# ON NEUTRON WAVE-PACKETS, NEUTRON TRAPPING IN NANOSTRUCTURE & NEUTRON LIFETIME

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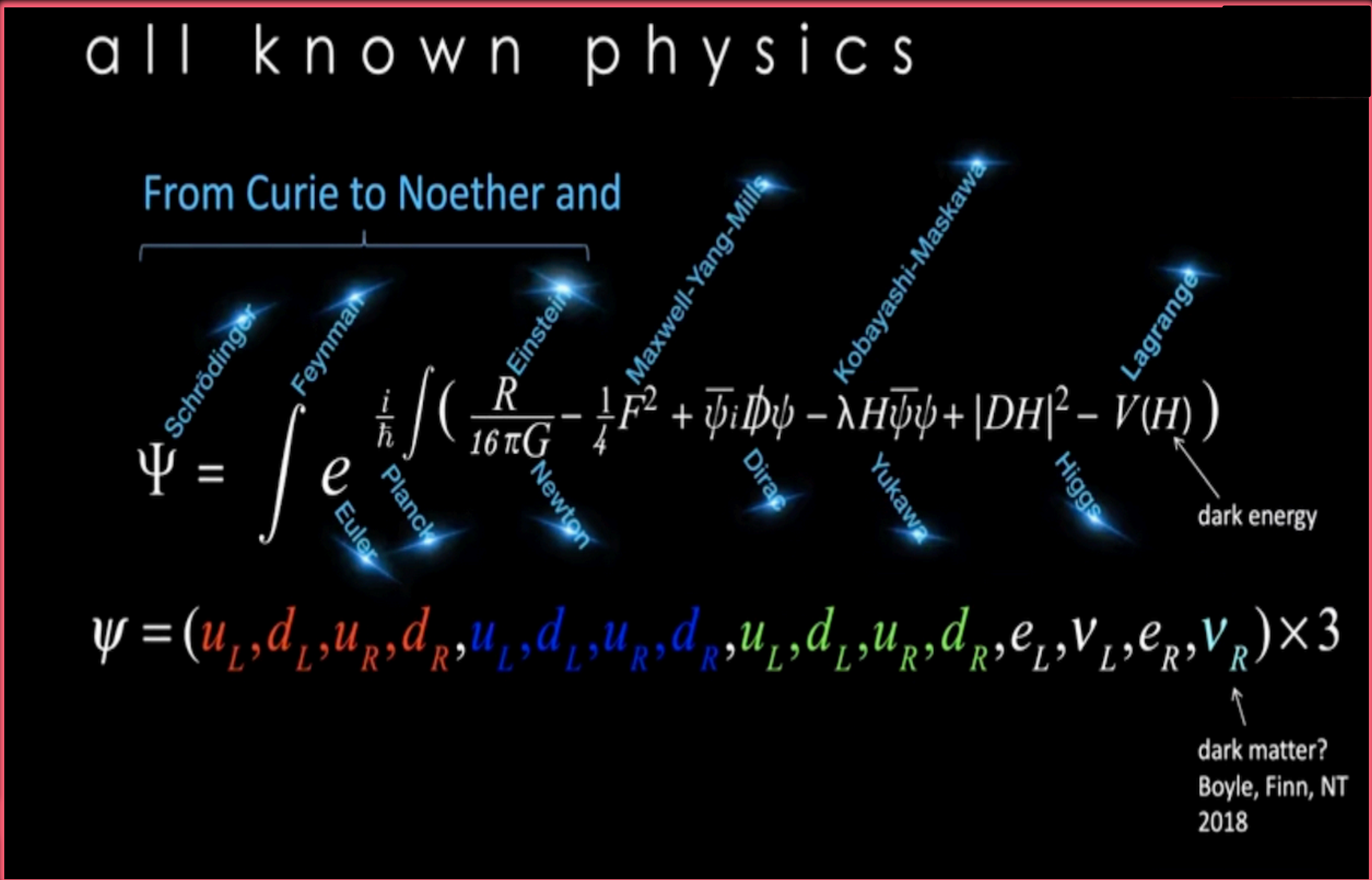
NRF National Research Foundation

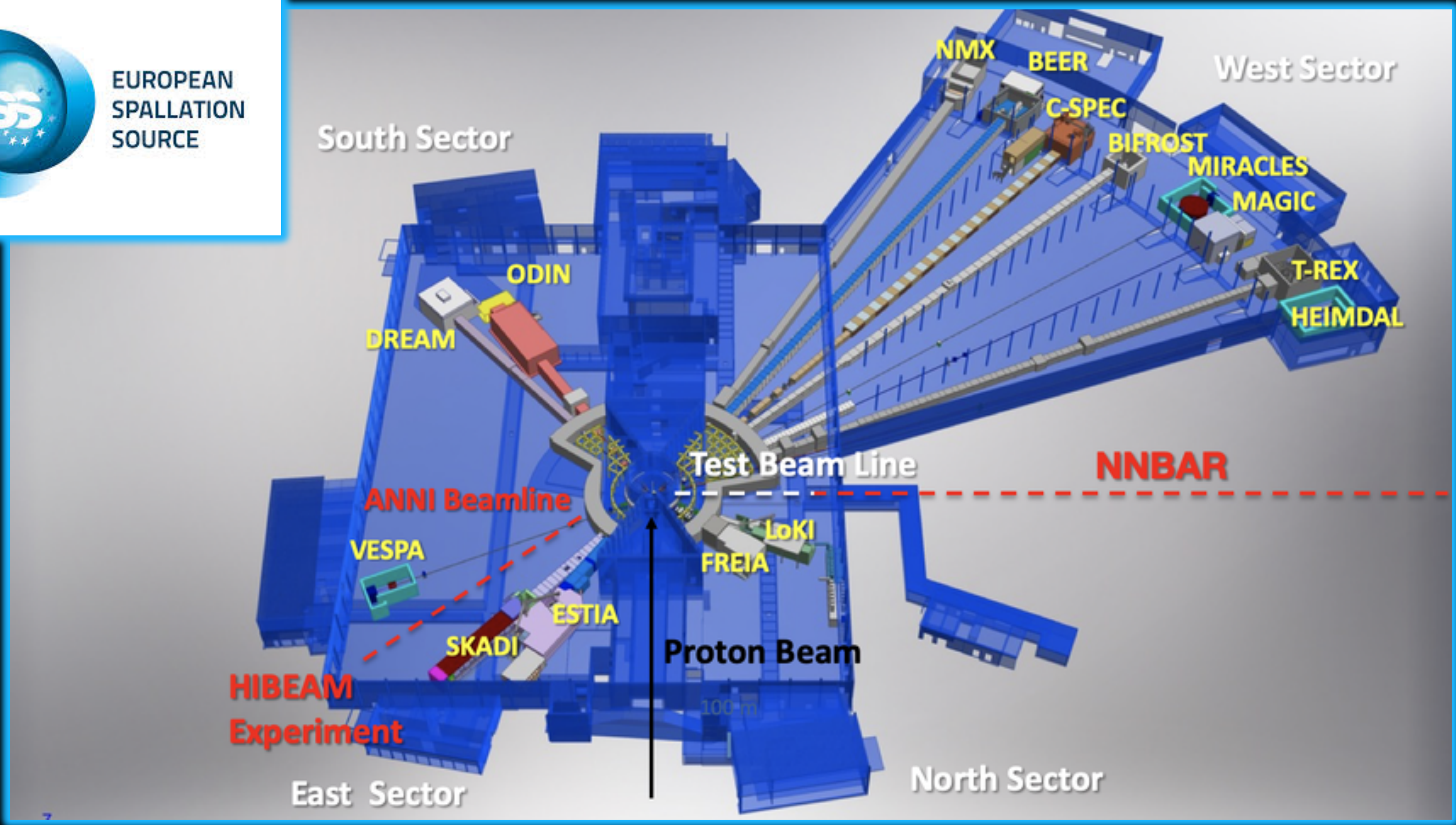
iThemba LABS Laboratory for Accelerator Based Sciences

