Laboratory for Neutron Physics, JINR, April 6 2015, Dubna, Russia

Non-standard applications of the Mossbauer Effect

Todor Ruskov

Institute for Nuclear Research and Nuclear Energy
Sofia, Bulgaria

Посвящается 100-летию со дня рождения Федора Львовича Шапиро

Dedicated to the 100th anniversary of Fyodor L'vovich Shapiro

- *Fyodor L'vovich Shapiro always supported us, the young enthusiasts, since he was also young and enthusiastic !*

- *F.L. Shapiro was always interested in nontrivial experiments !*

  He said, that the experiments (on the Mossbauer effect) performed in Dubna should be once which could not be performed elsewhere !

- Федор Львович Шапиро всегда поддерживал нас, молодых энтузиастов, т.к. он сам был молодым и энтузиастом !

- Шапиро проявлял интерес к нетривиальным экспериментам ! Он говорил, что в Дубне по мессбауэровской тематике надо делать то, что в других местах не могут сделать

First meeting F.L. Shapiro in early 60s in Dubna

At the beginning of the new 1960 year I arrived in Dubna, with my family, to start working at the Laboratory of Neutron Physics (at JINR). There was a real Russian winter in Dubna. While in Bulgaria, I had learned from people working in the same Lab, that Dr. Shapiro is a very talented physicist who directs most of the experimental research in the Lab, and so my first goal was to meet him … In that winter morning, there was a seminar scheduled in the Neutron Lab, and just before it started, there was a middle-aged man in the hallway who was walking towards me. It seemed like someone had informed Dr. Shapiro of my arrival. He came close to me, shook my hand, and introduced himself. I was immediately impressed by his welcoming nature, which had about it a friendliness, and so my previous apprehension immediately disappeared. I rememeber, the speaker was Zhora Samosvat who was smiling all the time! After the seminar Dr. Shapiro invited me to his office, where we have discussed in detail what I had been working on in Bulgaria, and what I would like to study in Dubna.

В начале 1960 года я прибыл в Дубну, вместе с семьей, и поступил на работу в Лабораторию нейтронной физики, В Дубне была настоящая русская зима. Еще в Болгарии мне говорили, что Шапиро это тот человек, который непосредсвтвено руководит экспериментальной работой в ЛНФ и первым моим делом было встретиться с ним…В это зимнее утро, в ЛНФ должен бы проходить семинар, и незадолго до его начала я увидел в коридоре человека среднего возраста, который направлялся ко мне. Похоже, что кто-то сказал Шапиро о моем приезде. Он подал мне руку и представился. На меня сразу произвел впечатление его открытый взгляд, и в то же время я почуствовал доброжелательность с его стороны. Помню, на семинаре с докладом выступал Жора Самосват, причем говоря, он все время улыбался. После семинара Шапиро пригласил меня к себе, в его комнате, где обстойно говорили о том, чем я занимался в Болгарии и чем хотел бы заниматься в Дубне.

Meeting Shapiro and his group members

Shapiro told me that here in Dubna they are still far from obtaining polarized neutrons, and he suggested sending me to the Institute for Theoretical and Experimental Physics (ITEP) in Moscow, where they had already been working with a polarized neutron beam. In that conversation, as I remember, he asked me what foreign languages I knew, besides Russian? I answered: English and French.

It is evident that Dr. Shapiro had great memory: one year later, when I came back from Moscow to join the Dubna Mossbauer group, he asked me to translate from French one review paper on the Mossbauer effect, written by Anatole Abragam.

At the end of the talk Dr. Shapiro suggested that I take a tour of the Neutron Lab so that I can get acquainted, see who is doing what, and only then give him my final decision. My guide to the Lab was Slava Lushchikov. Going from one laboratory room to another we finally ran into Yurii Ostanevich.

В связи с моим желанием заниматься поляризованными нейтронами, Шапиро сказал, что в Дубне, пока, далеко от их получения, и предложил командировать меня в ИТЭФ, в Москву, где уже был пучок поляризованных нейтронов. Он также спросил меня какими иностранными языками, кроме русского я владею, на что я ответил: французский и английский.

Явно у него была хорошая память, потому что год спустя, когда я вернулся в Дубну и перешел в мессбауэровскую группу, он попросил меня перевести с французского большую статью об эффекте Мессбауэра Анатоля Абрагама.

В конце разговора, Федор Львович велел познакомить меня со всем, что делается ЛНФ. Моим гидом был Слава Лущиков. Мы переходили от одного физика к другому и попали в конце к Юрию Останевичу.

First meeting with Yura Ostanevich (about the Mossbauer effect)

Yurii Ostanevich showed me the Mossbauer experiment. In the course of our conversation, he happened to mention that the gamma emission and absorption lines are "shifted" out from each other, and owing to the thermal vibrations of the atoms the resonance absorption does not occur. I then asked, "And why aren't the nuclei frozen?" He answered, "Well, that's how Mossbauer proceeded," and pointed to the cryostat.

Later in my ruminations I returned several times to this conversation, and I found it strange that without understanding the complete picture of this phenomenon, I had followed the right track...

Юрий Останевич познакомил меня с мессбауэровским экспериментом. В ходе беседы он как-то обмолвился, что гамма-линии (испускания и поглощения) “сдвигаются” друг относительно друга, и кроме того уширяются в результате тепловых колебаний атомов, так что резонансное поглощение не происходит. Тогда я спросил: "А почему ядра не заморозить?". Он мне ответил: "А вот так Мессбауэр и поступил", -- и пальцем указал на криостат….

