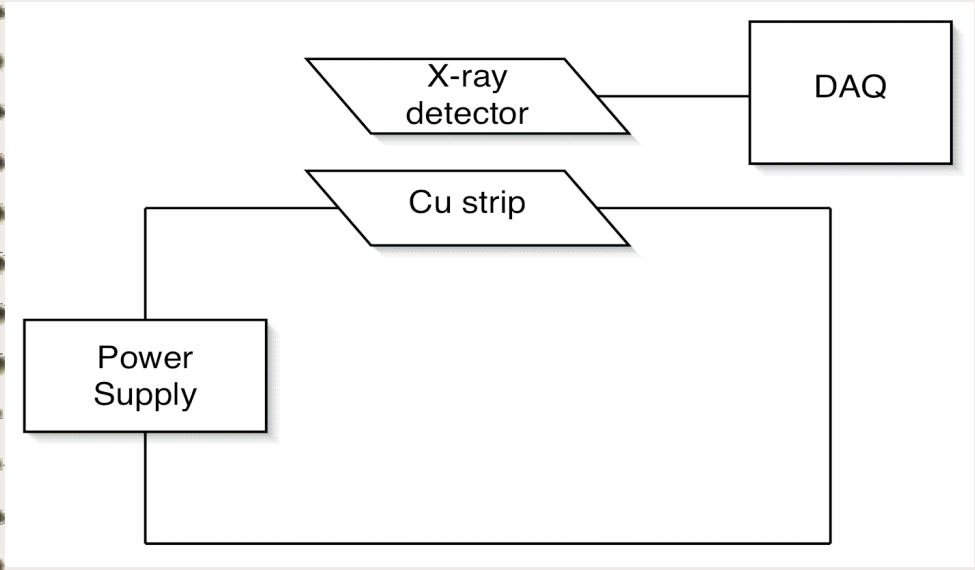


They have the energy displaced with respect to the “normal” one (~ Z-1)
-> gives a specific signature

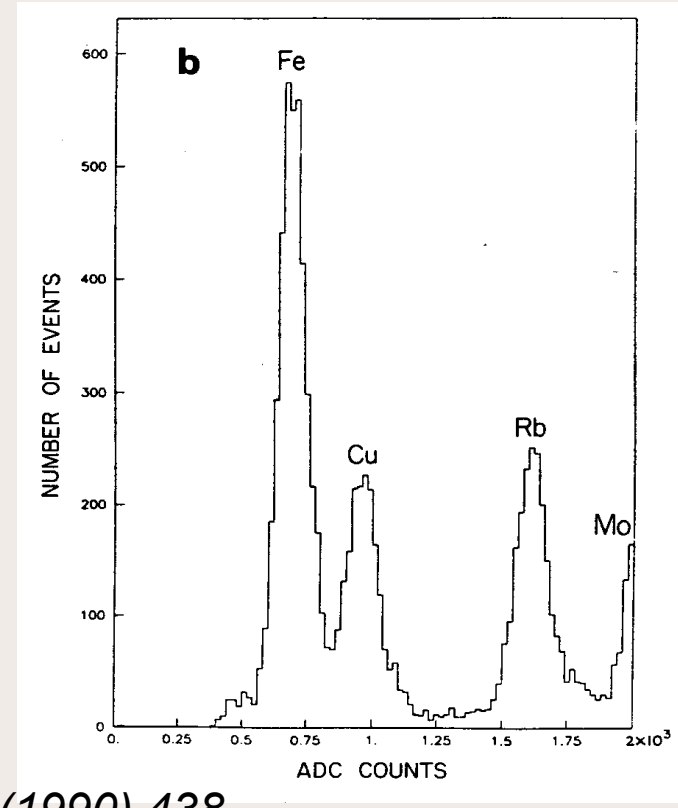
4. First experiment of the kind: Ramberg & Snow

Ramberg e-mail: It is a pleasure to hear from you about this topic. I had such fun doing it. I worked on it as a graduate student with George Snow, who has passed away now. It was done in the basement of a building here at Fermilab with a fairly high current source (50A or so). We got a lot of publicity about this experiment….