# NEUTRON LIFETIME



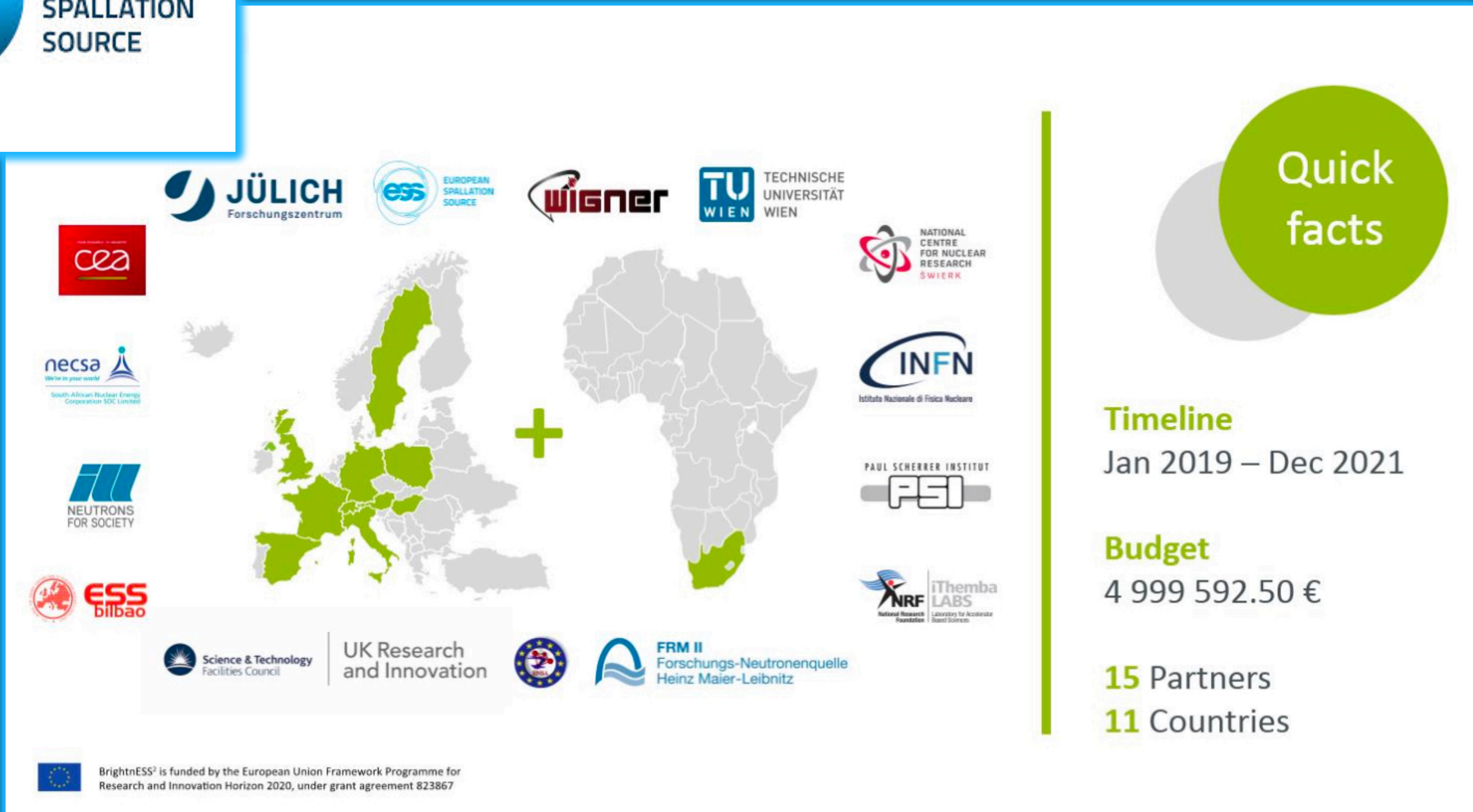
# EUROPEAN SPALLATION SOURCE

EUROPEAN SPALLATION SOURCE

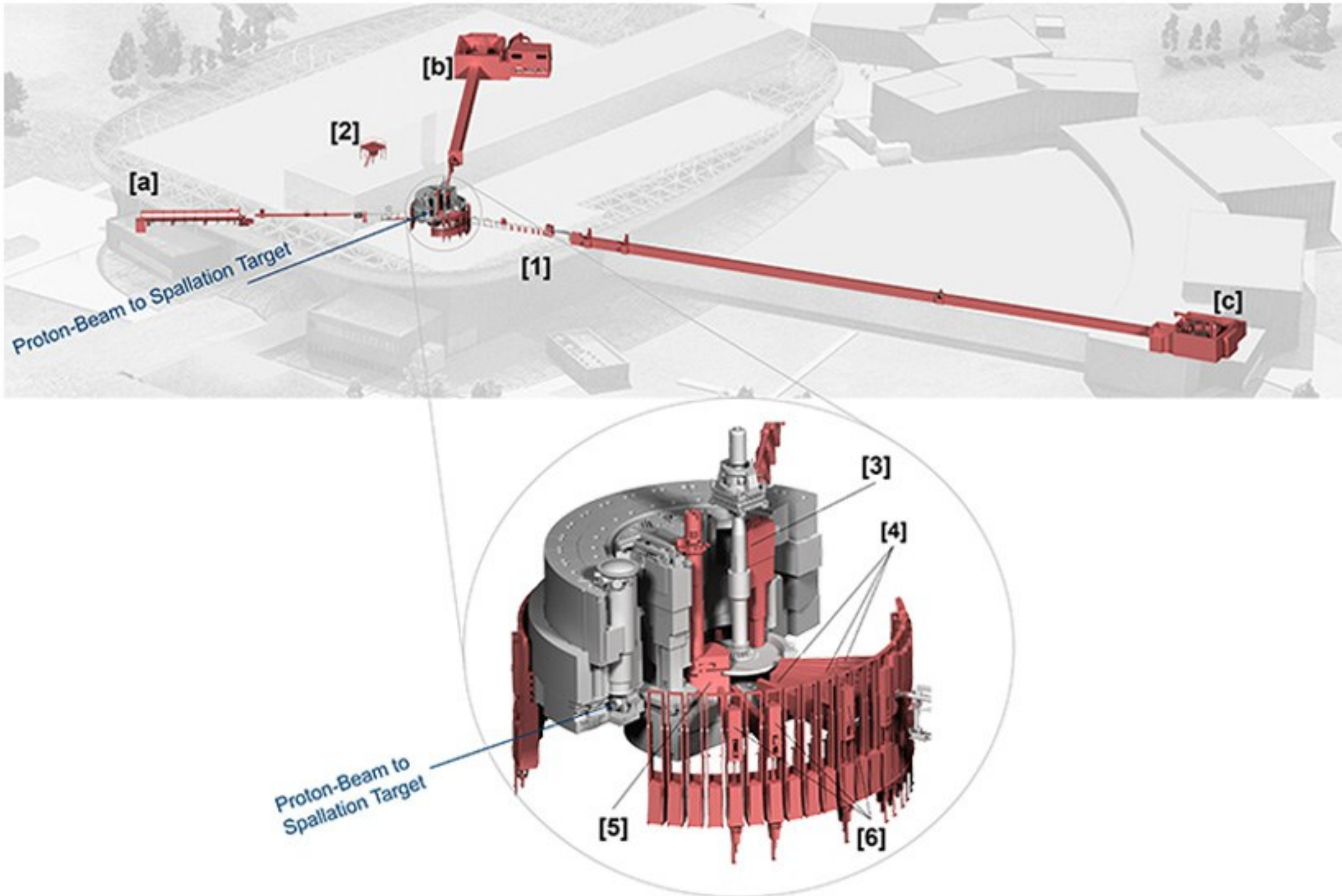


# EUROPEAN SPALLATION SOURCE: BRITHNESS

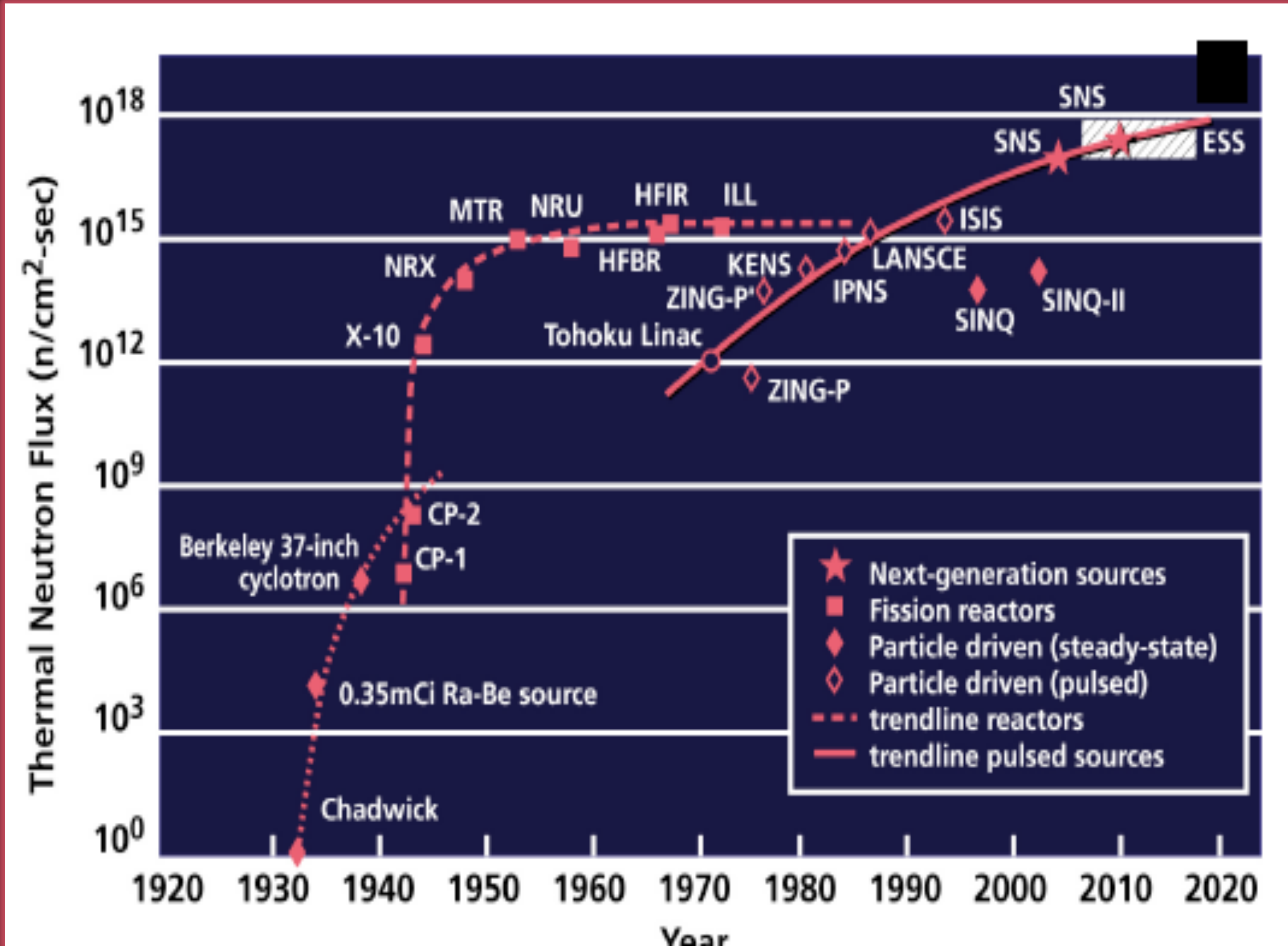
EUROPEAN SPALLATION SOURCE



# EUROPEAN SPALLATION SOURCE: ULTRACOLD NEUTRONS SOURCE



# ULTRA-COLD NEUTRON SOURCES



# THE NEUTRON: DIAMOND JUBILEE

## Possible Existence of a Neutron

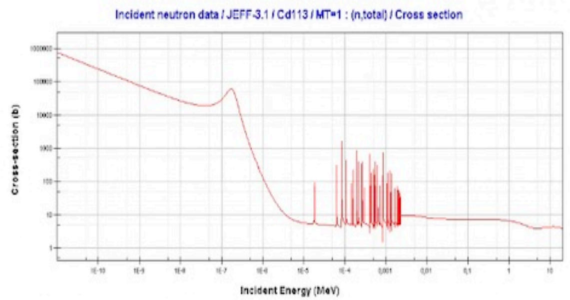
James Chadwick
*Nature,* p. 312 (Feb. 27, 1932)

It has been shown by Bothe and others that beryllium when bombarded by α-p[illegible]f polonium emits a radiation of great penetrating power, which has been an absorption coefficient in lead of about 0.3 $(cm)^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly $3 \times 10^9$ cm. per sec. They suggested that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of $50 \times 10^6$ electron volts.
I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier, and the sudden production of ions by the entry of a particle, such as a proton or α-particle, is recorded by the deflexion of an oscillograph. These experiments have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about $3.2 \times 10^9$ cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

If we ascribe the ejection of the proton to a Compton recoil from a quantum of $52 \times 10^6$ electron volts, then the nitrogen recoil atom arising by a similar process should have an energy not greater than about 400,000 volts, should produce not more than about 10,000 ions, and have a range in air at N.T.P. of about 1.3 mm. Actually, some of the recoil atoms in nitrogen produce at least 30,000 ions. In collaboration with Dr. Feather, I have observed the recoil atoms in an expansion chamber, and their range, estimated visually, was sometimes as much as 3 mm at N.T.P.

# THE NEUTRON: DIAMOND JUBILEE

- **Cold Neutrons** (0 eV; 0.025 eV). Neutrons in thermal equilibrium with very cold surroundings such as liquid deuterium. This spectrum is used for neutron scattering experiments.
- **Thermal Neutrons**. Neutrons in thermal equilibrium with a surrounding medium. Most probable energy at 20°C (68°F) for Maxwellian distribution is **0.025 eV** (~2 km/s). This part of the neutron's energy spectrum constitutes the most important spectrum **in thermal reactors**.
- **Epithermal Neutrons** (0.025 eV; 0.4 eV). Neutrons of kinetic energy are greater than thermal. Some reactor designs operate with an epithermal neutron spectrum. This design allows reaching a higher fuel breeding ratio than in thermal reactors.
- **Cadmium Neutrons** (0.4 eV; 0.5 eV). Neutrons of kinetic energy below the **cadmium cut-off** energy. One cadmium isotope, $^{113}Cd$, absorbs neutrons strongly only if they are below ~0.5 eV (cadmium cut-off energy).




Neutrons of kinetic energy below the cadmium cut-off energy (~0.5 eV) are strongly absorbed by 113-Cd. Source: JANIS (Java-based nuclear information software) www.oecd-nea.org/janis/

- **Epicadmium Neutrons** (0.5 eV; 1 eV). Neutrons of kinetic energy above the cadmium cut-off energy. These neutrons are not absorbed by cadmium.
- **Slow Neutrons** (1 eV; 10 eV).
- **Resonance Neutrons** (10 eV; 300 eV). **The resonance neutrons** are called resonance for their special behavior. At resonance energies, the cross-sections can reach peaks more than 100x higher than the base value of the cross-section. At these energies, the neutron capture significantly exceeds the probability of fission.

# OUTLINE

1- Generalities

2-Neutron lifetime,

3-Basics of neutron optics,

4A-Trapping neutron in Single Fabry-Perot nanoresonator Heisenberg uncertainty governed precision

4B-Free propogation of neutron in coupled Fabry-Perot nanoresonators with $^{10}B$

5- Conclusion/Foresight

# OUTLINE

1- Generalities

2-Neutron lifetime,

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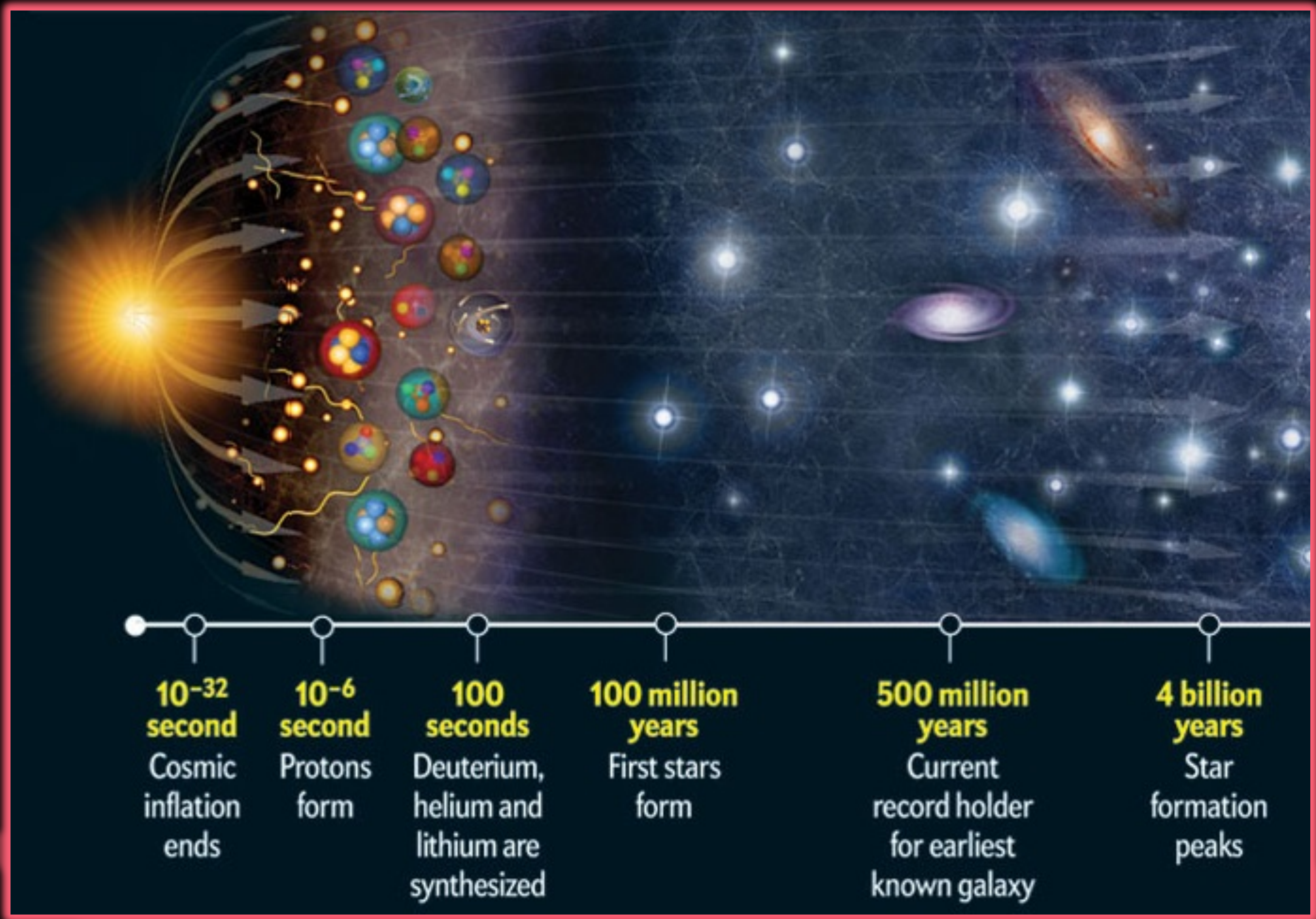
4B-Free propogation of neutron in coupled Fabry-Perot nanoresonators with $^{10}B$