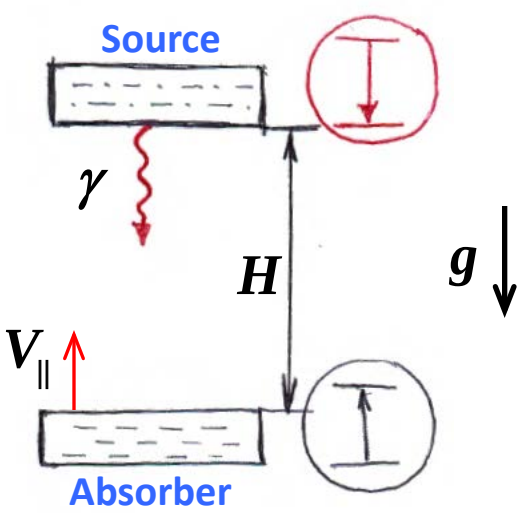
Позже, в своих размышлениях я несколько раз возвращался к этому разговору и как-то мне было странно, что тогда, не понимая полной картины этого явления, попал на верный след...

New ideas in Barit, Podgoretskii, & Shapiro paper

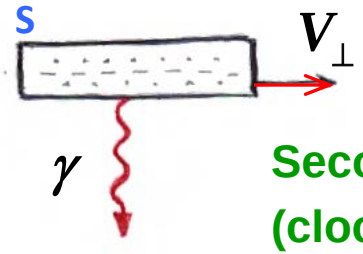
И.Я. Барит, М.И. Подгорецкий, Ф.Л. Шапиро, ЖЭТФ 38, 301 (1960), **November 4, 1959**

[Soviet Phys. JETP 11, 218 (1960)]

Equivalence principle & Gravity frequency shift



$$V_{\parallel} = g\frac{H}{c}, \quad \Delta\nu = \nu_0\left(\frac{V_{\parallel}}{c}\right) = \nu_0\left(\frac{gH}{c^2}\right)$$



Second order Doppler shift:

(clock time delay viewed by A)

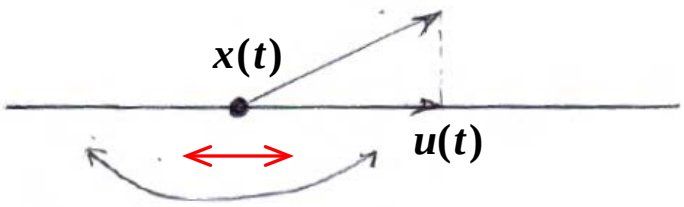
$$\Delta\nu_A = -\nu_0\left(\frac{V_{\perp}^2}{c^2}\right)$$

Nuclear Zeeman effect

Exploring the nuclear Zeeman effect may afford the possibility of investigating **the gamma transitions of polarized nuclei and the interactions with polarized gamma quanta.**

Just this possibility have been used by us in the experiment on **Searching of the Photon's Electric Dipole moment** (see below). In this case, for the nuclear polarization there is no need for very low temperatures or large magnetic fields.

Conference in Moscow: July 1960: the talks of Shapiro, Mossbauer, and Paund



$$\lambda\!\!\!^{-} = c / \omega_0$$

$$f_{DW} = \exp(-\frac{\overline{x}^2}{\lambda\!\!\!^{-2}})$$

Recoiless fraction:

Coincides with Quantum Mechanics !!

Shapiro -- Uspekhi Fiz. Nauk

- Classical Theory of the Mossbauer effect
- Other Mossb. Exp. in the USSR
- ^{67}Zn experiment of S.I. Aksenov et al.

Mossbauer -- Uspekhi Fiz. Nauk

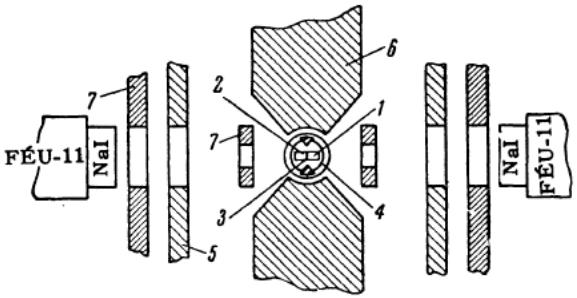
- Review of Mossb. effect experiments
- Determine Magnetic & Quadrupole moment of nuclei
- 13 Mossb. isotops observed so far !

Paund -- Uspekhi Fiz. Nauk

- Observe gravity red shift with ^{57}Fe, on a base of 22 meters, 4% accuracy

^{67}Zn experiment of Aksenov, Alfimenkov, Lushchikov, Ostanevich, Shapiro, Yen Wu-Kuang

- Resonance tunned via magnetic field
- Zn metal, 33% enriched,
- Small effect: 2.6 10^{-2} %