The experiment of Ramberg and Snow (RS)

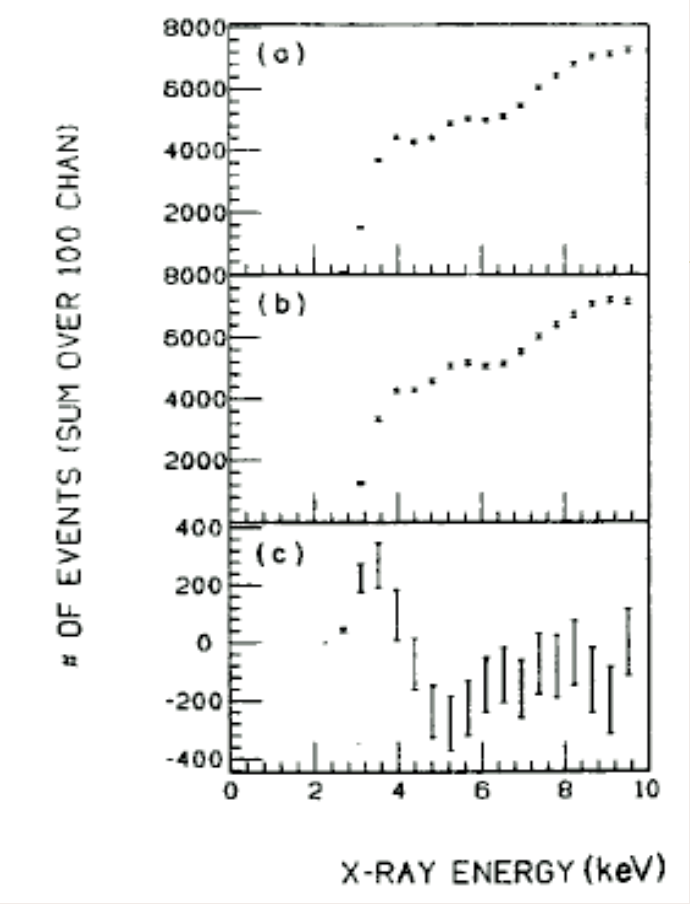


Detector calibration



Experiment performed in the Muon building at Fermilab with a prototype setup

E. Ramberg and G. A. Snow, Phys. Lett. ***B238*** *(1990) 438*



Search for anomalous electronic transitions in Cu (~ 7.6 keV instead of 8.05 keV) generated by the transition of one electron (from the current circulated in Cu) from 2p to 1s already filled by 2 electrons

In contact with Paris group – Paul Indelicato – for the precise calculation

Fig. 2. (a) Number of triggers summed over 100 ADC channels, plotted versus equivalent X-ray energy with current-on in copper strip below X-ray counter. (Note the points are separated by 50 channels, so that only every other point is statistically independent). (b) Same as (a) but with no current passing through an identical strip of copper. (c) Difference between (a) and (b) after normalization at the 9.5 keV point.

Theories of Violation of Statistics, O.W. Greenberg (2000) hep-th/0007054

1.4 Parons

Following Ignatiev and Kuzmin we introduced a parameter β that gives the deformation of the Green trilinear commutation relations. For $\beta \to 1$ the relations reduce to those of the $p = 2$ paraferm field; for $\beta \to 0$ the double occupancy is completely suppressed and the theory is equivalent to a fermi theory. A random state of two paronic electrons has the violation parameter $\beta^2/2$. Mohapatra and I checked that the norms are positive for states of up to three particles. At this stage, we were carried away with enthusiasm, named these particles "parons" since their algebra is a deformation of the parastatistics algebra, and thought we had found a local theory with small violation of the exclusion principle. Unknown to us Govorkov[15], using a detailed algebraic argument, already had shown in generality that any deformation of the Green commutation relations necessarily has states with negative squared norms in the Fock-like representation. For our model, the first such negative-probability state occurs for four particles in the representation of S_4 with three boxes in the first row and one in the second. We were able to understand Govorkov's result qualitatively as follows: [15] Since parastatistics of order p is related by a Klein transformation to a model with exact $SO(p)$ or $SU(p)$ internal symmetry, a deformation of parastatistics which interpolates between Fermi and paraferm statistics of order two would be equivalent to interpolating between the trivial group whose only element is the identity and a theory with $SO(2)$ or $SU(2)$ internal symmetry. This is impossible, since there is no such interpolating group.