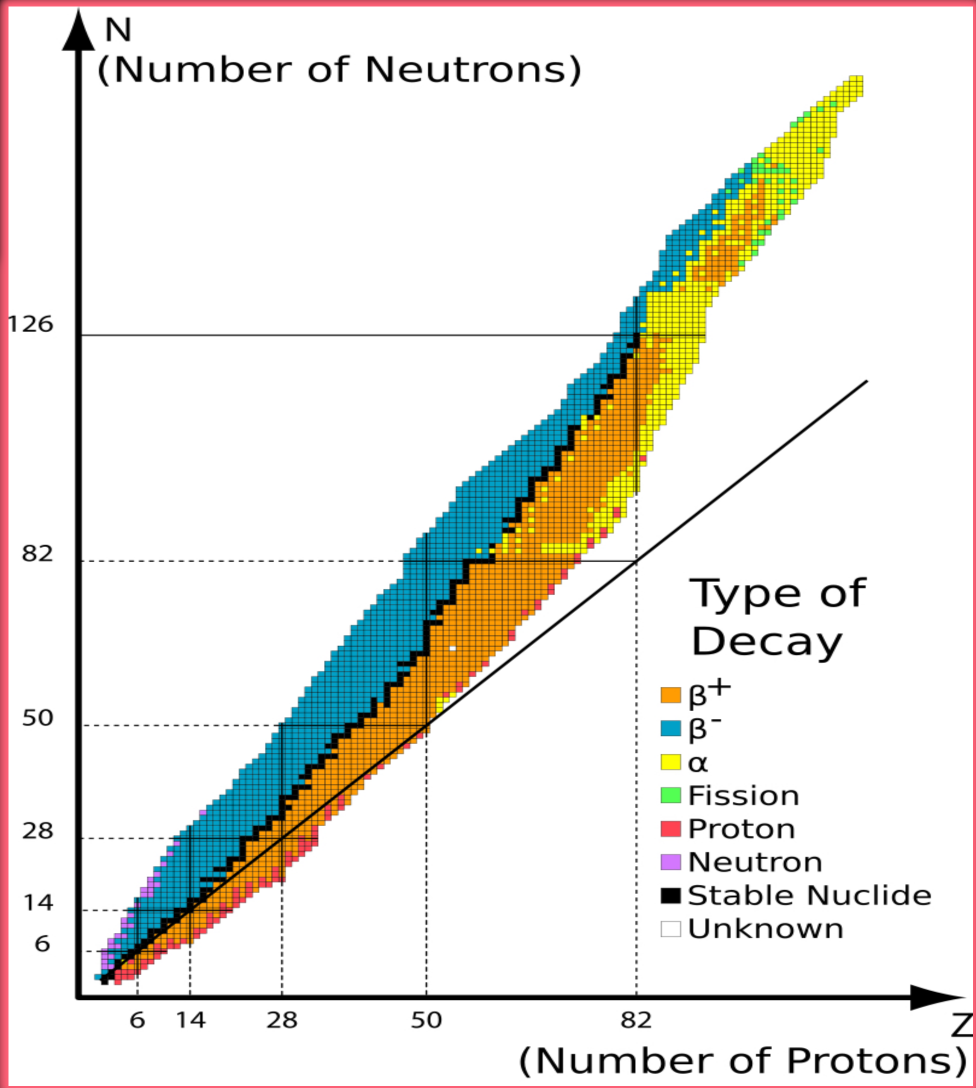
5- Conclusion/Foresight

# NEUTRON: ELEMENTS PERSPECTIVE

# NEUTRON: COSMOLOGY PERSPECTIVE

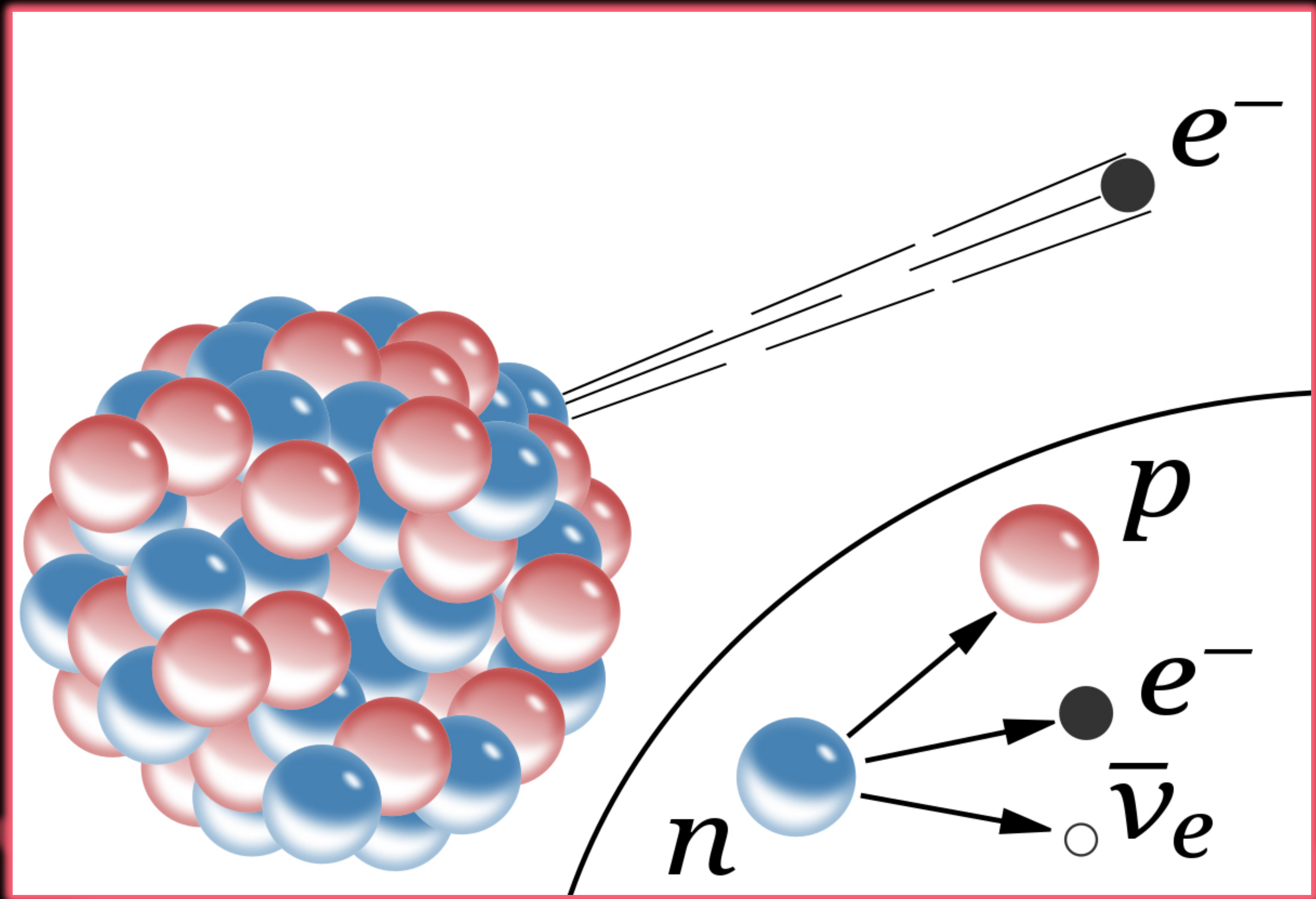


# NEUTRON: β–DECAY
# & NUCLEAR-CHART PERSPECTIVE

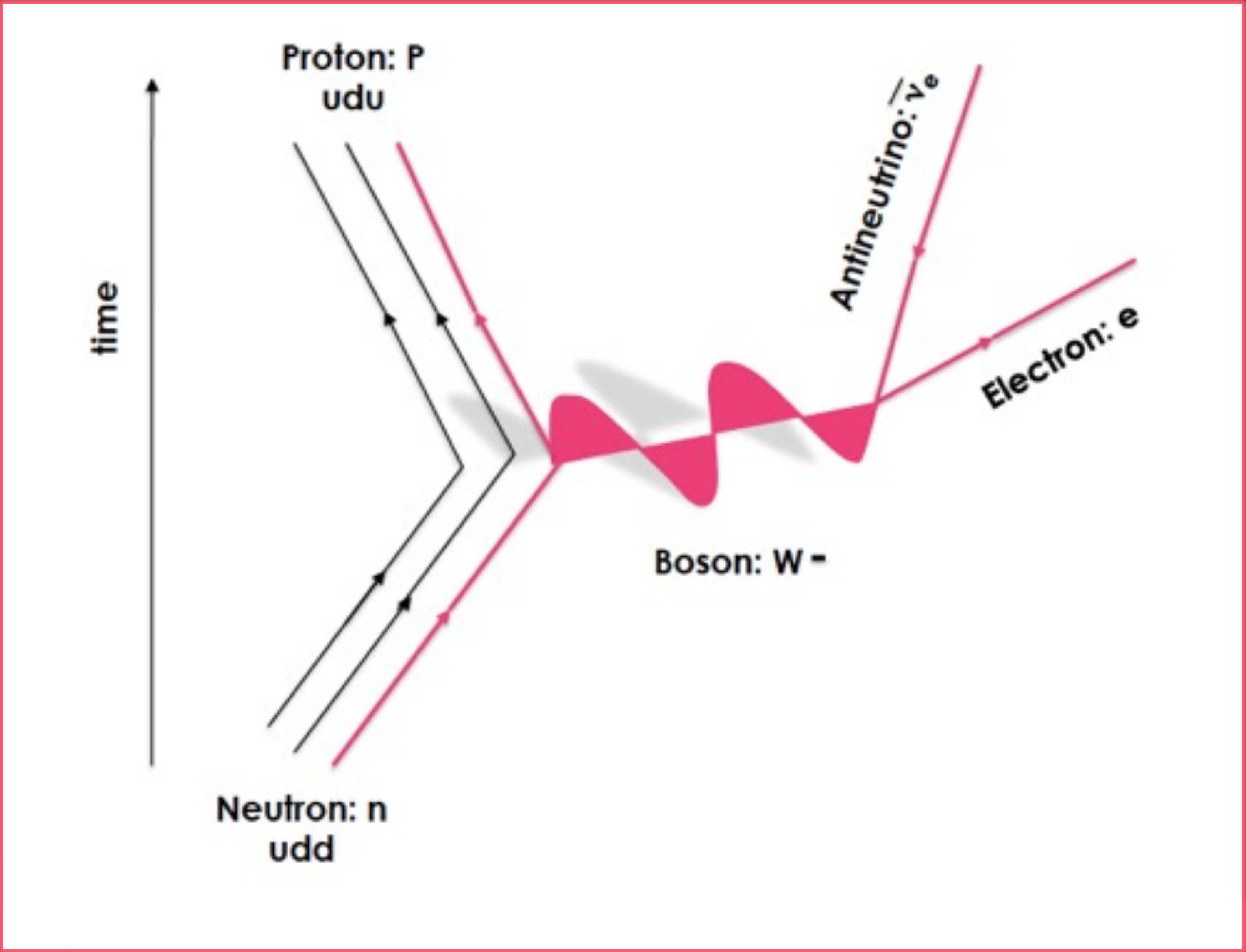



## $\beta^+$ DECAY

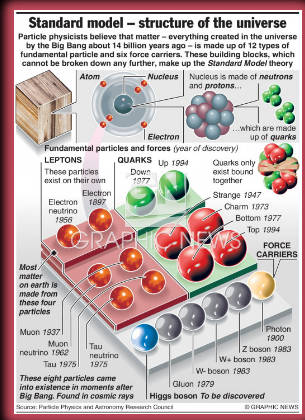
# NEUTRON: β–DECAY



# NEUTRON: β–DECAY



# NEUTRON: 4 FORCES S.M. & Q.M.

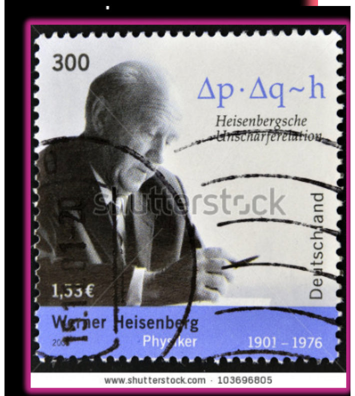


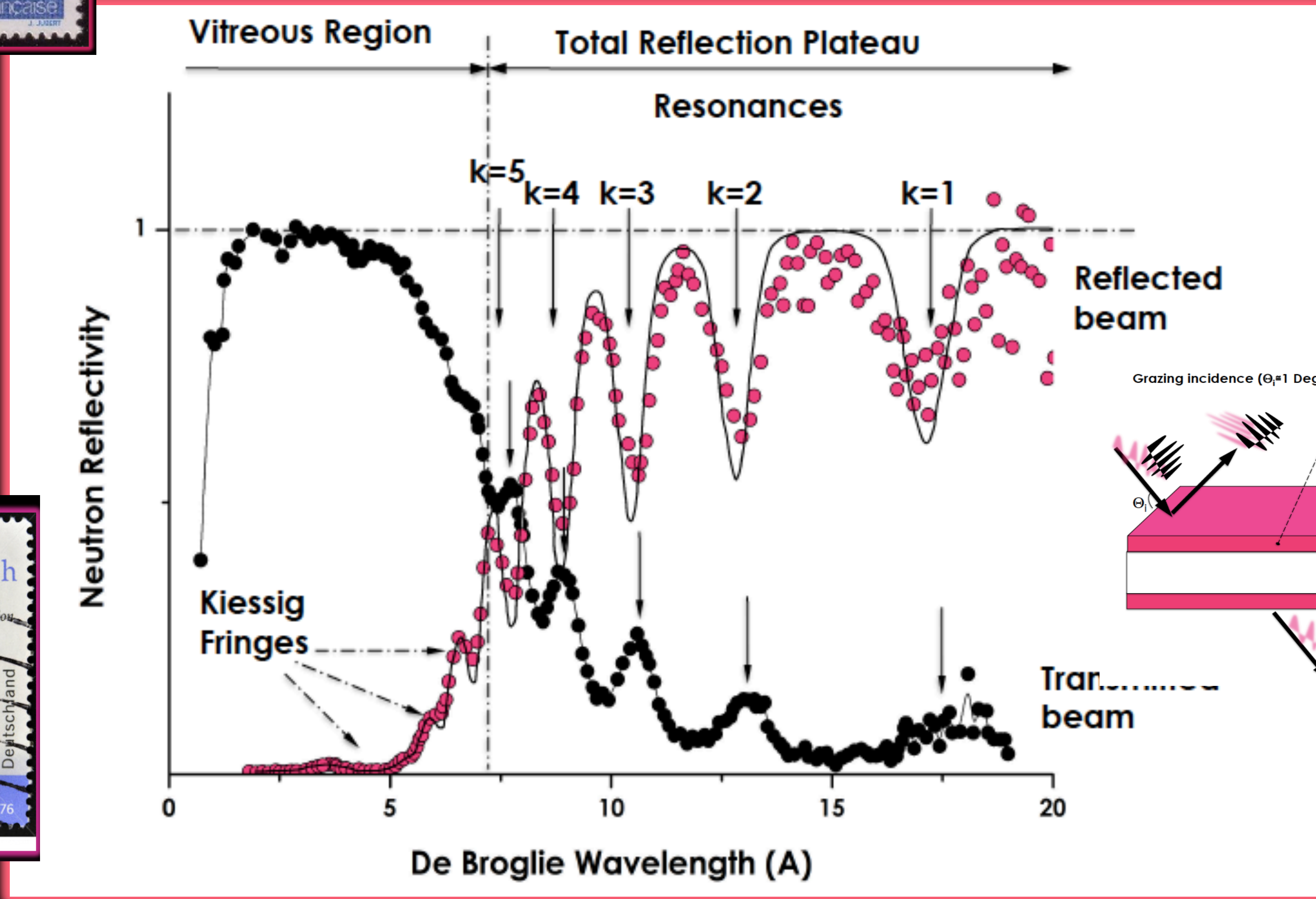

- Postulated 1920: Rutherford
- Confirmed 1933 : Chadwick
- Sensitive to the 4 forces
- β-Decay & Standard model

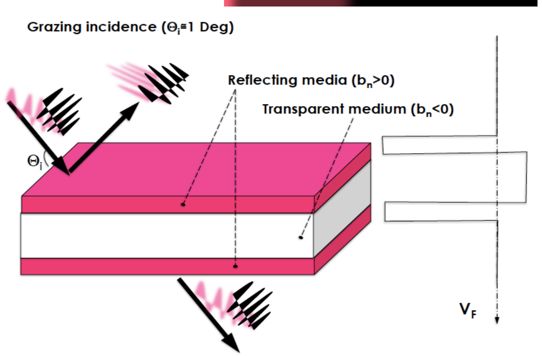
- Wave-particle duality & Ideal Quantum Mech.
- Total Reflection 1946
- Interferometry 1973
- Neutron Optics