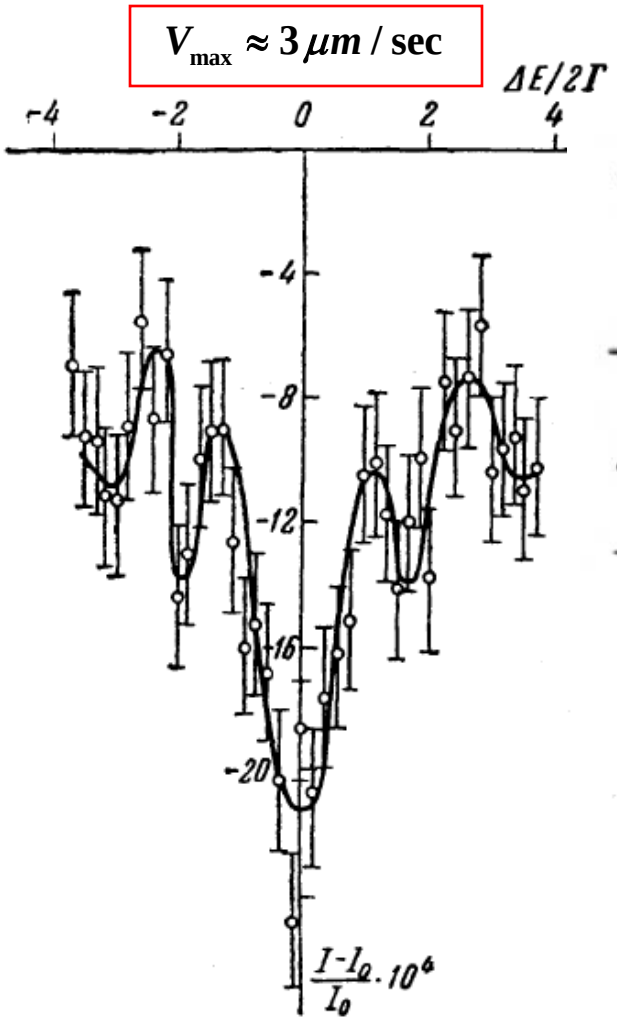
^{67}Zn experiment of Craig et al.

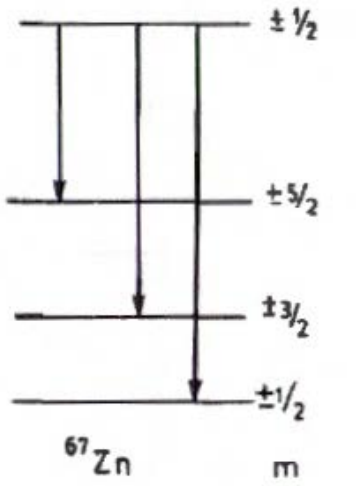
- Resonance tunned via magnetic field
- ZnO (S + A), A: 92.4% enriched,
- 10 times bigger effect: ~ 0.3 %

Dubna breakthrough: first ^{67}Zn resonance spectrum and the possibility to measure small energy shifts

В.П. Алфименков, Ю.М. Останевич, Т. Русков, А.В. Стрелков, Ф.Л. Шапиро, Ень У Гуан

ЖЭТФ т.42, 1029 (1962), December 9, 1961 [Soviet Phys. JETP 15, 713 (1962)]





^{67}Zn experiment of Alfimenkov et al.

- Resonance via Doppler modulation
  (natural LW/93 keV = $\delta = 5\ 10^{-16}$)
- ZnO (S + A), A: 33% enriched
- Max resonance effect: 0.2 %
  (Linewidth is about 10 times the natural LW)
- Observe resonance structure: evidence of spin-1/2 excited state & Quadrupole splitting
- Estimate f' = 0.02 (of absorption)
- Estimate Debye Temperature of 300K (ZnO)

^{67}Zn experiment of Alfimenkov et al. – Impact on Theory !!!

D.A. Kirzhnits and V.A. Chechin, Yadernaya Fizika 1968 estimated elementary length $L \approx 10^{-20}\ cm$ of Quantized Space !

Theories with elementary length "L" were developed by Yu.A. Gol'fand (1959) and V.G. Kadyshevskii (1961)

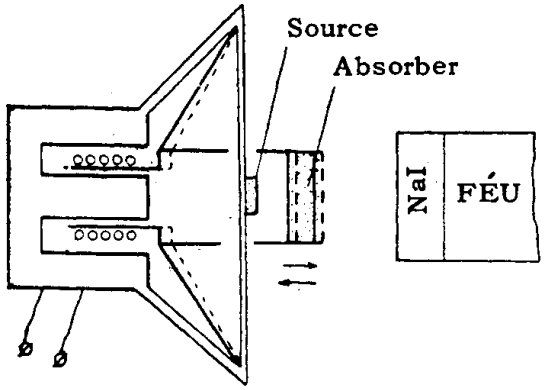
The Dubna Mossbauer group in early 1961

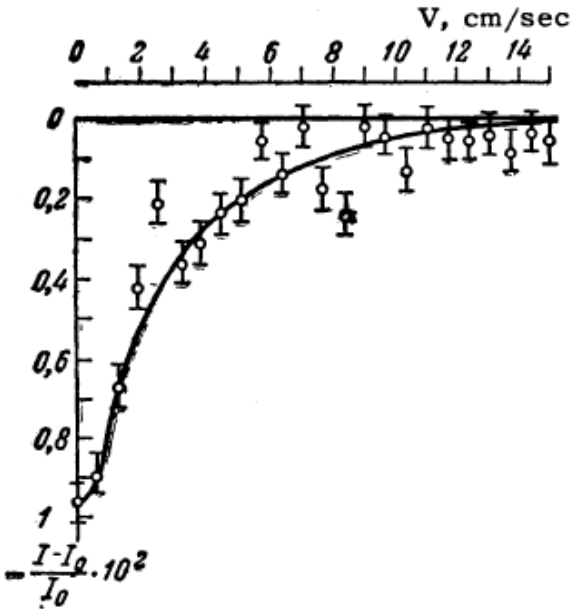
From left to right: Alexander Strelkov, Viktor Alfimenkov (the group leader), Yen Wu-Kuang, Todor Ruskov, Yurii Ostanevich

^{149}Sm: Dubna first observation of resonance spectrum and determination of level scheme