Data analysis in the RS experiment

Number of "new" electrons:	$N_{new} = \frac{1}{e}\int_T I(t)dt$
Number of scatters just below (in front of) the detector:	$N_{\text{int}} = diam/m.f.p. = D/\mu$
Capture probability:	> (1/10) scattering probability
Useful solid angle:	$\pi/8$
Fraction of "visible" current:	λ/z
Expected number of X-rays:	$N_X \geq \frac{1}{2}\beta^2 N_{new}\frac{N_{\text{int}}}{10}$

$$N_X \geq \frac{1}{2}\beta^2 N_{new}\frac{N_{\text{int}}}{10} = \frac{\beta^2(\Sigma I \Delta t)D}{e\mu\rho z\sigma}$$

$$\int_T I(t)dt = 15.44\cdot 10^6\ C$$

$$D = 0.025\ m$$

$$\mu = 3.9\cdot 10^{-8}\ m$$

$$\rho = 8.96\cdot 10^3\ kg\cdot m^{-3}$$

$$\sigma = 10\ m^2\cdot kg^{-1}$$

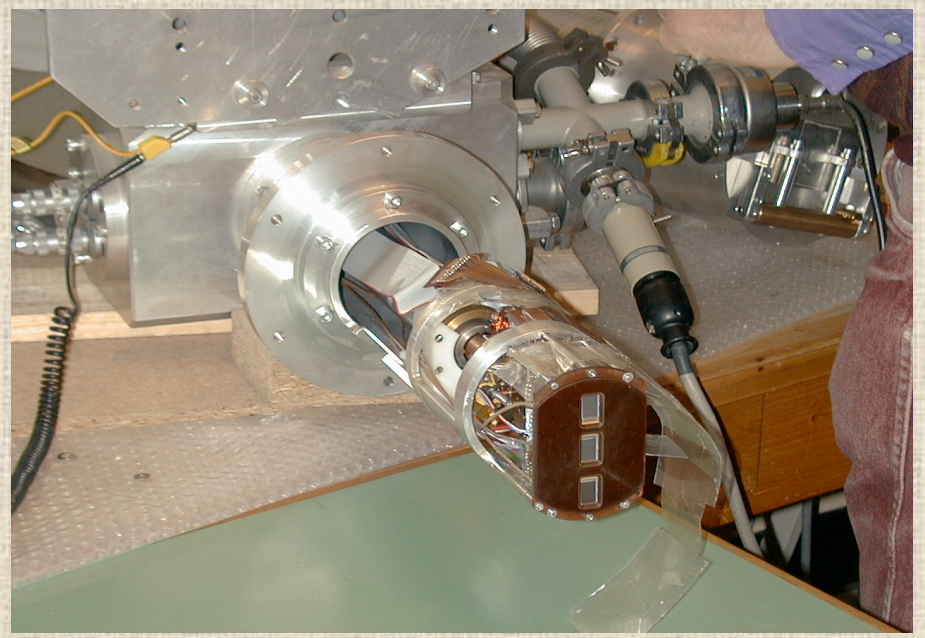
$$z = 1.5\cdot 10^{-3}\ m$$

$$N_X \geq \beta^2\left(0.90\cdot 10^{28}\right)$$

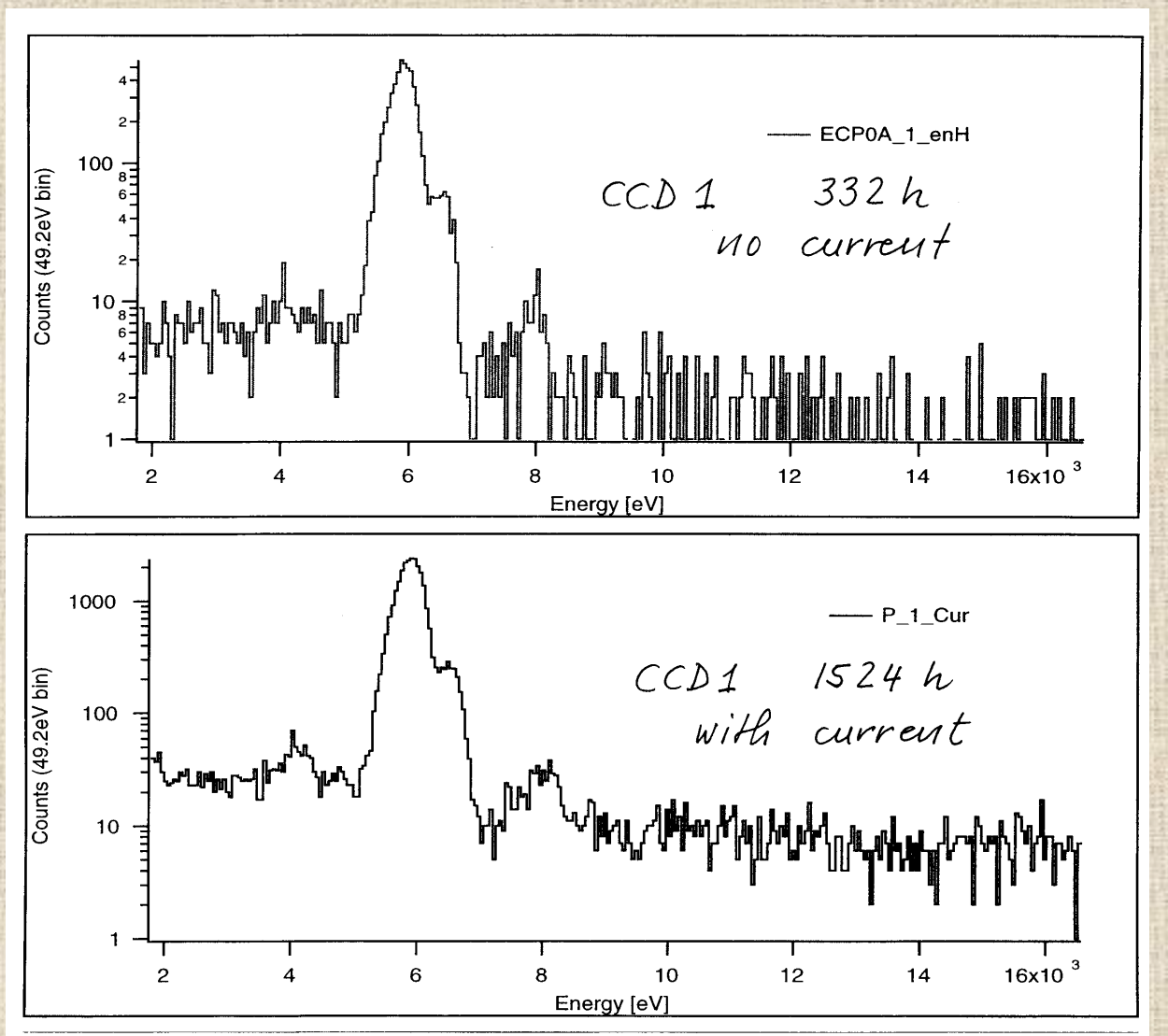
$$\beta^2/2 \leq 1.7\cdot 10^{-26}(>95\%C.L.)$$

5. Preliminary results obtained with a test setup

3 CCD setup installed in the basement at Neuchatel (same principle as R&S)



Measured spectrum



$$\beta^2 / 2 \leq 0.95 \cdot 10^{-27}$$

6. The VIP experiment VIolation of the Pauli Exclusion Principle

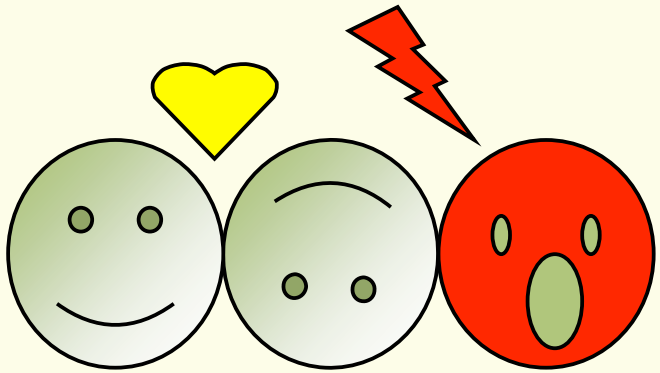
VIP Collaboration:

LNF- INFN, Frascati, Italy

INFN, Trieste, Italy

IMEP- ÖAW, Vienna, Austria

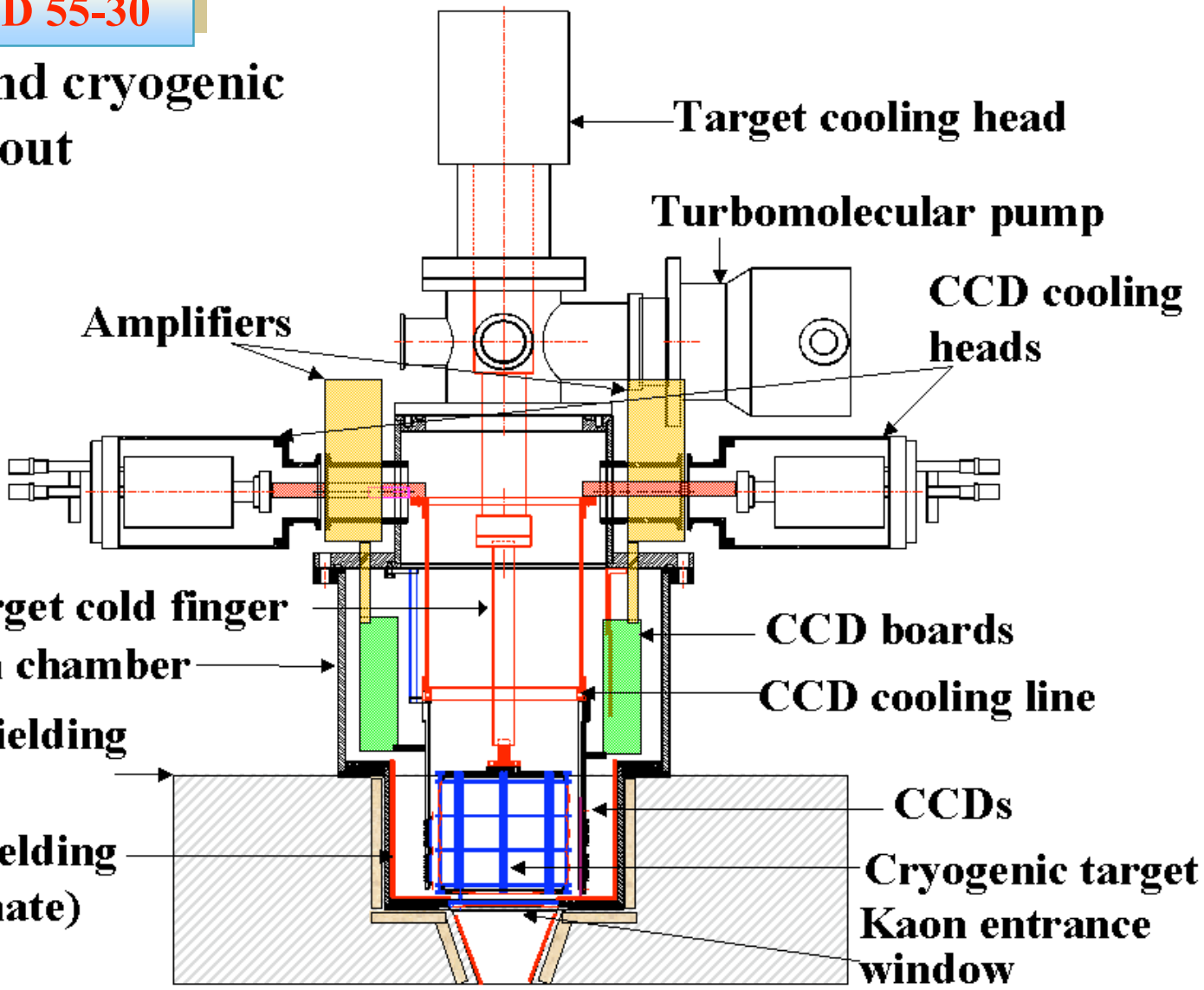
IFIN – HH, Bucharest, Romania



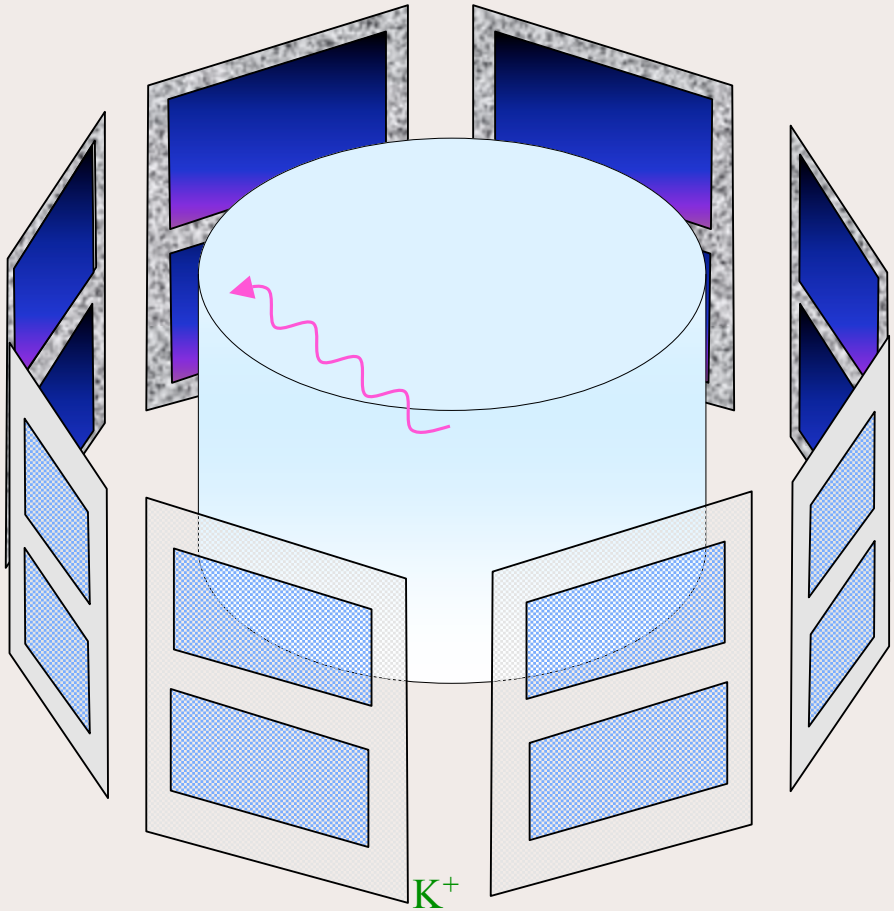
Actual DEAR setup

equipped with 16 CCD 55-30

Target and cryogenic setup layout

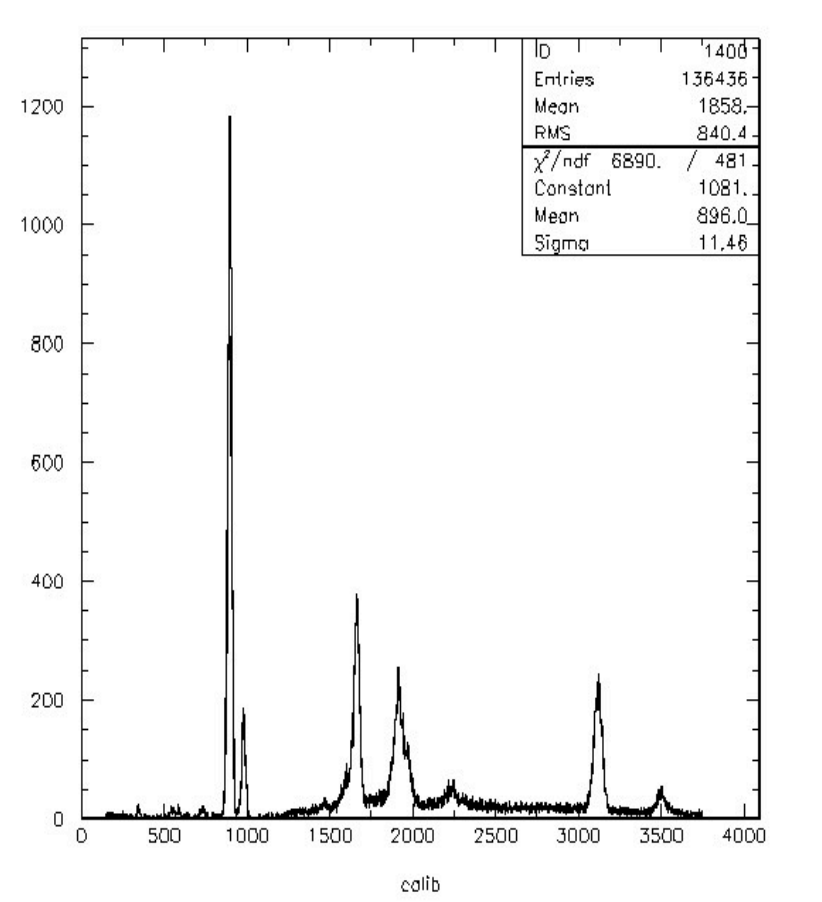


CCD-55 detectors positioning in the cryogenic setup



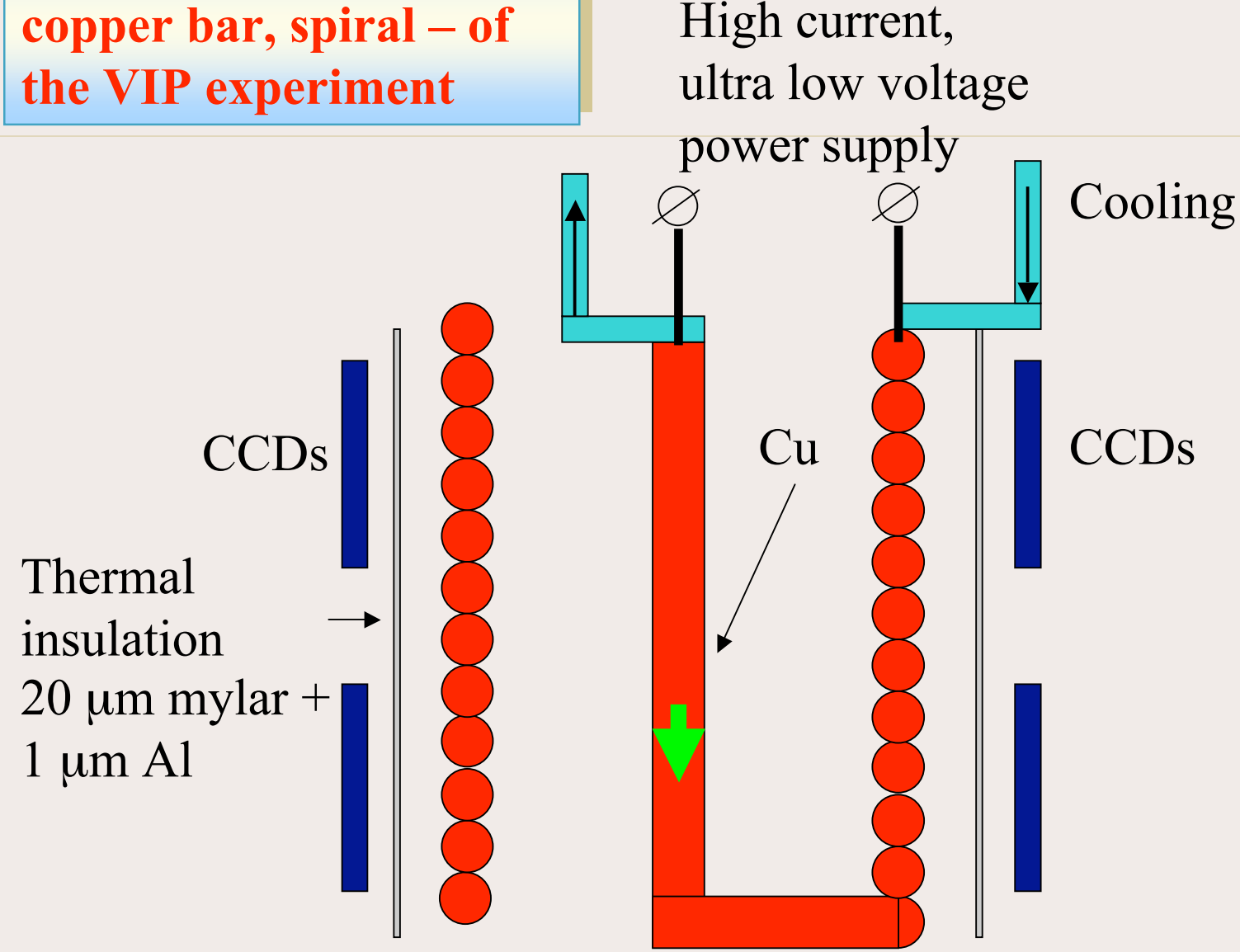
Present (April 2004) CCD status

Nr.	Ti Kα FWHM [eV]	err.
ccd 1	0	0
ccd 2	164.9912	0.5
ccd 3	154.609	0.3
ccd 4	164.8449	0.6
ccd 5	137.6652	0.3
ccd 6	175.8235	0.4