# FRUSTRATED TOTAL REFLECTION of NEUTRON WAVE-PACKETS.



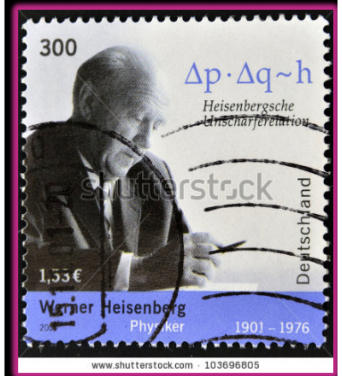


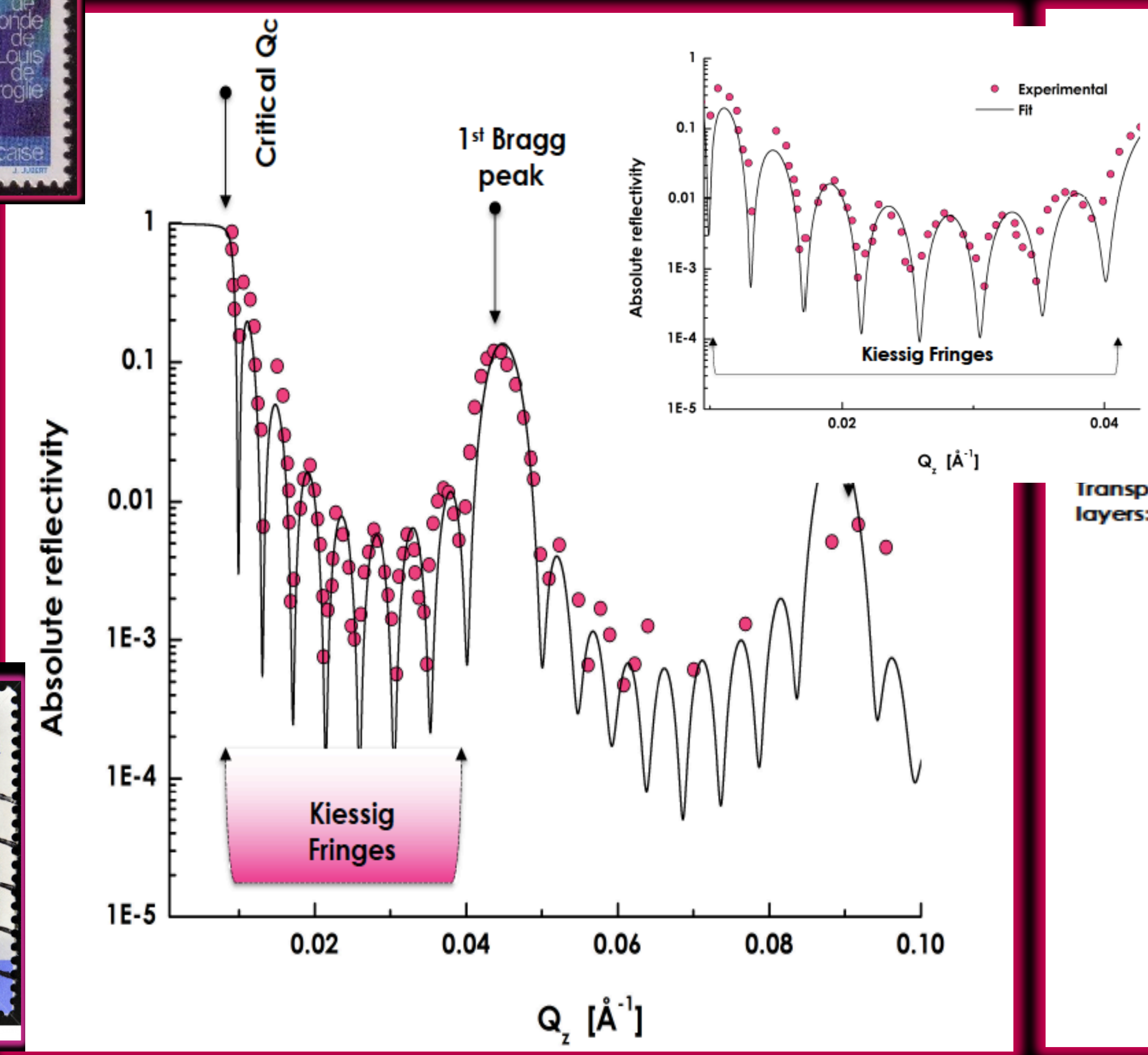



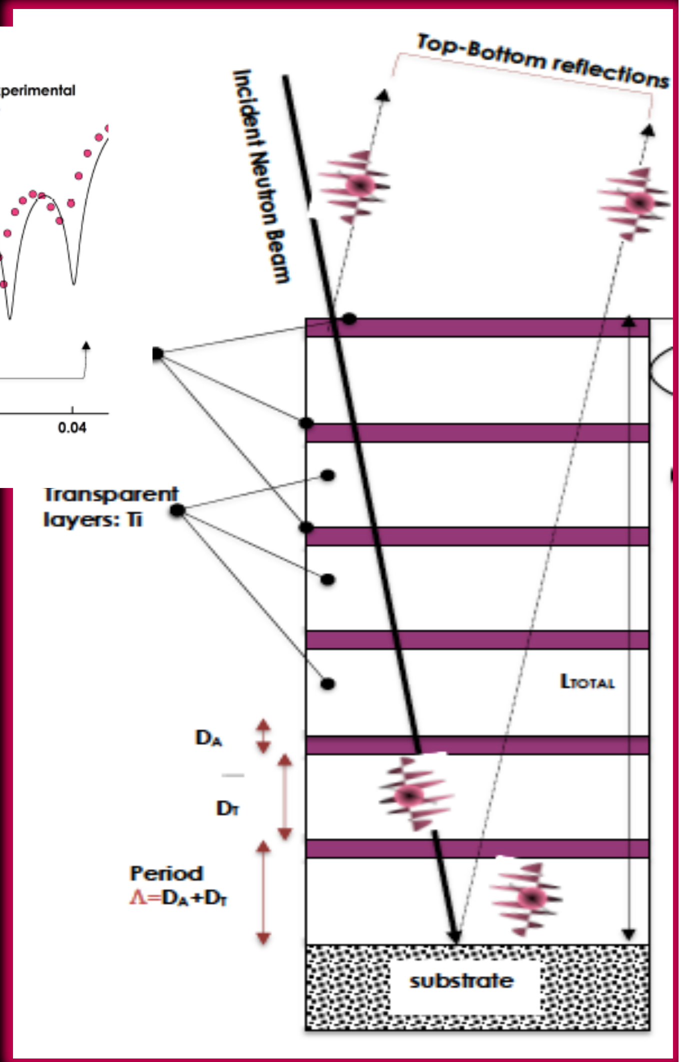



# NEUTRON WAVE-PACKETS: FULL TRANSPARENCY THROUGH BORON






*Neutron Diamond Jubilee, U2ACN2, Sept.2022, Lund-Sweden, UCN-ESS2022*

# NEUTRON WAVE-MATTER : SUMMARY

Journal of Neutron Research 00 (20xx) 1–16
DOI 10.3233/JNR-220015
IOS Press 

## On the trapping of neutrons in Fabry–Pérot nano-structures and potential applications for cold neutron lifetime Investigations

M. Maaza [a,b,*], B. Pardo [c,†], D. Hamidi [a,b], M. Akbari [a,b], R. Morad [a,b], M. Henini [a,b,d] and A. Gibaud [a,b,e]

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[b] *Nanosciences African Network (NANOAFNET), iThemba Laboratories for Accelerators Based Sciences, iThemba LABS-National Research Foundation, PO Box 722, Somerset West, Western Cape Province, South Africa*
[c] *Institut d'Optique Théorique & Appliquée, Université Paris-Saclay, France*
[d] *Physics Department, University of Nottingham, Nottingham, UK*
[e] *IMMM, UMR 6283 CNRS, Université of Le Maine, Bd O. Messiaen, 72085 Le Mans cedex 09, Le Mans, France*

**Abstract.** Correlated to the neutron total reflection phenomenon is the so-called frustrated total reflection, also known as neutron channeling, observed with both thermal and cold neutrons. Within this contribution, such a phenomenon is validated in various additional distinctive Fabry–Pérot nano-resonating configurations; namely in: (i) dual reflection and transmission neutron Fabry–Pérot nano-resonator (Ni/V/Ni/Si substrate), (ii) isotope-based neutron Fabry–Pérot nano-resonator ($^{58}$Ni/$^{62}$Ni/$^{58}$Ni/Silicon substrate), and (iii) multilayered neutron Fabry–Pérot nano-resonator of 8 superposed ($B_4C$/Ti/$B_4C$) single nano-resonators. While such Fabry–Pérot nano-resonators allow effective neutron trapping, the precision of the trapping time of free neutrons in such nano-resonators is governed by the Heisenberg uncertainty and hence offers, a priori, an additional attractive precise approach for potential lifetime investigations. Depending on the configuration of the Fabry–Pérot nano-resonators and the available cold neutron beam, the trapping time is found to be within the temporal regime of 3 to 19 ps. While the main intention of this contribution is to validate the possibility of trapping cold neutrons in nano-structured Fabry–Pérot resonators with a picosecond precision in various configurations, it is hoped that these preliminary results will attract the interest of the neutron lifetime community specifically and the neutron scattering community in general. The potential integration of such trapping method into the bottle or beam methods would elucidate the origin of the difference in neutron lifetime between the two approaches.

Keywords: Neutron trapping, Fabry–Pérot nano-resonators, frustrated total reflection, neutron waveguiding, neutron lifetime, total reflection, Zeldovich–Vinogradov configuration, $B_4C$, Fermi pseudo-potential

# NEUTRON WAVE-MATTER: ODYSSEY-1987

Nuclear Instruments and Methods in Physics Research A326 (1993) 531–537
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

## New optical transmission device to produce high monochromatic and high polarized neutron beams based on the tunneling frustrated total reflection in neutron guides

M. Maaza

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*Institut d'Optique Théorique et Appliquée, Bat 503, Université Paris Sud, Orsay, France*

Received 23 July 1992 and in revised form 12 October 1992

It has been shown that the tunneling of neutrons can be used in classical neutron guides to extract high monochromatic and/or high polarized cold neutron beams. This can be achieved by implanting $^{58}$Ni–Ti–$^{58}$Ni or $^{58}$Ni–Co–$^{58}$Ni Fabry–Pérot interferometers under total reflection condition in the neutron guide. According to the computed results, this tunneling phenomenon of neutrons manifests itself by the existence of sharp resonances in the $^{58}$Ni total reflection plateau. These resonances are localized at different spectral positions $\lambda^{r}_{\pm}$ for the monochromatization and $\lambda^{r}_{+}$, $\lambda^{r}_{-}$ for the polarization. The narrow spectral bandwidth of the tunneling transmitted beam can reach values of the order of $\Delta\lambda \approx 0.01$ Å and a strong transmissivity higher than 99%. The number and the spectral position of these resonances vary mainly with the characteristics of the spacer layer Ti or Co whereas their spectral bandwidths are imposed by the thickness of the reflecting $^{58}$Ni layers of the Fabry–Pérot interferometer. To obtain low resonance orders, the use of a nonmagnetic substrate with a negative nuclear scattering length density and a perfect collimated polychromatic neutron beam is required.

# NEUTRON WAVE-MATTER: ODYSSEY-1987

Physics Reports 514 (2012) 177–198

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Physics Reports

journal homepage: www.elsevier.com/locate/physrep

ELSEVIER


## Nano-structured Fabry–Pérot resonators in neutron optics & tunneling of neutron wave-particles

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Total reflection
Frustrated total reflection
Tunneling phenomenon
Resonance

**ABSTRACT**

Correlated to the quantum mechanics wave-particle duality, the optical analogy between electromagnetic waves and cold neutrons manifests itself through several interference phenomena particularly the so called Frustrated Total Reflection i.e., the tunneling process in Fabry–Pérot nano-structured cavities. Prominent resonant situations offered by this configuration allow the attainment of numerous fundamental investigations and surface-interface studies as well as to devise new kinds of neutron optics devices. This review contribution reports such possibilities in addition to the recently observed peculiar Goos–Hänchen longitudinal shift of neutron wave-particles which was predicted by Sir Isaac Newton as early as 1730.

# NEUTRON WAVE-MATTER: ODYSSEY-1987

*J. Appl. Cryst.* (1993). **26**, 327–333

## Tunneling Reflection with Polarized Slow Neutrons: Polarized-Neutron Total Frustrated Reflection

By M. Mâaza

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(*Received 2 July 1992; accepted 2 October 1992*)

### Abstract

This work describes the conditions required to observe the tunneling phenomenon in the grazing-angle reflection configuration of both polarized and unpolarized monochromatic neutron waves. According to the computed results, this neutron-tunneling phenomenon manifests itself by the existence of sharp resonances in the total reflection plateau. Their angular positions depend on the polarization state of the incident neutron waves. We treat the case where all these tunneling resonances (high and low orders) in the total-reflection plateau are observed. This can be

complete when the evanescent wave meets the second medium and a proportion of the incident electromagnetic evanescent wave will appear in the second medium. The reflectivity at the first interface (air–first-medium interface) will be less than total. This, as Baumeister (1967) has pointed out, is very similar to the behavior of fundamental particles tunneling through a potential barrier; such is the case for electrons in quantum semiconductor wells. Practically, this evanescent-waves effect is applied to the study of surface plasmons in Kretschmann geometry (Otto, 1968; Abelès, 1971).

# NEUTRON WAVE-MATTER: ODYSSEY-1987

Physics Letters A 181 (1993) 276–282
North-Holland

PHYSICS LETTERS A

## New generation of neutron interferometers based on tunneling frustrated total reflection of polarized neutron waves

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Received 3 May 1993; accepted for publication 10 August 1993
Communicated by J.P. Vigier

We present a new generation of neutron interferometers using a new splitting mode. The method is based on the tunneling frustrated total reflection of neutron waves. The splitting of an incident neutron beam into two coherent partial beams is achieved by using magnetized Fabry–Perot resonators. These resonators which work under total reflection conditions, are constituted of stacks of $^{58}$Ni/Co/$^{58}$Ni/bulk Co. More specifically, when the resonance condition of the Fabry–Perot resonators is fulfilled, resonant spin down waves are totally tunneled while the corresponding spin up waves are totally reflected. The number of these tunneling resonances changes mainly with the thickness of the spacer layer of Co while their band-pass is linked to the thickness of the reflecting $^{58}$Ni layers.

# NEUTRON WAVE-MATTER: ODYSSEY-1987

N·H
ELSEVIER

21 November 1994

PHYSICS LETTERS A

Physics Letters A 195 (1994) 1–8

## Shearing neutron interferometry and possibilities of studying interfacial diffusion processes between two highly dilute solutions ☆

M. Mâaza [a,b], B. Pardo [a], S. Shamlal Mallick [a], F. Bridou [a], D.A. Korneev [b], L.P. Chernenko [b], C. Sella [c]

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Received 14 October 1993; revised manuscript received 6 September 1994; accepted for publication 13 September 1994
Communicated by J.P. Vigier

**Abstract**

We deal with the adaptation of the classical shearing interferometry in neutron optics and suggest a shearing neutron interferometer device. A polarized monochromatic neutron plane wave–particle front is distorted in passing through a diffusion cell containing two liquids in accordance with the variation of the concentration in the solution. This distorted front is sheared into two coherent fronts. The related interference spectrum varies in time and the diffusion coefficient can be deduced. The proposed method would be convenient to measure diffusion coefficient for very low concentrations smaller than $10^{-3}$ g/cm$^3$.

# NEUTRON WAVE-MATTER: ODYSSEY-1987

ELSEVIER

2 December 1996

PHYSICS LETTERS A

Physics Letters A 223 (1996) 145–148

## Neutron tunneling and neutron lifetime in a Ni–V–Ni Fabry–Perot thin film resonator

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Received 13 June 1996; accepted for publication 16 September 1996
Communicated by P.R. Holland

**Abstract**

Observations are reported on the appearance of frustrated total reflection, i.e. the tunnelling phenomenon, with cold neutron wave-particles. This tunnelling resonance was observed in a thin film Ni–V–Ni Fabry–Perot cavity by time of flight grazing angle neutron reflectometry. This frustrated total reflection phenomenon was used to estimate the neutron lifetime, which varies from approximately 0.1 to 1 μs.

# NEUTRON WAVE-MATTER: ODYSSEY-1987

ELSEVIER

20 October 1997

PHYSICS LETTERS A

Physics Letters A 235 (1997) 19–23

## Zeeman neutron tunneling in "Ni–Co–Ni" thin film resonators

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[b] *Institut d'Optique Théorique & Appliquée, Bat. 503, Université d'Orsay, Orsay 91403, France*
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Received 5 February 1997; revised manuscript received 2 June 1997; accepted for publication 4 July 1997
Communicated by J.P. Vigier

**Abstract**

Polarized neutron tunneling measurements are reported, achieved by using simple and double thin film Ni–Co–Ni Fabry–Perot resonators operating in the total reflection geometry in the polarized configuration. Due to the Zeeman magnetic interaction term in the cobalt layers mainly, a spatial separation of the spin up and down states results. The Zeeman tunneling splitting within such resonators can be exploited to produce monochromatic and polarized neutron beams in the range of $\lambda \geqslant 10$ Å. © 1997 Elsevier Science B.V.

*Keywords:* Zeeman interaction; Tunneling; Polarized neutrons

# NEUTRON WAVE-MATTER: ODYSSEY-1987

PERGAMON

Solid State Communications 111 (1999) 23–28

solid
state
communications

## V–Ni multilayered monochromators and supermirrors for cold neutrons

M. Maaza[a,*], J.P. Chauvineau[b], B. Pardo[b], A. Raynal[b], A. Menelle[c], F. Bridou[b], J. Corno[b]

[a]*Physics Department, University of the Witwatersrand, Wits 2050, Johannesburg, South Africa*
[b]*Institut d'Optique Théorique and Appliquée, Université Paris-Sud, Bat. 503, 91403 Orsay Cedex, France*
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Received 12 December 1998; accepted 15 March 1999 by R.T. Phillips

**Abstract**

We present experimental neutron reflectivity results showing that it is possible to use V–Ni multilayered systems as cold neutron monochromators and supermirrors. Compared to the Ni–Ti optics devices, the V–Ni stacks present sharp interfaces characterised by a low interfacial roughness and very small interfacial diffusion. 

*Keywords:* A. Nanostructures; C. X-ray scattering; D. Optical properties; E. Neutron scattering

# NEUTRON WAVE-MATTER: ODYSSEY-1987

PERGAMON

Solid State Communications 112 (1999) 177–181

solid state communications

www.elsevier.com/locate/ssc

## Thermal stability of Co–Ti multilayered neutron polarizers

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Received 12 December 1998; accepted 15 March 1999 by R.T. Phillips

**Abstract**

Thermal stability of multilayered Co–Ti neutron optic polarizers with a period of the order of 103 Å is investigated. The diffusion kinetics is determined by using the Du Mond and Youtz's method with grazing angle neutron reflectometry in the temperature range of 293–723 K. It was found that the diffusion is mainly directed from Co-layers towards the Ti-layers. The effective interdiffusion coefficient $D_{eff}$ of cobalt into titanium is calculated from the rate of decrease of the first reflected Bragg peak related to the artificial periodicity of the multilayer with the annealing temperature $T$. The temperature dependence of $D_{eff}$ is found to be described approximately by $D_{eff} \approx (D_0 \exp(-0.25\ \mathrm{eV}/k_B T))\ \mathrm{cm}^2\ \mathrm{s}^{-1}$. 