В.П. Алфименков, Ю.М. Останевич, Т. Русков, А.В. Стрелков, Ф.Л. Шапиро, Ень У Гуан

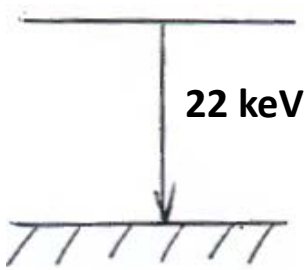
ЖЭТФ т.42, 1036 (1962), December 9, 1961 [Soviet Phys. JETP 15, 718 (1962)]



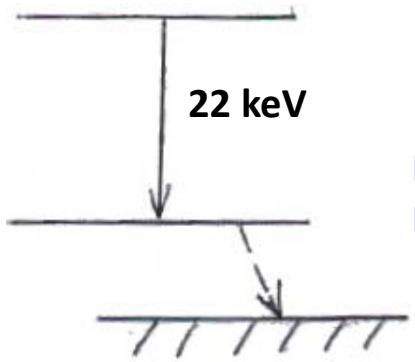


^{149}Sm experiment of Alfimenkov et al.

- **Resonance via Doppler modulation**
  Estimated natural Line Width < 6 10^{-7} eV
- **Source: Sm_2O_3 + $^{149}Eu_2O_3$**
- **Absorber: Sm_2O_3 on microphone membrane**
- **natural abundance**
- **Max resonance effect: 1 %**
- **Observed Mossbauer Effect => a transition to the Ground State (YES-NO experiment)**



GS ?



Yes: ME
Yes: GS

No: ME
No: GS

^{165}Ho: Sofia, Bulgaria: first observation of resonance Mossbauer spectrum in 1963

^{165}Dy obtained via **n-capture of ^{164}Dy. Our Lab** was **few ten meters** from the **reactor**

In 1963 I returned to Bulgaria and decided to continue the Mossbauer studies begun in Dubna.

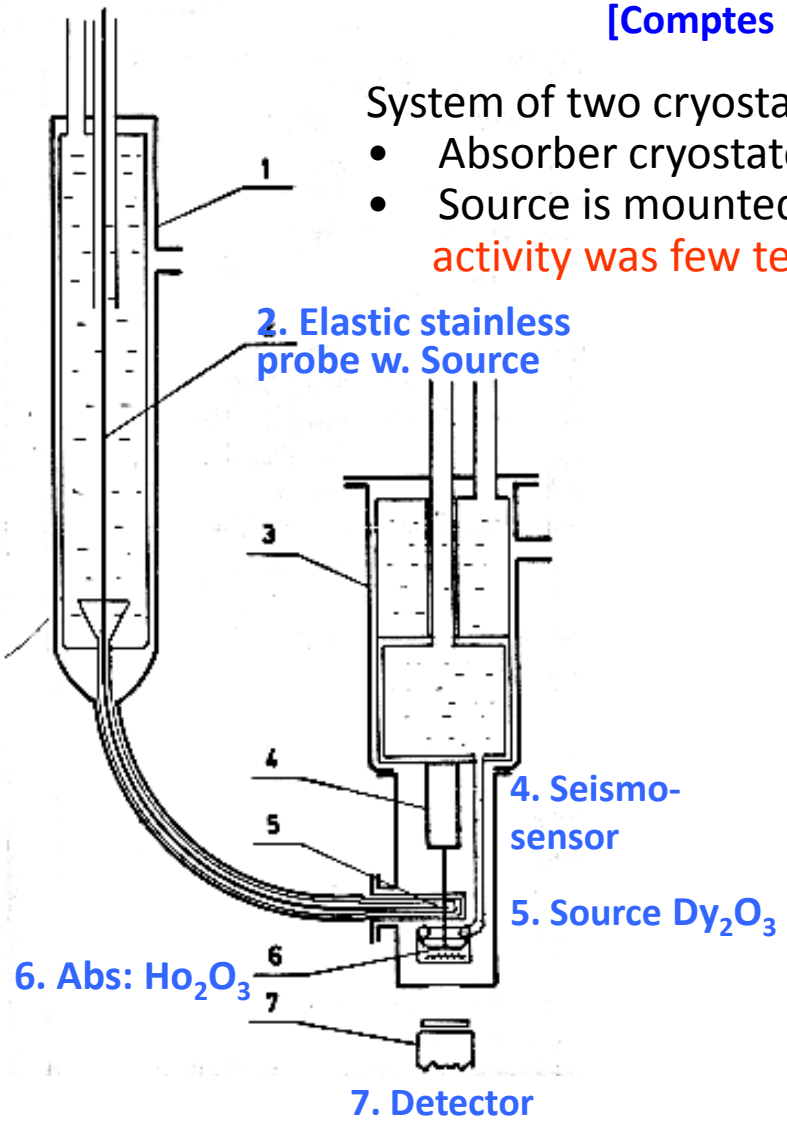
Our **experimental nuclear reactor IRT 1000** have been just started and there were a possibility to observe (in principle) the Mossbauer effect in nuclei, where the parent isotope can be obtained via neutron capture.

I focused on **^{165}Ho** 94.7 keV g-transition, obtained from the beta-decay of **^{165}Dy** (139 min half-life).