ccd 7	206.3519	0.6
ccd 8	221.9715	0.7
ccd 9	152.7059	0.5
ccd 10	198.6705	0.8
ccd 11	150.4683	0.4
ccd 12	227.9897	0.9
ccd 13	142.0626	0.4
ccd 14	135.5815	0.7
ccd 15	138.6213	0.4
ccd 16	147.2229	0.5



DEAR setup in the laboratory:

The new "target-cell" – copper bar, spiral – of the VIP experiment



With respect to test-setup at Neuchatel
(duration ~ 3 months):

FWHM (7.6 keV) = 170 – 200 eV => factor 2
CCD surface = > factor ~ 30
Current: 50 A (factor ~ 5)
For 1 + 1 years of DAQ:
factor 6 signal
factor 25 background
Background reduction ~ **factor 100** (Gran Sasso)
(~ 2 counts/day in 1 FWHM at 7.64 keV)

$$\beta^2 / 2 \leq 10^{-30}$$

6. Plan of the measurements

Plan of the measurements

- *Till the end of 2004: test run at Gran Sasso laboratory with a 2CCD test setup to check the background level*
- *Beginning of 2005: transportation and installation of the VIP setup at LNGS;*
- *Debugging and calibration*
- *Start data taking*
- *Early 2005 – end 2006: DAQ (alternate periods of "signal" (with current) and "background" (without current) data)*

$$If\ \beta^2/2 \le 10^{-30}$$

search for nuclear γ-ray transitions forbidden by the Pauli principle.