*Keywords:* A. Surfaces and interfaces; A. Thin films; E. Neutron scattering

# NEUTRON WAVE-MATTER: ODYSSEY-1987

Journal of Neutron Research 00 (20xx) 1–16
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IOS Press 

## On the trapping of neutrons in Fabry–Pérot nano-structures and potential applications for cold neutron lifetime Investigations

M. Maaza [a,b,*], B. Pardo [c,†], D. Hamidi [a,b], M. Akbari [a,b], R. Morad [a,b], M. Henini [a,b,d] and A. Gibaud [a,b,e]

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**Abstract.** Correlated to the neutron total reflection phenomenon is the so-called frustrated total reflection, also known as neutron channeling, observed with both thermal and cold neutrons. Within this contribution, such a phenomenon is validated in various additional distinctive Fabry–Pérot nano-resonating configurations; namely in: (i) dual reflection and transmission neutron Fabry–Pérot nano-resonator (Ni/V/Ni/Si substrate), (ii) isotope-based neutron Fabry–Pérot nano-resonator ($^{58}$Ni/$^{62}$Ni/$^{58}$Ni/Silicon substrate), and (iii) multilayered neutron Fabry–Pérot nano-resonator of 8 superposed ($B_4C$/Ti/$B_4C$) single nano-resonators. While such Fabry–Pérot nano-resonators allow effective neutron trapping, the precision of the trapping time of free neutrons in such nano-resonators is governed by the Heisenberg uncertainty and hence offers, a priori, an additional attractive precise approach for potential lifetime investigations. Depending on the configuration of the Fabry–Pérot nano-resonators and the available cold neutron beam, the trapping time is found to be within the temporal regime of 3 to 19 ps. While the main intention of this contribution is to validate the possibility of trapping cold neutrons in nano-structured Fabry–Pérot resonators with a picosecond precision in various configurations, it is hoped that these preliminary results will attract the interest of the neutron lifetime community specifically and the neutron scattering community in general. The potential integration of such trapping method into the bottle or beam methods would elucidate the origin of the difference in neutron lifetime between the two approaches.

Keywords: Neutron trapping, Fabry–Pérot nano-resonators, frustrated total reflection, neutron waveguiding, neutron lifetime, total reflection, Zeldovich–Vinogradov configuration, $B_4C$, Fermi pseudo-potential



# NEUTRON WAVE-MATTER: ODYSSEY-1987

*Nouv. Rev. d'Optique appliquée*, 1970, **1**, n° 4, pp. 229-232

INSTITUT D'OPTIQUE THÉORIQUE ET APPLIQUÉE, LABORATOIRE ASSOCIÉ DU C. N. R. S.
*Bâtiment 503, Faculté des Sciences, F 91-Orsay*

## SUR L'APPLICATION DES COUCHES INTERFÉRENTIELLES A L'OPTIQUE DES RAYONS X ET DES NEUTRONS

par

P. CROCE et B. PARDO

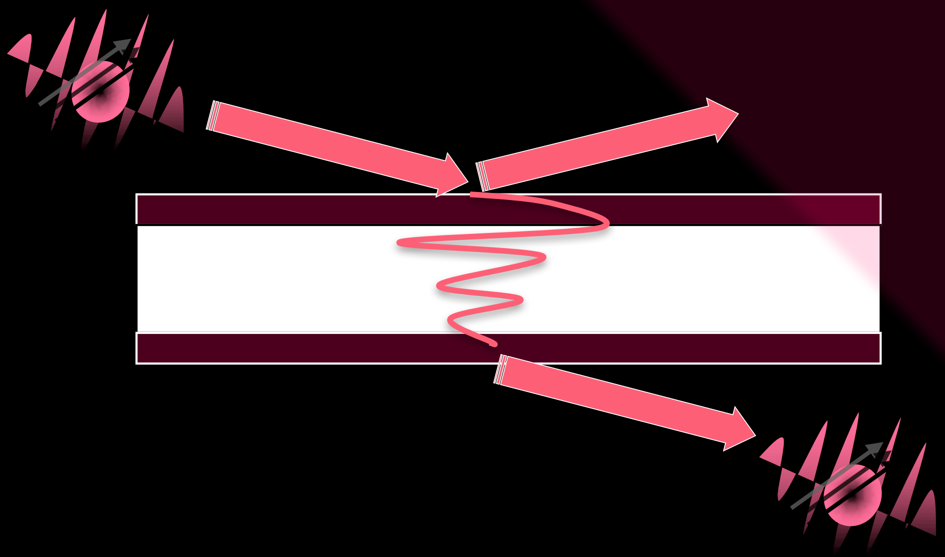
---

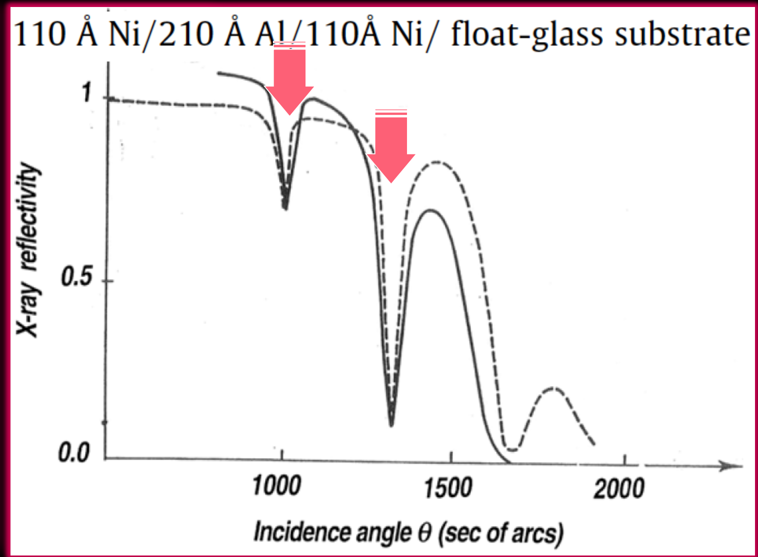
### *INTRODUCTION*

Dans une première partie nous étudierons la propagation des rayons X et des neutrons dans un système de couches multiples. Nous nous placerons dans le cas

dioptre). Nous verrons que du fait des faibles incidences et de la loi de dispersion, les déphasages, les coefficients de transmission et de réflexion des rayons X

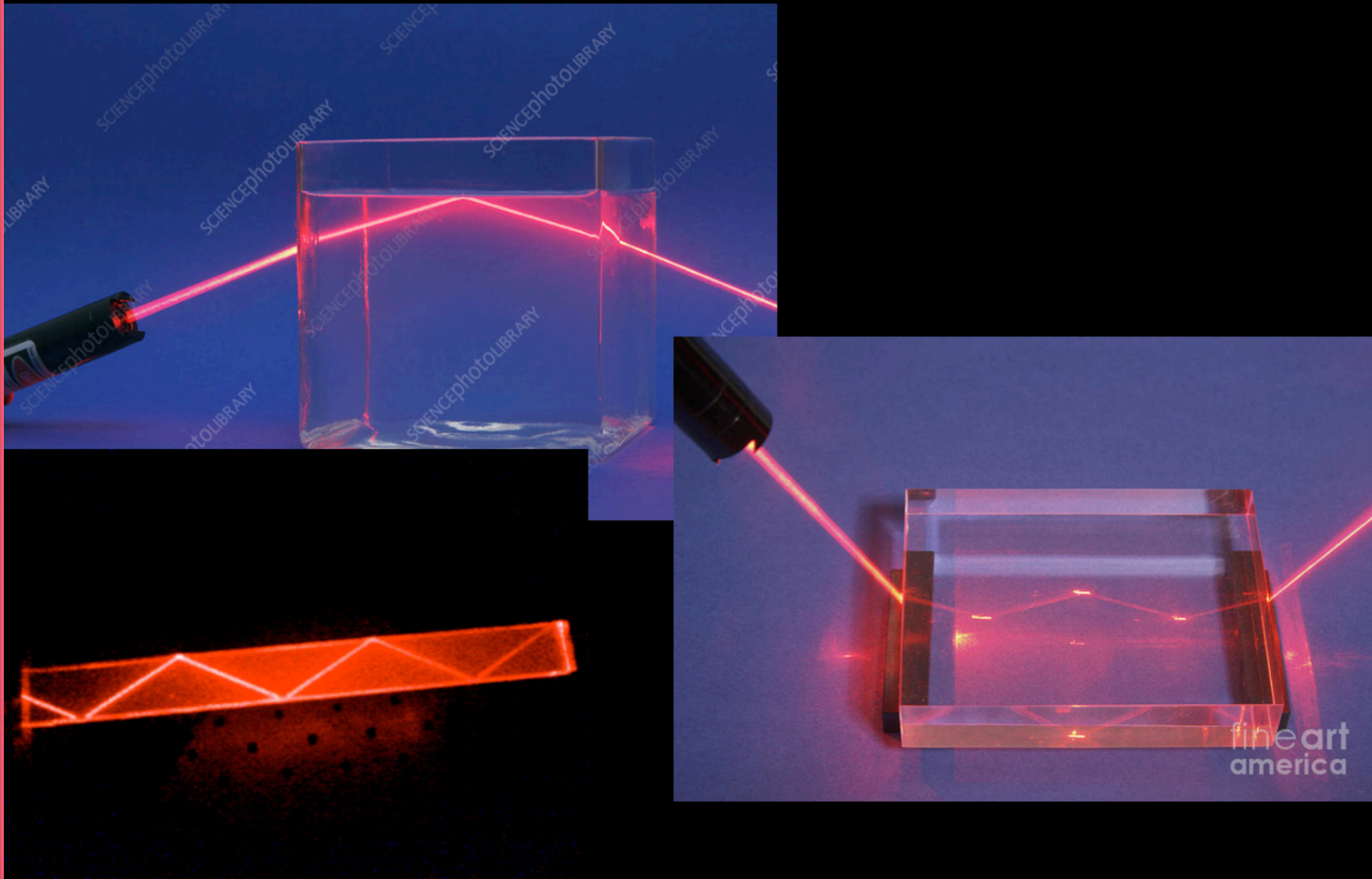
# NEUTRON WAVE-MATTER: ODYSSEY-1987






P. Croce, B. Pardo, Nouv. Rev. Opt. Appl. 1 (4) (1970) 229.

# TOTAL REFLECTION PHENOMENON



# OUTLINE

1- Generalities

2-Neutron lifetime,

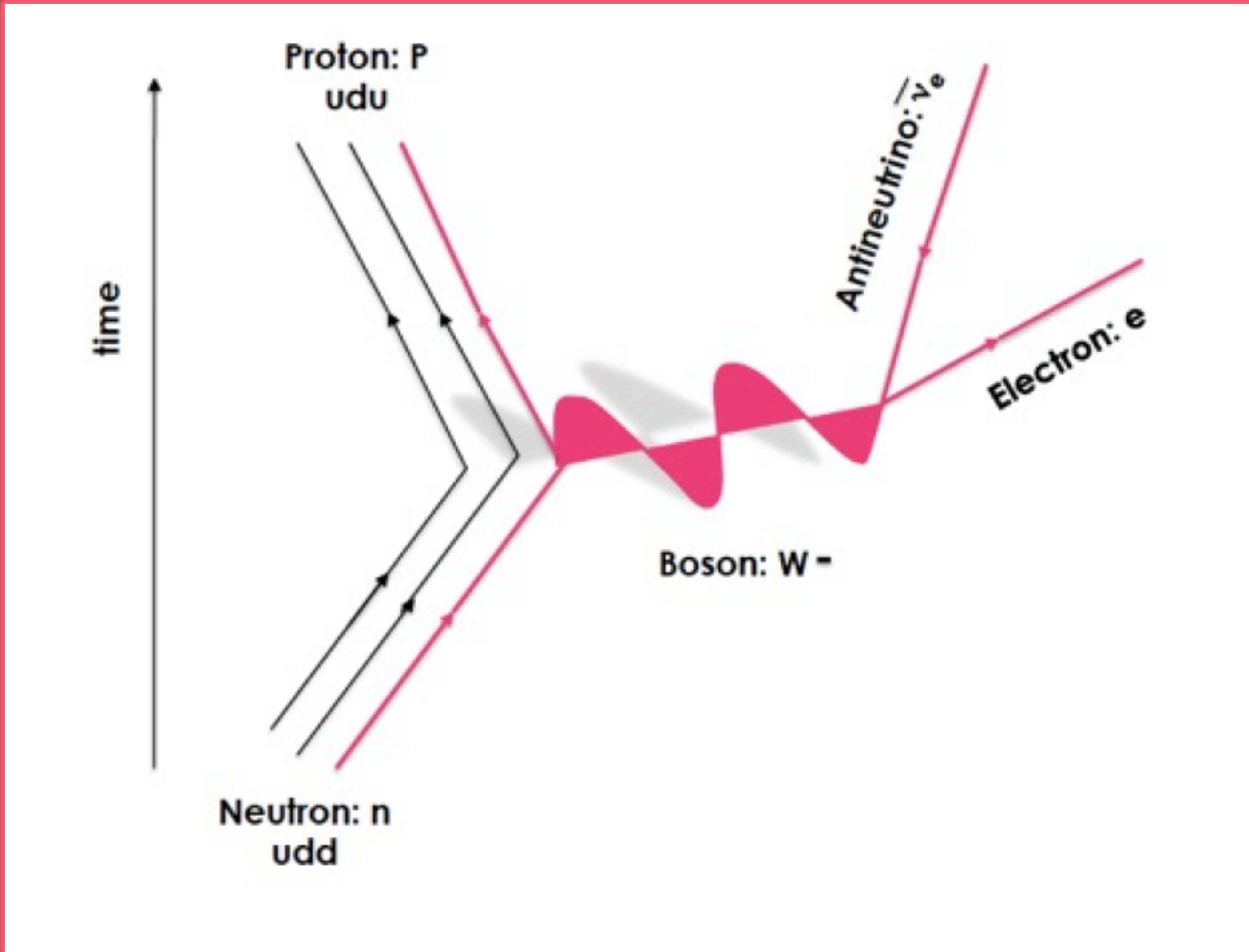
3-Basics of neutron optics,

4A-Trapping neutron in Single Fabry-Perot nanoresonator Heisenberg uncertainty governed precision

4B-Free propogation of neutron in coupled Fabry-Perot nanoresonators with $^{10}B$

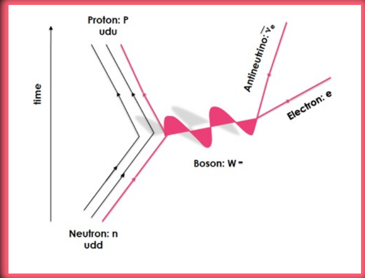
5- Conclusion/Foresight

# NEUTRON LIFETIME & S.M.




- Within the Standard model,the precision on $|Vud|$ is then of a prime importance and governed by the accuracy of the neutron's lifetime $\langle\tau_n\rangle$.