^{165}Ho: Sofia, Bulgaria: first observation of resonance Mossbauer spectrum in 1966

Т. Русков, Т. Томов, Х. Попов, Доклады Болгарской Академии Наук, т.19, 701 (1966)

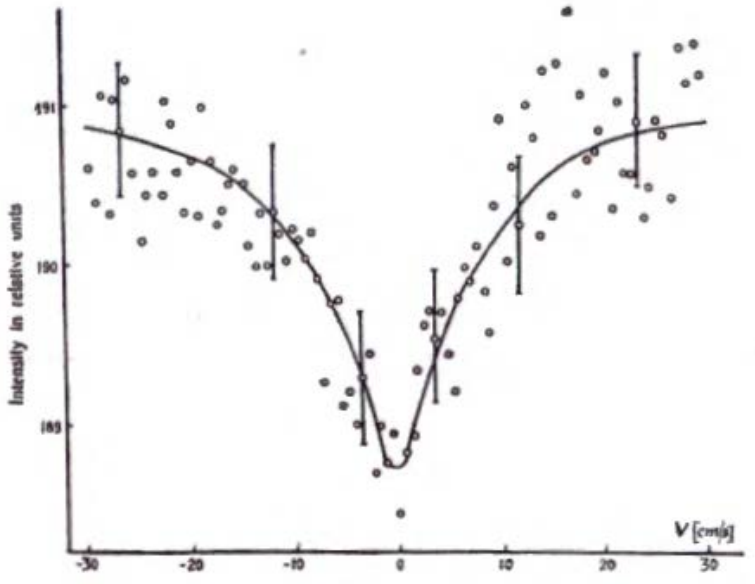
[Comptes rendus de l'Academie Bulgare des Sciances, 19, 701 (1966)]



System of two cryostates (77 K) is used:

- Absorber cryostate is waiting ready
- Source is mounted fast, since initial activity was few tens mCi !

$V_{max} \approx 30\,cm/\sec$

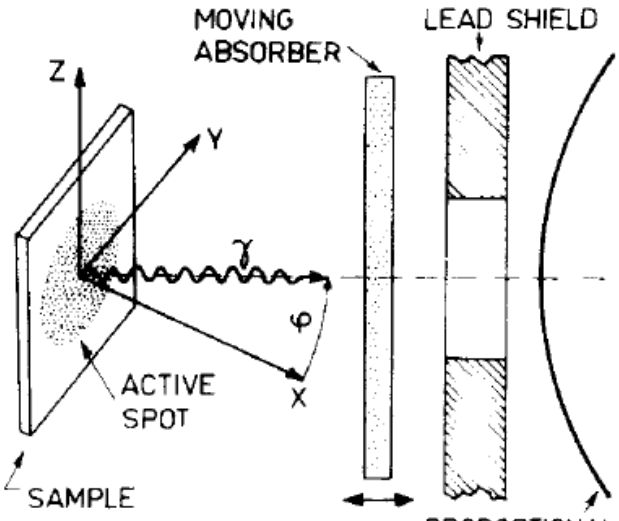


^{165}Ho experiment of Ruskov et al.

- **Resonance via Doppler modulation**
  Measured Line Width = 2.2 10^{-6} eV – one of the largest
- **Source: Dy_2O_3**
- **Absorber: Ho_2O_3 on a seismo-sensor**

Diffusion mechanism in solids and ^{57}Fe Mossbauer experiment at high temperatures (1030 ^{o}C)

S. Asenov, T. Ruskov, T. Tomov, I. Spirov, Physics Letters 79A, 349 (1980)



^{57}Fe(^{57}Co) Cu

Vacancy diffusional mechanism

Angular dependence on jump direction & distances

Interstitial mechanism

No angular dependence

Special rotating furnace/holder

Cu single crystal X-axis [100]

Angle φ between γ- direction and X-axis

Diffusion mechanism in solids theoretically predicted

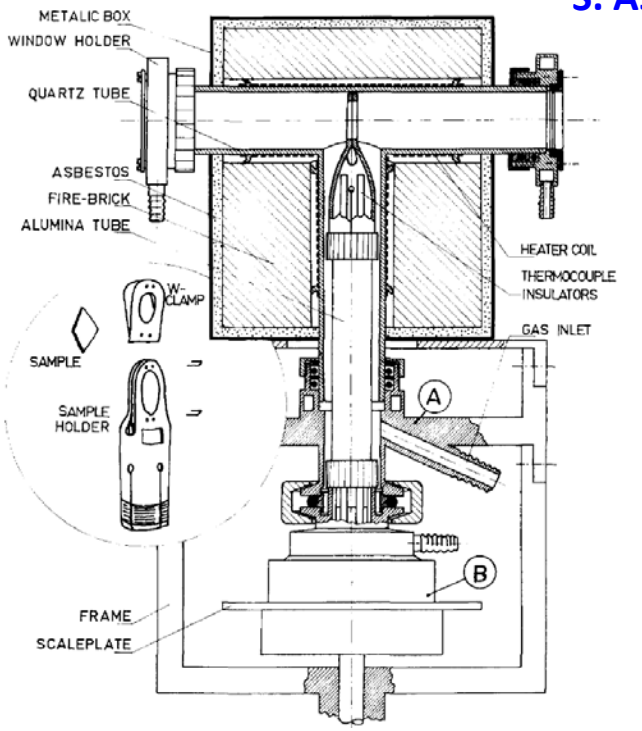
- M.A. Krovoglaz (1961) (see also Singwi & Sjolander)

- Our choice: ^{57}Fe(^{57}Co) in cubic Cu single-crystal.

Hard, non-trivial experiment at T= 1030 ^{o}C (only 30 ^{o}C below the melting point !)