The suggested approach, in principle, allows one to go very far in testing the Pauli principle: it may prove adequate even in the case when the violation of that principle was due to some quantum gravity effects at Planck scales.

The bound on the value of the Pauli principle violation parameter β which can be achieved in this kind of experiment can be estimated to be $\beta \lesssim 10^{-15}$.

We are indebted to V.A. Berezin, M.G. Kozlov, V.A. Matveev, V.A. Rubakov, M.E. Shaposhnikov and I.I. Tkachev for valuable suitable suggestions. One of the authors (A.I.) is grateful to C. Alabarelli, F. Delduc, A. De Rujula, A. Martin and C. Walter for their interest in the work and useful discussions; he would also like to thank the CERN Theoretical Physics Division at CERN for the kind hospitality extended to him.

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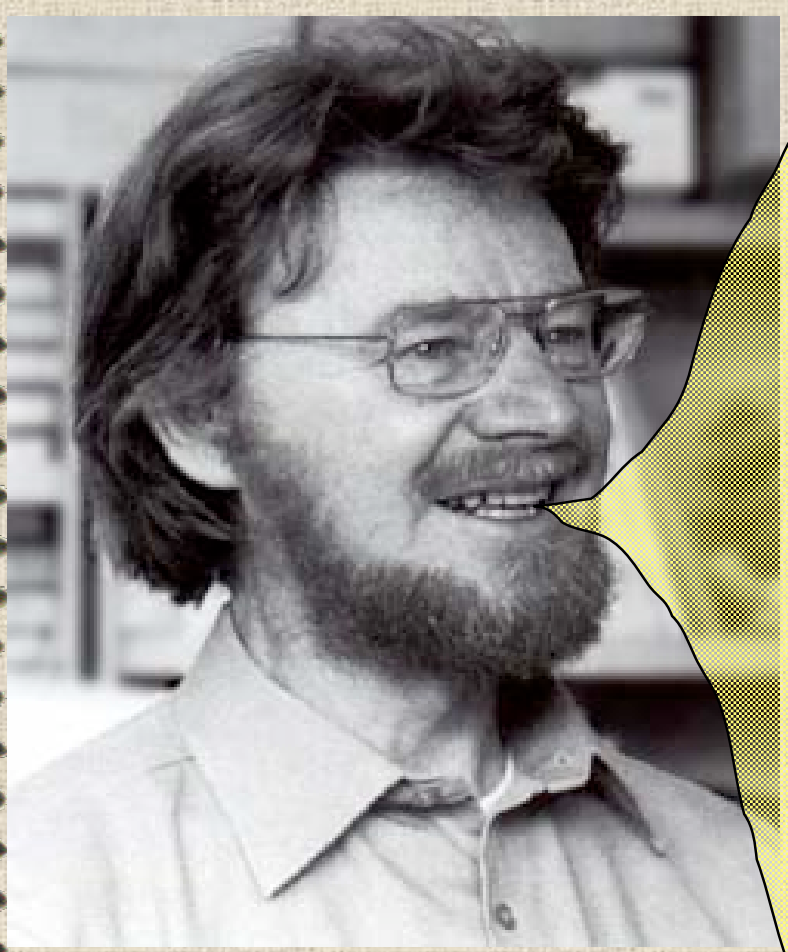
Gavrin, Ignatiev and Kuzmin

8. Instead of Conclusions

John Bell



Six possible worlds of quantum mechanics (1986):

To what extent are these possible worlds fictions? They are like literary fiction in that they are free inventions of the human mind. In theoretical physics sometimes the inventor knows from the beginning that the work is fiction, for example when it deals with a simplified world in which space has only one or two dimensions instead of three. More often it is not known till later, when the hypothesis has proved wrong, that fiction is involved. ***When being serious, when not exploring deliberately simplified models, the theoretical physicist differs from the novelist in thinking that maybe the story might be true.***

Lev Okun in the lab

"In spite of the fact that at present we have no theoretical self-consistent framework for a description of violation of charge conservation and/or the exclusion principle, I do not think that experimentalists should stop testing these fundamental concepts of modern physics.

In fundamental physics if something can be tested it should be tested."

(Comments Nucl. Part. Phys. 1989, vol 19, p. 99)

Invitation

Please stay tuned!