# NEUTRON LIFETIME & S.M.



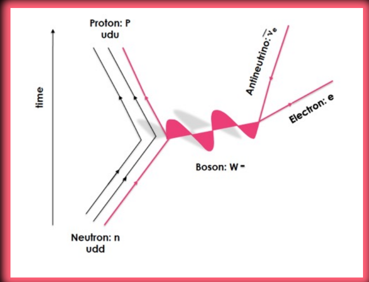

- Within the Standard Model, the **Cabibbo-Kobayashi-Maskawa matrix** describes the strength of transitions between quarks in weak interactions. The first raw of the matrix is given by a series of

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix}.$$

Using those values, one can check the unitarity of the CKM matrix. In particular, we find that the first-row matrix elements give:

$$|V_{\mathrm{ud}}|^2 + |V_{\mathrm{us}}|^2 + |V_{\mathrm{ub}}|^2 = 0.9985 \pm 0.0005\,;$$

# NEUTRON LIFETIME & S.M.

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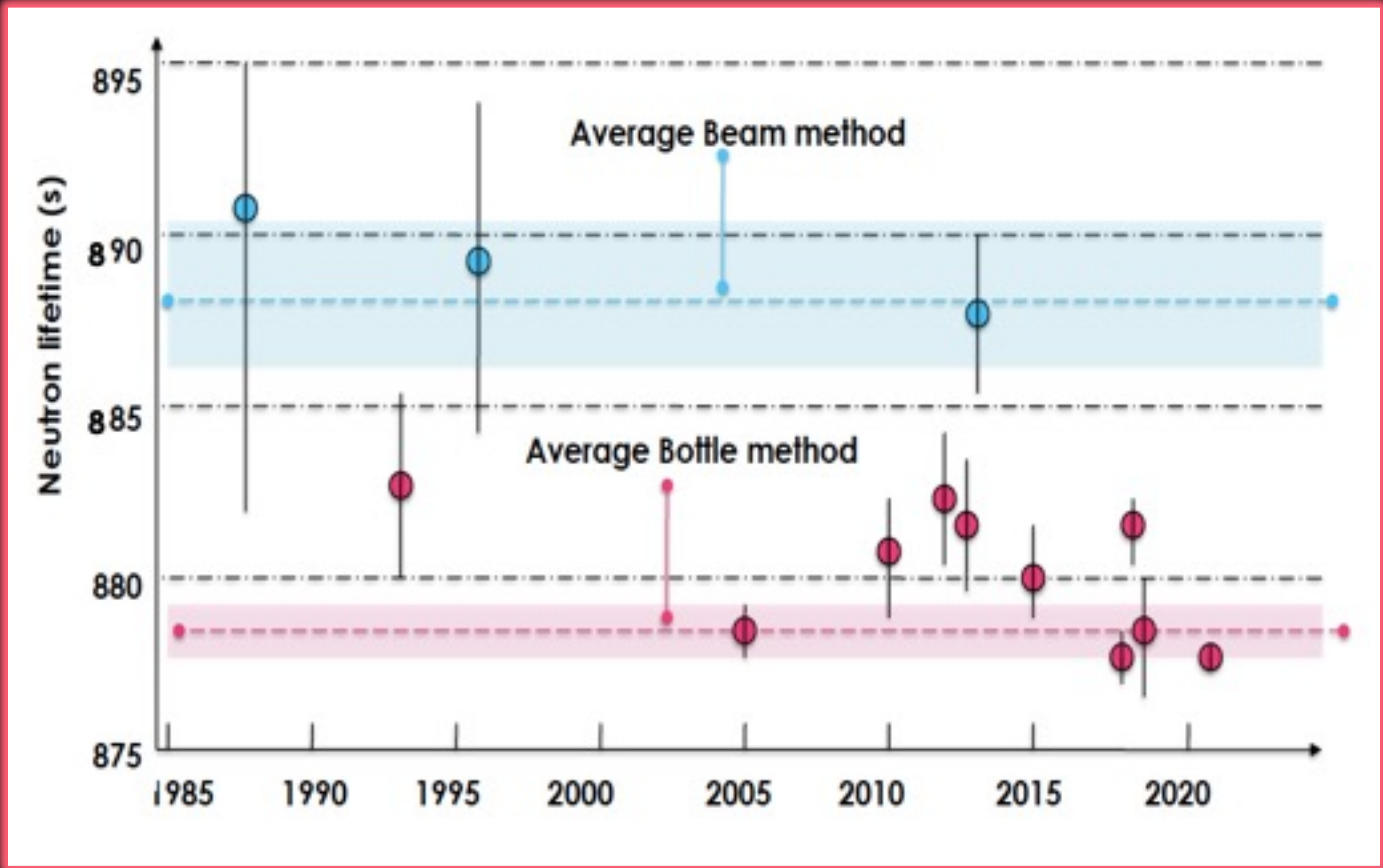
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994 \pm 0.0005 \, .$$

Most precise value of $|Vud|$ is derived from neutron decay

$$|Vud|^2 = (4908.7 \pm 1.9)/\langle \tau_n \rangle (1 + 3\varsigma^2)\varsigma,$$

$\varsigma$, being the ratio of the axial-vector and vector couplings.

# NEUTRON LIFETIME & S.M.



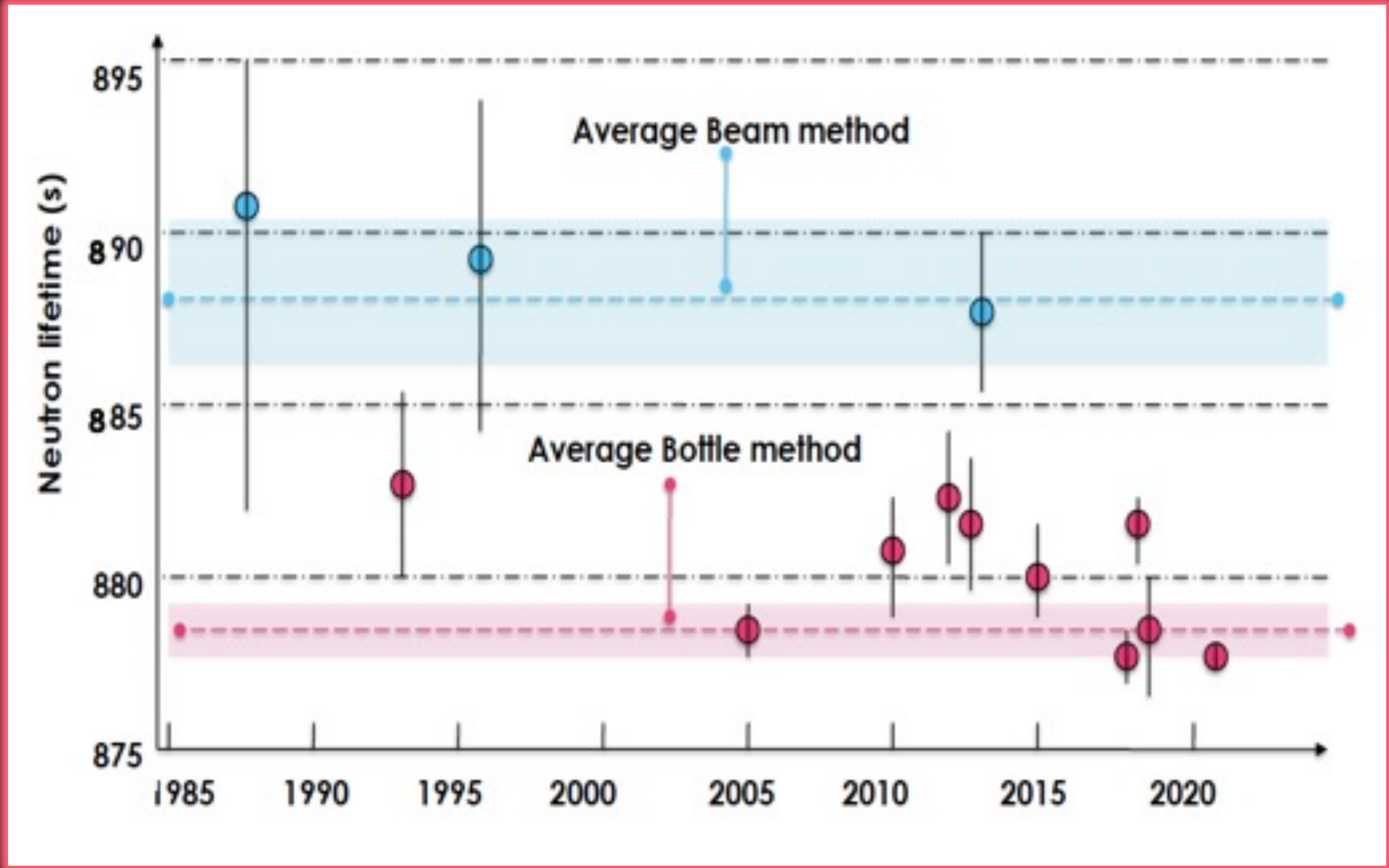

The average neutron lifetime derived from:

Beam approach was found to be $\langle \tau_n \rangle_{Beam} \sim 888.0 \pm 2.0$ s

Bottle technique of about $\langle \tau_n \rangle_{Bottle} \sim 879.4 \pm 0.6$ s [24,29,47].

This difference of ~10 s persists for years

# NEUTRON LIFETIME & S.M.




- This difference on $\langle \tau_n \rangle$ of $\sim 10\ s$ persisted over the years even if the two methods have been modified to enhance the experimental accuracy,

*Neutron Diamond Jubilee, U2ACN2, Sept.2022, Lund-Sweden, UCN-ESS2022*

# NEUTRON LIFETIME & S.M.

- Lifetime: $\langle\tau_n\rangle$ Used to predict the ratio of protons to helium atoms in the primordial universe and to search for physics beyond the Standard Model of particle physics. Relative abundance H/He

During Universe 1st few mins:

$$n/p=\exp(-\Delta m/kT_{freeze})\approx 1/6.$$

PARTICLE PHYSICS

## Physicists close in on neutron puzzle

*Researchers are narrowing down their measurements of how long the subatomic particle survives on its own.*

**BY ALEXANDRA WITZE IN DENVER, COLORADO**

Physicists are drawing nearer to answering a long-standing mystery of the Universe: how long a neutron lives.

Neutrons are electrically neutral particles that usually combine with protons to make up atomic nuclei. Some neutrons are not bound up in atoms; these free-floating neutrons decay radioactively into other particles in minutes.

But physicists can't agree on precisely how long it takes a neutron to die. Using one laboratory approach, they measure the average neutron lifetime as 14 minutes 39 seconds. Using a different approach, they get 8 seconds longer.

"We don't know why they're different," says Shannon Hoogerheide, a physicist at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. "We really need to understand and eliminate this discrepancy." She and other scientists debated new ways to solve the problem this month at a meeting of the American Physical Society in Denver, Colorado.

Pinpointing the lifetime of a neutron is important for understanding how much hydrogen, helium and other light elements formed in the first few minutes after the Universe was born 13.8 billion years ago. Scientists also think that pinning down the neutron's lifetime would help to constrain measurements of other subatomic particles.

One way of clocking the neutron's lifespan is to put some of the particles in a bottle and count how many are left after a period of time. This 'bottle' method has been tried at several laboratories, including the Los Alamos National Laboratory in New Mexico[1] and the Institut Laue–Langevin in Grenoble, France. On average, they come up with a neutron lifetime of 14 minutes 39 seconds.

The other way is to feed neutrons into a detector that counts the protons created as the neutrons decay. This 'beam' method has been used at NIST and at the Japan Proton Accelerator Research Complex in Tokai. The Japanese work has just begun, but the NIST team reported in 2013 that its neutrons live eight seconds longer, on average, than those in the bottle method[2].

That's a big problem, because the beam and bottle measurements don't overlap, even when their margins of error are taken into account. So physicists have been looking for ways to explain why neutrons might be disappearing from bottles faster than from beams.

One possibility is that one of the two methods is doing something wrong. In that case, researchers might want to combine beam

# NEUTRON LIFETIME TECHNIQUES

- QED: The Magneto-Gravitational UCN Trap
- Lifetime: $\tau_n$=877.7 +/- 0.6 s

Science

RESEARCH ARTICLES

Cite as: R. W. Pattie Jr. *et al.*, *Science* 10.1126/science.aan8895 (2018).

## Measurement of the neutron lifetime using a magneto-gravitational trap and in situ detection

R. W. Pattie Jr.,[1] N. B. Callahan,[2] C. Cude-Woods,[1,3] E. R. Adamek,[2] L. J. Broussard,[4] S. M. Engel,[6] D. E. Fellers,[1] W. Fox,[2] P. Geltenbort,[7] K. P. Hickerson,[8] M. A. Hoffbauer,[1] A. T. Hol MacDonald,[1] M. Makela,[1] C. L. Morris,[1] J. D. Ortiz,[1] J. Ramsey,[1] D. J. Salvat,[11] A. Saunders, Tang,[1] J. Vanderwerp,[2] B. Vogelaar,[5] P. L. Walstrom,[1] Z. Wang,[1] W. Wei,[1] H. L. Weaver,[1] J. Zeck[1,3]

[1]Los Alamos National Laboratory, Los Alamos, NM 87545, USA. [2]Center for Exploration of Energy and Matter an 47408, USA. [3]Triangle Universities Nuclear Laboratory and North Carolina State University, Raleigh, NC 27695, USA. [5]Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA. [7]Institut Laue-Langevin, Grenoble, France. [8]Kellogg Radiation Laboratory, California Institute of Technology, Pa Technological University, Cookeville, TN 38505, USA. [10]Department of Physics and Astronomy, DePauw Univers Physics, University of Washington, Seattle, WA 98195-1560, USA. [12]Joint Institute for Nuclear Research, Dubna,

*Corresponding author. Email: asaunders@lanl.gov

†Present address: Sandia National Laboratories, Albuquerque, NM 87185, USA.

The precise value of the mean neutron lifetime, $\tau_n$, plays an importan and cosmology. It is used to predict the ratio of protons to helium at search for physics beyond the Standard Model of particle physics. W present in previous trap experiments by levitating polarized ultracol asymmetric storage trap using a repulsive magnetic field gradient so interact with material trap walls. As a result of this approach and the the lifetime reported here [877.7 ± 0.7 (stat) +0.4/−0.2 (sys) second than the quoted uncertainties.

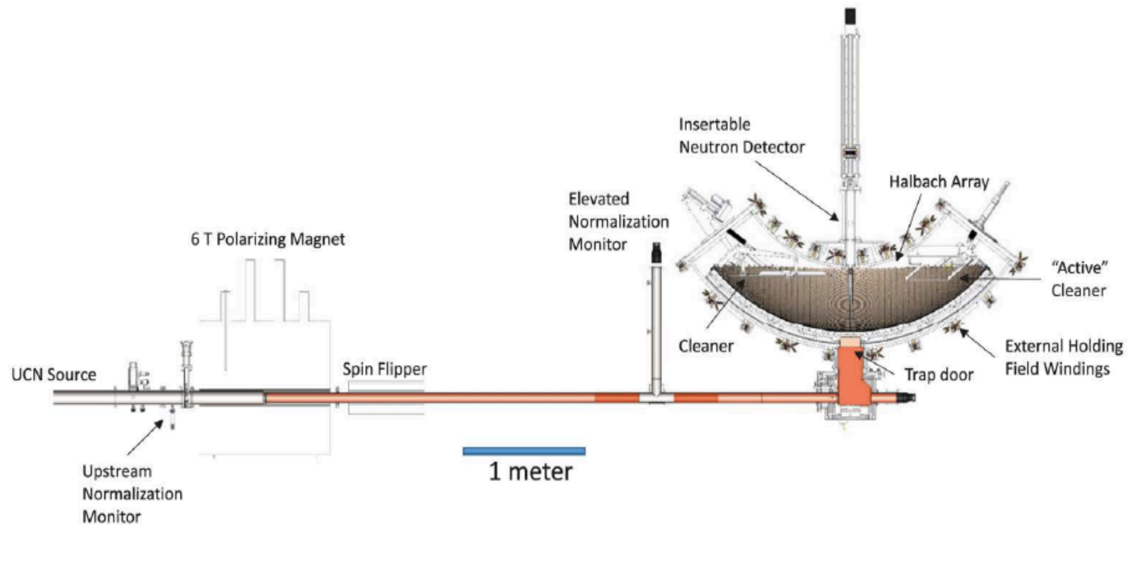



Fig. 1. Fig. 1. Layout of the UCN beam line and trap used for these measurements.