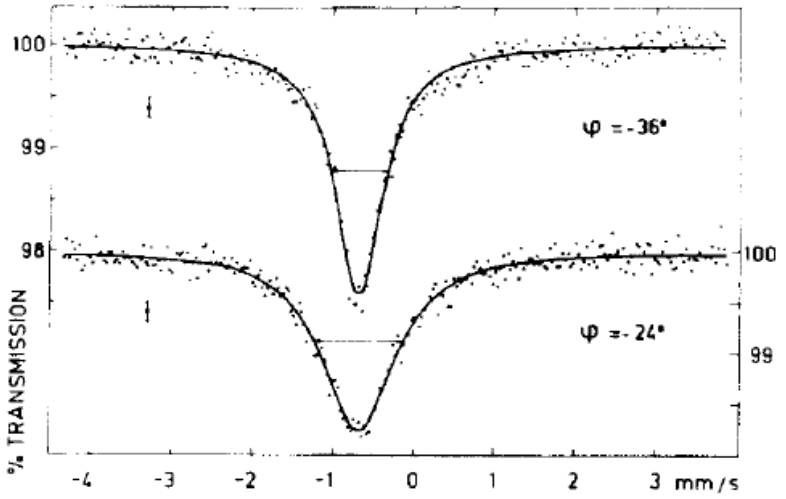
First direct observation of the diffusion mechanism in solids with ^{57}Fe at high temperatures (1030 °C)

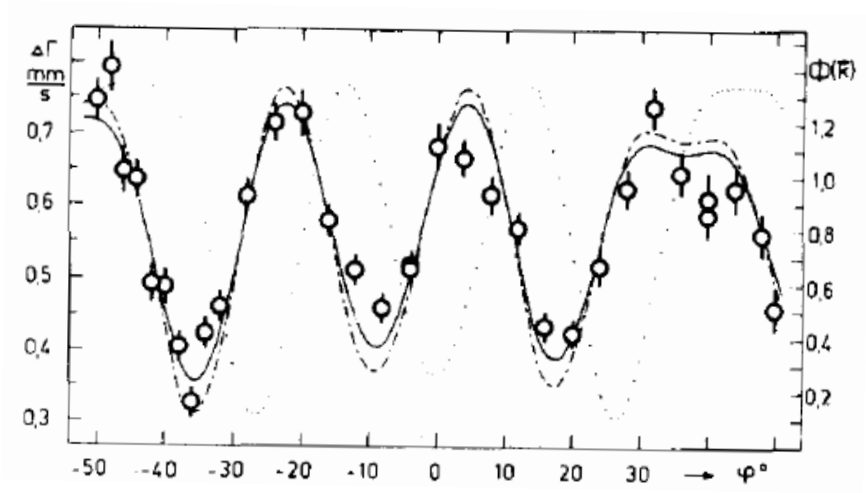
S. Asenov, T. Ruskov, T. Tomov, I. Spirov, Physics Letters 79A, 349 (1980)



High-temp. Mossbauer furnace with rotating sample-holder

Typical Mossbauer spectra for two different angles -36°, -24°



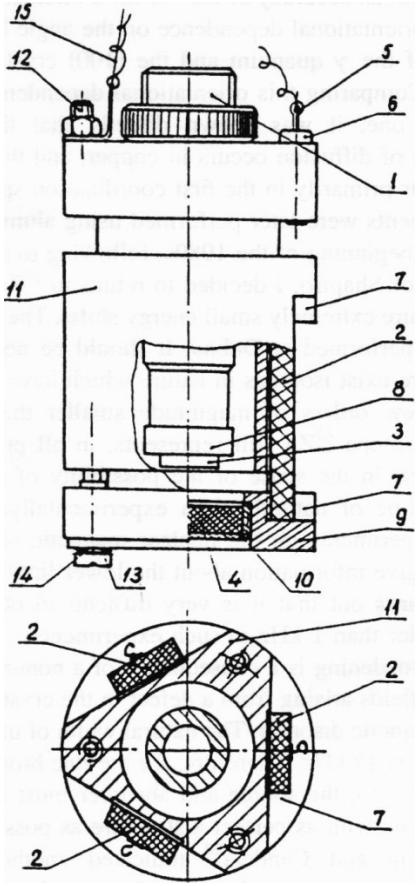


Angular dependent diffusional broadening vs. Theory

^{57}Fe experiment of T. Ruskov et al.

- Resonance via Doppler modulation
- Source: $^{57}Fe(^{57}Co)$ Cu
- Absorber: $Na_4Fe(CN)_6\ 10H_2O$

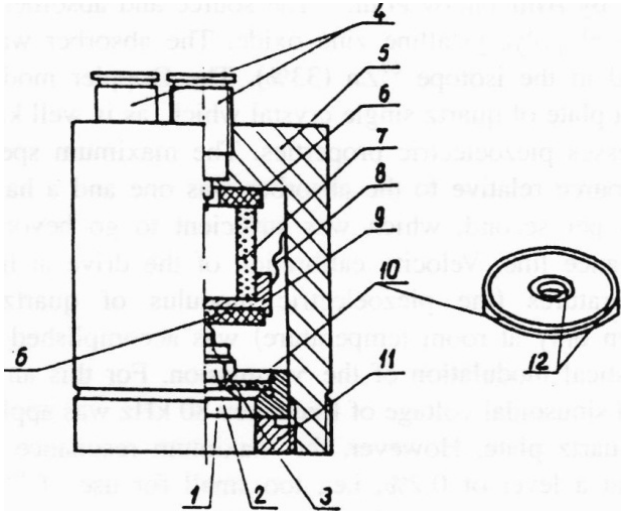
Reaching the limit of natural line width with ^{67}Zn for measuring extremely small energy shifts



Drive with quartz piezo-motor (2); tension distributed via beryllium bronze (14)