# NEUTRON LIFETIME TECHNIQUES

- QED: Time of Flight Method
- Lifetime: $\tau_n$=885.7 +/- 2.0 s

Vol 444|21/28 December 2006|doi:10.1038/nature05390 nature

LETTERS

## Observation of the radiative decay mode of the free neutron

Jeffrey S. Nico[1], Maynard S. Dewey[1], Thomas R. Gentile[1], H. Pieter Mumm[1], Alan K. Thompson[1], Brian M. Fisher[2], Isaac Kremsky[2], Fred E. Wietfeldt[2], Timothy E. Chupp[3], Robert L. Cooper[3], Elizabeth J. Beise[4], Kristin G. Kiriluk[4], James Byrne[5] & Kevin J. Coakley[6]

**The theory of quantum electrodynamics (QED) predicts that beta decay of the neutron into a proton, electron and antineutrino should be accompanied by a continuous spectrum of soft photons. While this inner bremsstrahlung branch has been previously measured in nuclear beta and electron capture decay, it has never been observed in free neutron decay. Recently, the photon energy spectrum and branching ratio for neutron radiative decay have been calculated using two approaches: a standard QED framework[1–3] and heavy baryon chiral perturbation theory[4] (an effective theory of hadrons based on the symmetries of quantum chromodynamics). The QED calculation treats the nucleons as point-like, whereas the latter approach includes the effect of nucleon structure in a systematic way. Here we observe the radiative decay mode of free neutrons, measuring photons in coincidence with both the emitted electron and proton. We determined a branching ratio of $(3.13 \pm 0.34) \times 10^{-3}$ (68 per cent level of confidence) in the energy region between 15 and 340 keV, where the uncertainty is dominated by systematic effects. The value is consistent with the predictions of both theoretical approaches; the characteristic energy spectrum of the radiated photons, which differs from the uncorrelated background spectrum, is also consistent with the calculated spectrum. This result may provide opportunities for more detailed investigations of the weak interaction processes involved in neutron beta decay.**

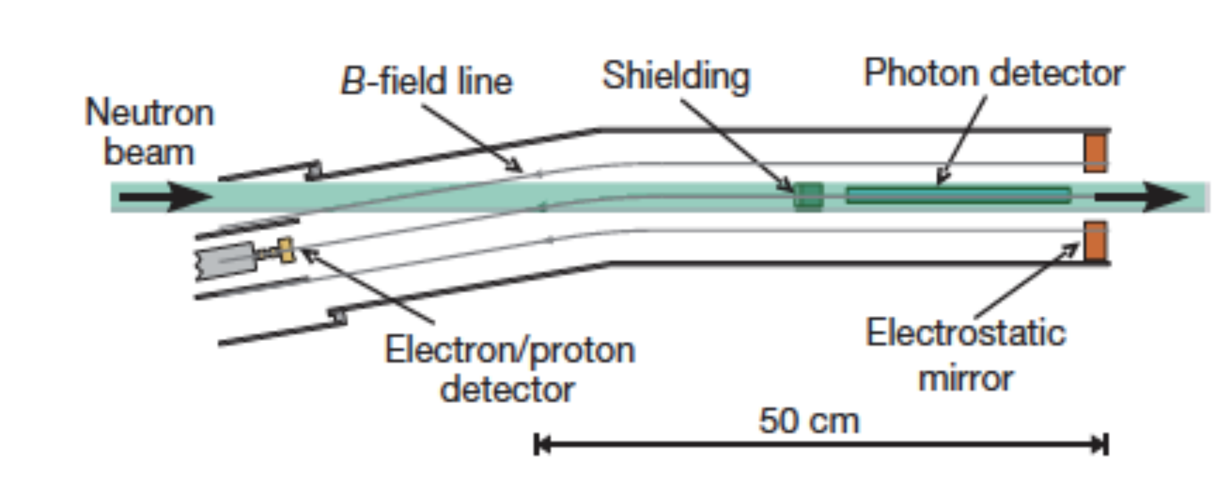


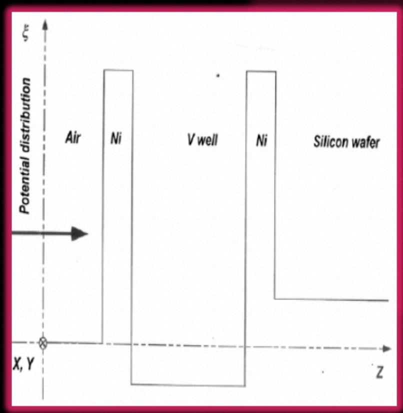

**Figure 1 | Detection scheme for measuring the radiative decay of the**

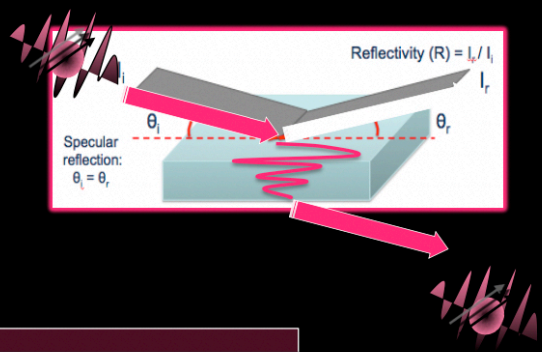
# NEUTRON WAVE-PACKET, TUNNELLING & TRAPPING

- Trapping Neutrons in Fabry-Perot nano-resonator
- Wave-particle duality ( De Broglie)
- Total reflection ( Fermi)
- Heisenberg uncertainty (Heisenberg)

.

- 200 Å Ni-1000 Å $^{nat}$V-200Å Ni /0.1 mmSilicon
- $D_r$ =200 Å Ni •$D_S$=1000 Å $^{nat}$V •Θi =0.5 deg
- Fabry-Perot structure (FPResonance Equation).




$$\tanh(2\pi x_{\pm} D_r) = \tan(2\Phi_{\pm}) / \tan(2\pi D_s / \Lambda)$$

# OUTLINE

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United Nations Educational, Scientific and Cultural Organization

UNESCO-UNISA Africa Chair in Nanosciences/Nanotechnology (South Africa)

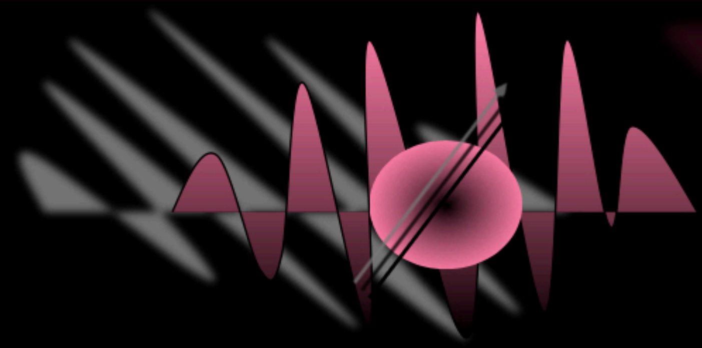
# NEUTRON OPTICS:BASICS

## WavePacket & Schrodinger Equation.

The de Broglie wave-particle duality [15] associates a wavevector, $\mathbf{k} = m\mathbf{v}/\hbar$, with a neutron propagating through a medium, where $\mathbf{v}$ is the neutron velocity, $m$ its mass, and $\hbar = 1.05457 \times 10^{-34}$ Js is the reduced Planck constant. The wavefunction can be represented as a 3D wavepacket (in Dirac notation),

$$|\Psi(t)\rangle = \int d\mathbf{k}\ \mu_{\mathbf{k}} e^{-i\omega_{\mathbf{k}} t} |\mathbf{k}\rangle, \tag{1.1}$$

with $\omega_k = E/\hbar$, where $E$ is the energy, $\mu_{\mathbf{k}}$ is the probability amplitude. The state $|\mathbf{k}\rangle$ is a plane wave component with position representation $\psi_{\mathbf{k}} = \langle r|\mathbf{k}\rangle = e^{i\mathbf{k}\cdot\mathbf{r}}$, with wavevector $\mathbf{k} = k_x\hat{e}_x + k_y\hat{e}_y + k_z\hat{e}_z$ and $\mathbf{r} = x\hat{e}_x + y\hat{e}_y + z\hat{e}_z$.




*ASP-CERN Webinar 4-08-2020*

# NEUTRON OPTICS:BASICS

The propagation of a neutron through a medium is governed by the matter-wave Schrödinger equation. In a time independent potential, under steady state conditions, the Schrödinger equation in the position representation is,

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r})\right]\Psi(\mathbf{r}) = E\Psi(\mathbf{r}),$$

$$V(\mathbf{r}) = \sum_j \frac{2\pi\hbar^2}{m} b_j \delta(\mathbf{r}-\mathbf{r}_j),$$

where $V(\mathbf{r})$ is the potential energy of the particle, and $E$ is the total energy of the p... The equation can be written in a form that is similar to the Helmholtz equation in ... optics as,


$$\nabla^2\Psi(\mathbf{r}) + K(\mathbf{r})^2\Psi(\mathbf{r}) = 0,$$

with $K(\mathbf{r}) = \sqrt{2m[E - V(\mathbf{r})]}/\hbar$ is the medium dependent wavevector. $V(\mathbf{r})$ c... various forms including electromagnetic, gravitational, and nuclear. Of interest to us is the nuclear and magnetic interaction which will be explored in the next section in detail. One common way to characterize them is via the refractive index, defined as [2, 3],

$$n \equiv \frac{K(\mathbf{r})}{k} = \sqrt{\frac{2m[E - V(\mathbf{r})]}{2mE}} \simeq 1 - \frac{\overline{V}}{2E},$$

$$V(\mathbf{r}) = \sum_j \frac{2\pi\hbar^2}{m} b_j \delta(\mathbf{r}-\mathbf{r}_j),$$

where $k = \sqrt{2mE\hbar^{-2}}$ is the wavevector in free space. The approximation in Eq. (1.7) is valid for thermal neutrons as the potential $V(\mathbf{r})$ can be expressed in a form equal to the optical potential, $\overline{V}$, which for most materials is of the order $10^{-5}eV$.

# NEUTRON OPTICS:BASICS

$$V_O = \frac{2\pi\hbar^2}{m} N\bar{b}, \text{ where } N\bar{b} = \sum_j b_j \delta(\mathbf{r} - \mathbf{r}_j). \tag{1.9}$$

$N\bar{b}$ is the local mean scattering length density, which represents the response of the overall system as multiple copies of a single atom of the same kind. Generally, $\bar{b}$ is complex with typical values in the femtometre scale. Moreover, this value leads to a scattering cross-section defined as $\bar{\sigma}_s = 4\pi|\bar{b}|^2$ and an absorption cross-section defined as $\bar{\sigma}_a = 4\pi \mathsf{Im}[b]^2 k^{-1}$, where $\mathsf{Im}[\bar{b}]$ is the imaginary component.

When a neutron beam is shined on an absorbing target of effective thickness $D$, the intensity of transmitted neutron is related to the incident intensity, $I_0$, by [19],

$$I = I_0 e^{-\bar{\sigma}_a N D}. \tag{1.10}$$

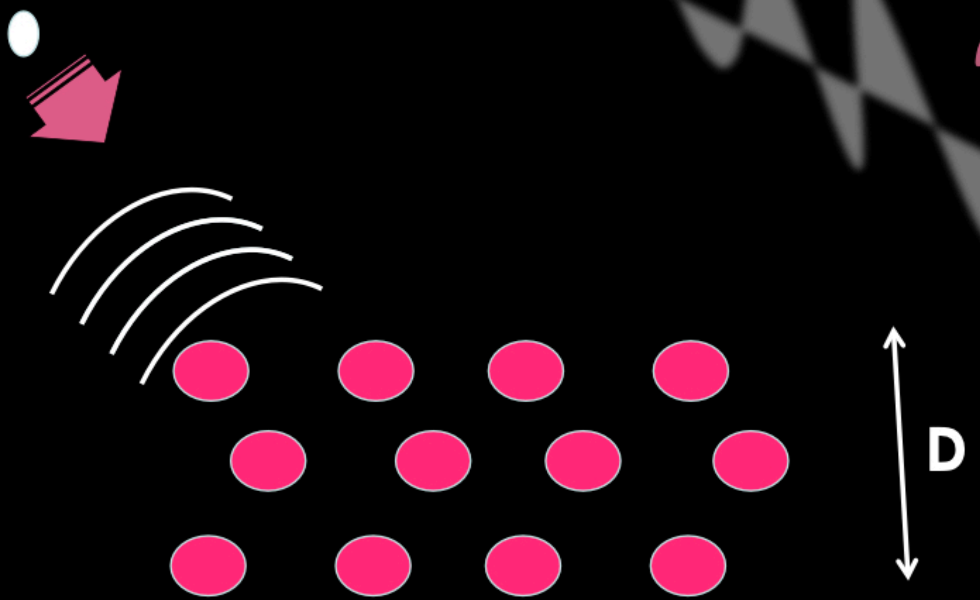
Materials with high $\bar{\sigma}_a$ including lead, cadmium, gadolinium, are commonly used as neutron absorbers. For most materials, $\mathsf{Re}[\bar{b}] > 0$, with the few exceptions of $^2$H, $^{48}$Ti, and $^{62}$Ni

The general form of the complex refractive index from a spin-independent scattering material is [3, 2],

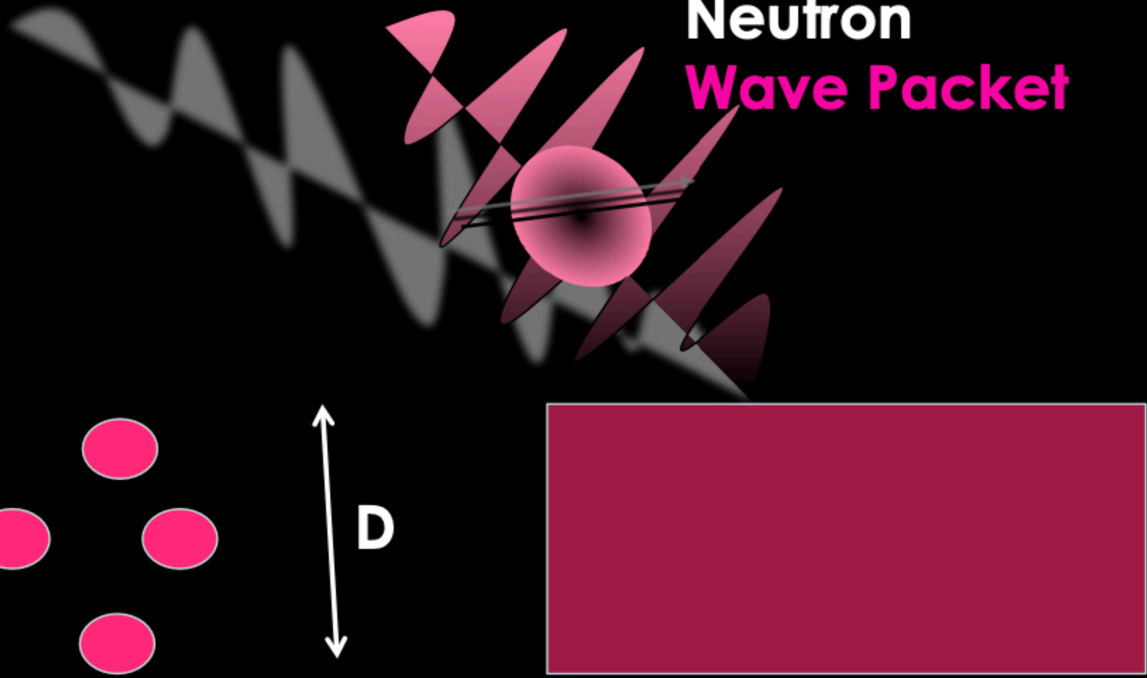
$$n \equiv 1 - \frac{\lambda^2 N}{2\pi} \sqrt{\bar{b}^2 - \left(\frac{\bar{\sigma}_r}{2\lambda}\right)^2} + i\frac{\bar{\sigma}_r N \lambda}{4\pi}, \tag{1.11}$$