Previous improvement of ^{67}Zn technique and ours

- **de Waard&Perlow essentially repeat us 8 years later (1970) !**
- **Helisto *et al* reach energy sensitivity of 3 10^{-18} (1984); gravity red shift accuracy not improved on base of 1 meter (1981)**
- **T Ruskov *et al* use quartz drive, w. better frequency spectrum reaching similar energy sensitivity**
- **T Ruskov *et al* use a compact PZT w. displacement sensor (1985-86) Displacement accuracy: 4 10^{-12} m; use monocryst. ZnO (S+A);**
- **T Ruskov *et al* uses reaction ^{67}Zn(d,n)^{67}Ga; irradiation damage prevented via cooling the target of ZnO mono-crystal (1988-89)**



Piezoceramic drive: parallel quartz plates(6),piezoceramic cylinder (7), sensor, piezo-washer (10), silvered electrodes (12)

Searching photon's electric dipole moment with ^{67}Zn

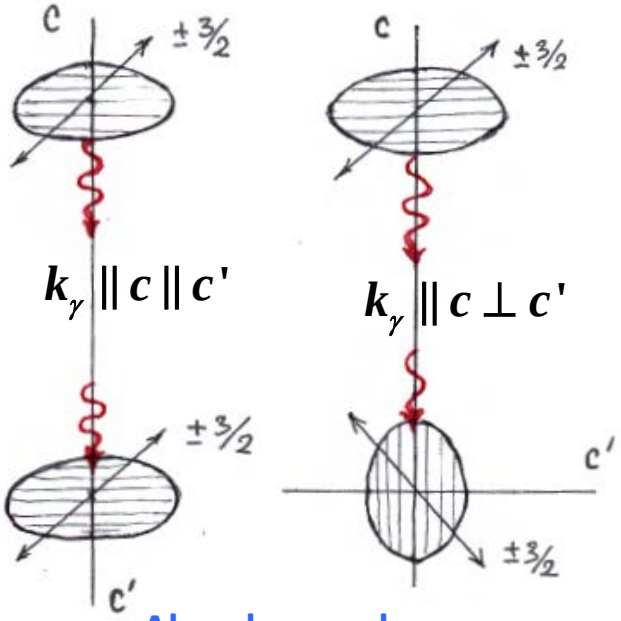
Classical energy change of a Dipole

$$\delta E = \int_{z1}^{z1} d_z \frac{\partial E_z}{\partial z} dz = d_z (E_2 - E_1)$$

E.D.M. of a particle => CP violation, Landau (1957)

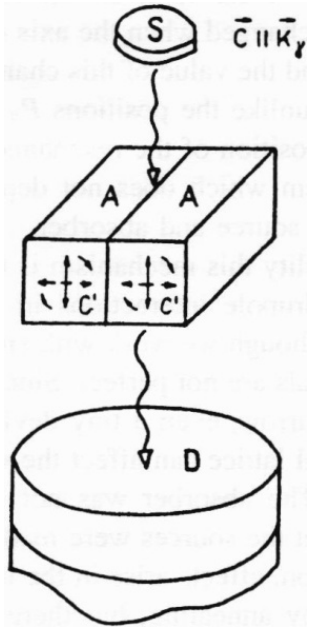
- **Dyson&Fremlin did not see effect with ^{57}Fe in Electromagn resonator => upper bound on E.D.M. of d < 10^{-10} e.cm**
- **T Ruskov *et al* use the Electric field of ^{67}Zn nucleus (emitter & absorber), via final state interaction with the Photon !**

^{67}Zn Ground State Quadrupole deformation => Field change

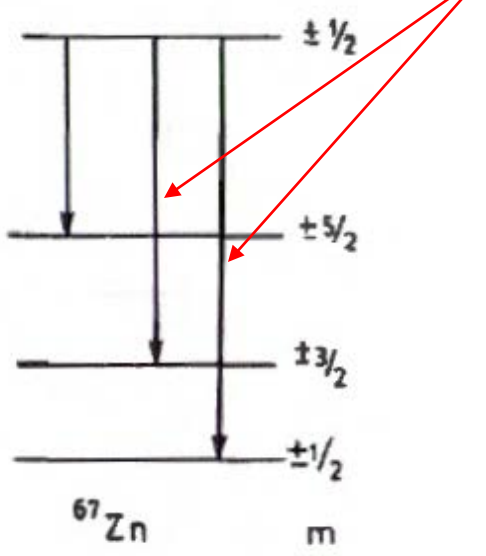


Absorber nucleus rotates with the crystal

Source & Absorber single-crystal, natural abundance

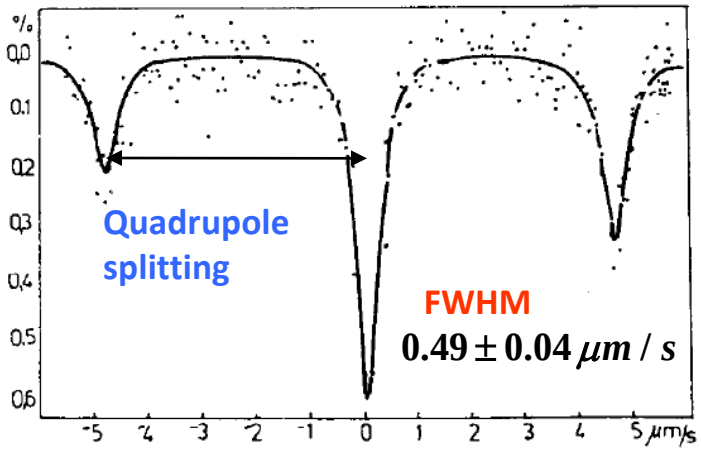


Corresponding transitions in S & A: Nuclei are aligned, NO NEED of nuclear polarization !!



Observing photon's E.D.M. with ^{67}Zn

T. Ruskov, R. Ruskov, I. Spirov, A. Kirov, T. Tomov, S. Asenov, Nucl. Inst. Methods, B36, 82 (1989)



S: ZnO single-crystal; A: ZnO polycryst, %92 enriched

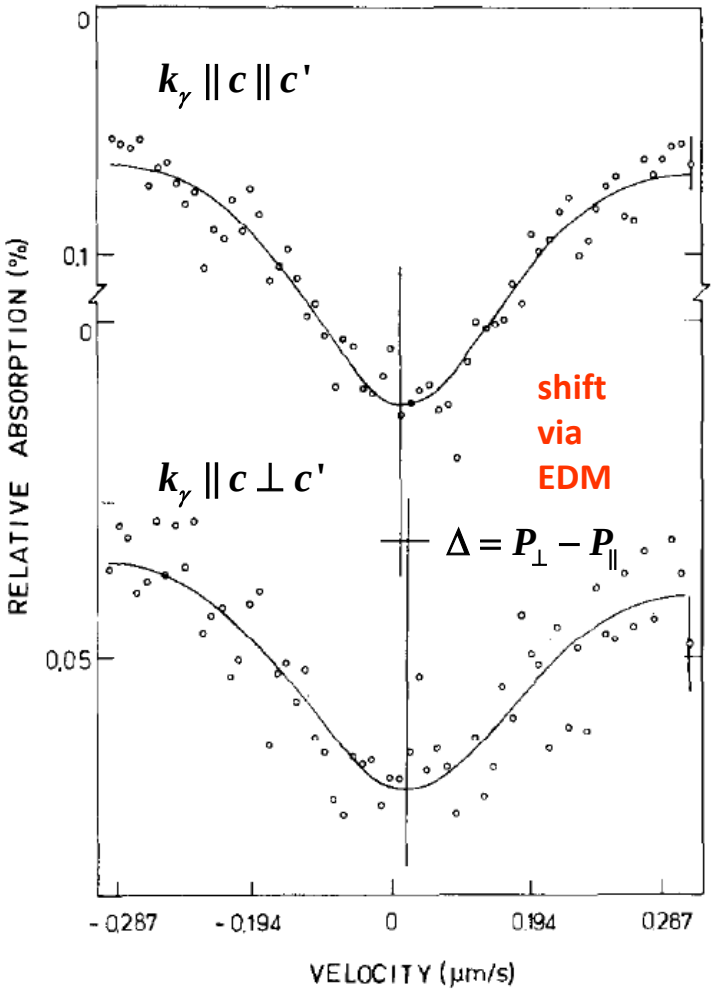
Positions change each run (due to different Source isomer shift.

However, the change $\Delta = P_{\perp} - P_{\parallel}$ is positive & same

Estimated EDM

$$d_z \approx \frac{\bar{\Delta}}{(5/6)\Delta E_{3/2} + (1/6)\Delta E_{1/2}}$$

$$\approx 1.3 \times 10^{-25}\ e \cdot cm$$



Alternatives via different Quadrupole splitting in S & A, or via Interference of nuclear/atomic processes cannot explain the data.

Average shift

$$\bar{\Delta} = 0.0098 \pm 0.0048\ \mu m / s$$

Несколько заключительных слов о Федоре Львовиче Шапиро

Заканчивая, хотелось бы сказать несколько заключительных слов о Федоре Львовиче Шапиро. Он был человеком, который в науке всегда искал изюминку. Новую идею схватывал быстро. По мелочам не разбрасывался, но это не означало, что подробности, иногда весьма существенные для дела, ускользали от него. Помню, в Дубне была лекция Палевского, и Шапиро переводил с английского. Перевод был настолько тщательным и подробным, что даже оставалось ощущение, что Шапиро добавлял что-то от себя.

К нам, молодым, он относился очень толерантно и благосклонно. К нему можно было подойти с любым вопросом, в любое время, на работе, в электричке и т.д. Если не мог ответить на заданный вопрос сразу, он разбирался сам и через час-два или через день-другой давал ответ.

Во время ночных измерений, а их хватало, можно было поспать немножко в его комнате на диване, и, вообще, когда он бывал в Москве, он предлагал нам свою комнату для занятий.

Some concluding words about Fyodor L'vovich Shapiro

I would like to conclude by saying a few words about Fedor L'vovich Shapiro. Shapiro was a man who always sought the gems in science. He grasped a new idea quickly. He did not worry about details, but this does not mean that the details, sometimes very important for the work, escaped him. I remember a lecture given at Dubna by Palevsky which Shapiro translated from English. The translation was so careful and detailed that one even had the feeling that Shapiro had added something himself.

He was very tolerant and well-disposed to us young people. One could go to him with any question at any time, during work, on the train, and so on. If he couldn't answer a question immediately, he thought about it and gave the answer in an hour or two or in a day or two. During night measurements, of which there were certainly enough, one could take a nap on the sofa in his room and, in general, when he was in Moscow he let us use his room as a quiet place to work.

If I had to characterize him briefly, I would say that he was a pragmatic enthusiast. His enthusiasm always had a forward thrust, and his pragmatism was manifested in the fact that he did everything possible under the conditions which society imposed upon him.

Вместо заключения: В детском садике, Дубна 1960х и будущее России