# NEUTRON OPTICS:BASICS

**Neutron Particle**




**Neutron**
**Wave Packet**



**Discontinuous scattering medium**
**Delta function type interaction**

**Continuous scattering medium**

$$V_O = \frac{2\pi\hbar^2}{m} N\bar{b}, \text{ where } N\bar{b} = \sum_j b_j \delta(\mathbf{r}-\mathbf{r}_j).$$

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# NEUTRON OPTICS:BASICS

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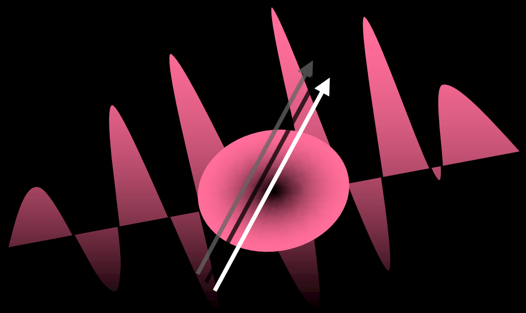
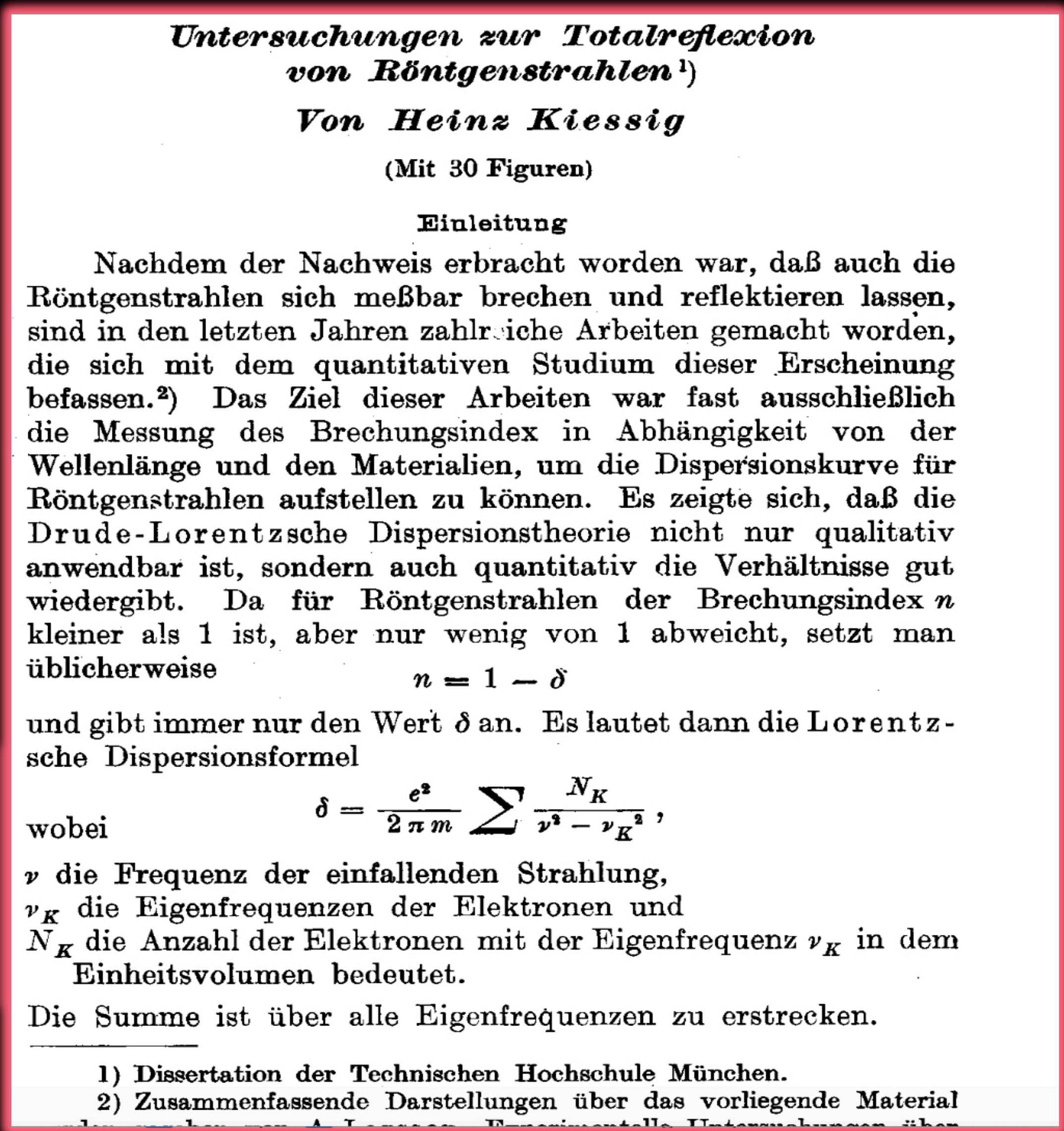
# X-RAYS OPTICS:





**_Untersuchungen zur Totalreflexion von Röntgenstrahlen_**[1])

**_Von Heinz Kiessig_**

(Mit 30 Figuren)

**Einleitung**

Nachdem der Nachweis erbracht worden war, daß auch die Röntgenstrahlen sich meßbar brechen und reflektieren lassen, sind in den letzten Jahren zahlreiche Arbeiten gemacht worden, die sich mit dem quantitativen Studium dieser Erscheinung befassen.[2]) Das Ziel dieser Arbeiten war fast ausschließlich die Messung des Brechungsindex in Abhängigkeit von der Wellenlänge und den Materialien, um die Dispersionskurve für Röntgenstrahlen aufstellen zu können. Es zeigte sich, daß die Drude-Lorentzsche Dispersionstheorie nicht nur qualitativ anwendbar ist, sondern auch quantitativ die Verhältnisse gut wiedergibt. Da für Röntgenstrahlen der Brechungsindex $n$ kleiner als 1 ist, aber nur wenig von 1 abweicht, setzt man üblicherweise

$$n = 1 - \delta$$

und gibt immer nur den Wert $\delta$ an. Es lautet dann die Lorentzsche Dispersionsformel

$$\delta = \frac{e^2}{2\pi m} \sum \frac{N_K}{\nu^2 - \nu_K^2},$$

wobei

$\nu$ die Frequenz der einfallenden Strahlung,
$\nu_K$ die Eigenfrequenzen der Elektronen und
$N_K$ die Anzahl der Elektronen mit der Eigenfrequenz $\nu_K$ in dem Einheitsvolumen bedeutet.

Die Summe ist über alle Eigenfrequenzen zu erstrecken.

---

1) Dissertation der Technischen Hochschule München.
2) Zusammenfassende Darstellungen über das vorliegende Material

Neutron Wave-Packet ==Photon in S-polarization state

# NUCLEAR SCATTERING AMPLITUDE.

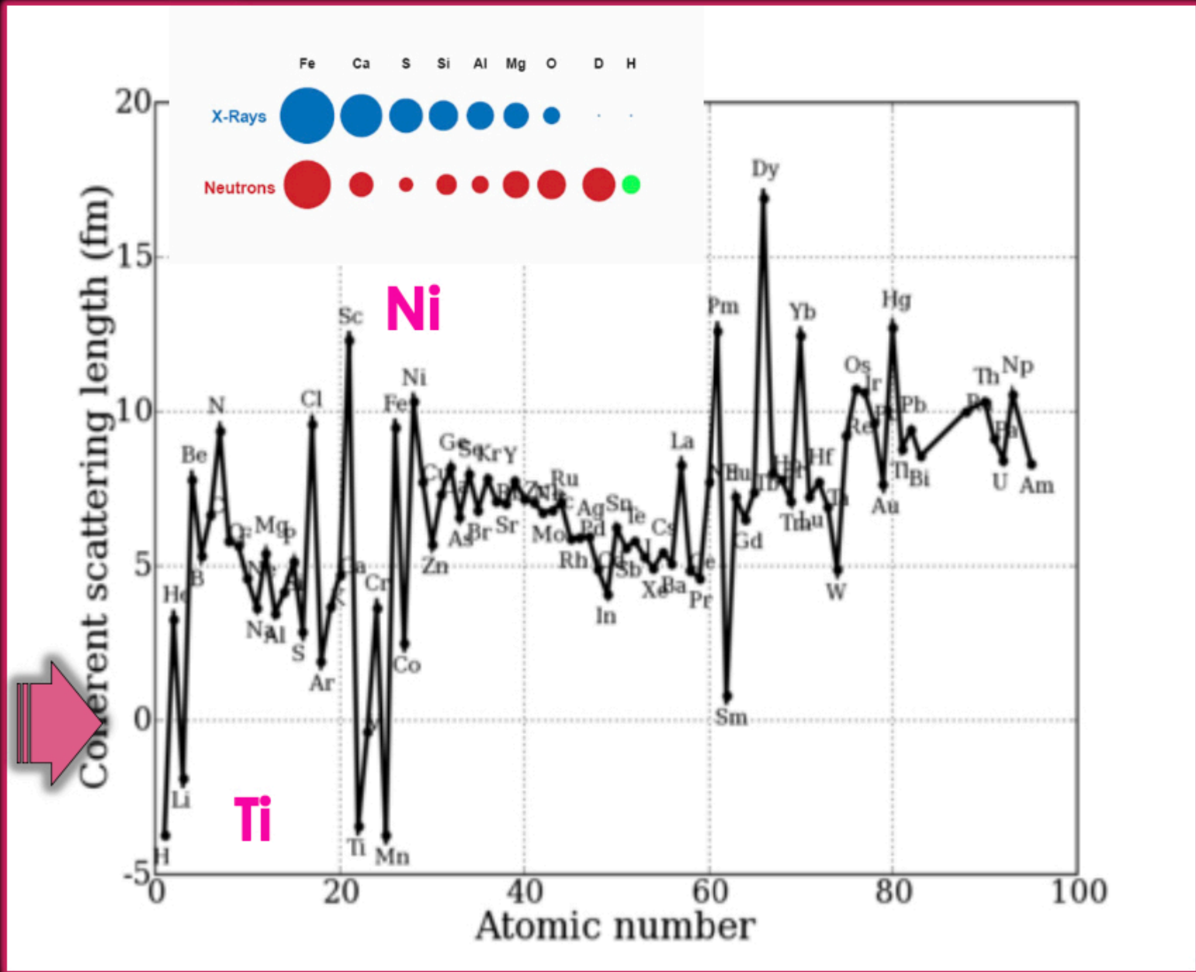
bNi= +10.31
$b^{58}$Ni= +14.41

bTi= - 3.438
$b^{48}$Ti= - 6.08

bV= -0.3824
bMn= -3.73

bDy= -+16.92

$\sigma_a$Dy= -+994.13




*ASP-CERN Webinar 4-08-2020*

# NUCLEAR SCATTERING AMPLITUDE.

Table 1. **Neutron scattering lengths and cross sections of the elements and their isotopes.**


**VARLEY F. SEARS**
*AECL Research, Chalk River Laboratories*
*Chalk River, Ontario, Canada K0J 1J0*

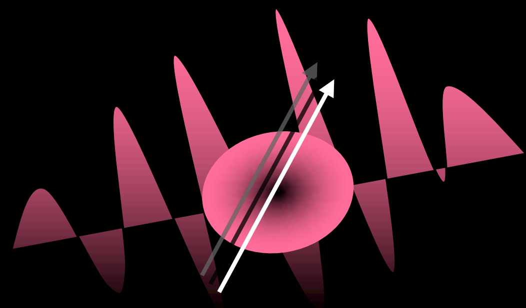

| Column | Symbol | Unit | Quantity |
|---|---|---|---|
| 1 | | | element |
| 2 | $Z$ | | atomic number |
| 3 | $A$ | | mass number |
| 4 | $I(p)$ | | spin (parity) of the nuclear ground state |
| 5 | $c$ | % | natural abundance (For radioisotopes the half-life is given instead.) |
| 6 | $b_c$ | fm | bound coherent scattering length |
| 7 | $b_i$ | fm | bound incoherent scattering length |
| 8 | $s_c$ | barn[1] | bound coherent scattering cross section |
| 9 | $s_i$ | barn | bound incoherent scattering cross section |
| 10 | $s_s$ | barn | total bound scattering cross section |
| 11 | $s_a$ | barn | absorption cross section for 2200 m/s neutrons[2] |

(1) 1 barn = 100 fm²
(2) $E = 25.30$ meV, $k = 3.494$ Å$^{-1}$, $\lambda = 1.798$ Å

| | $Z$ | $A$ | $I(\pi)$ | $c$ | $b_c$ | $b_i$ | $\sigma_c$ | $\sigma_i$ | $\sigma_s$ | $\sigma_a$ |
|---|---|---|---|---|---|---|---|---|---|---|
| H | 1 | | | | −3.7390(11) | | 1.7568(10) | 80.26(6) | 82.02(6) | 0.3326(7) |
| | | 1 | 1/2(+) | 99.985 | −3.7406(11) | 25.274(9) | 1.7583(10) | 80.27(6) | 82.03(6) | 0.3326(7) |
| | | 2 | 1(+) | 0.015 | 6.671(4) | 4.04(3) | 5.592(7) | 2.05(3) | 7.64(3) | 0.000519(7) |
| | | 3 | 1/2(+) | (12.32 a) | 4.792(27) | −1.04(17) | 2.89(3) | 0.14(4) | 3.03(5) | 0 |
| He | 2 | | | | 3.26(3) | | 1.34(2) | 0 | 1.34(2) | 0.00747(1) |
| | | 3 | 1/2(+) | 0.00014 | 5.74(7) | −2.5(6) | 4.42(10) | 1.6(4) | 6.0(4) | 5333.(7.) |
| | | | | | −1.483(2)$i$ | +2.568(3)$i$ | | | | |
| | | 4 | 0(+) | 99.99986 | 3.26(3) | 0 | 1.34(2) | 0 | 1.34(2) | 0 |
| Li | 3 | | | | −1.90(2) | | 0.454(10) | 0.92(3) | 1.37(3) | 70.5(3) |
| | | 6 | 1(+) | 7.5 | 2.00(11) | −1.89(10) | 0.51(5) | 0.46(5) | 0.97(7) | 940.(4.) |
| | | | | | −0.261(1)$i$ | +0.26(1)$i$ | | | | |
| | | 7 | 3/2(−) | 92.5 | −2.22(2) | −2.49(5) | 0.619(11) | 0.78(3) | 1.40(3) | 0.0454(3) |
| Be | 4 | 9 | 3/2(−) | 100 | 7.79(1) | 0.12(3) | 7.63(2) | 0.0018(9) | 7.63(2) | 0.0076(8) |
| B | 5 | | | | 5.30(4) | | 3.54(5) | 1.70(12) | 5.24(11) | 767.(8.) |
| | | | | | −0.213(2)$i$ | | | | | |
| | | 10 | 3(+) | 20.0 | −0.1(3) | −4.7(3) | 0.144(8) | 3.0(4) | 3.1(4) | 3835.(9.) |
| | | | | | −1.066(3)$i$ | +1.231(3)$i$ | | | | |
| | | 11 | 3/2(−) | 80.0 | 6.65(4) | −1.3(2) | 5.56(7) | 0.21(7) | 5.77(10) | 0.0055(33) |
| C | 6 | | | | 6.6460(12) | | 5.550(2) | 0.001(4) | 5.551(3) | 0.00350(7) |
| | | 12 | 0(+) | 98.90 | 6.6511(16) | 0 | 5.559(3) | 0 | 5.559(3) | 0.00353(7) |
| | | 13 | 1/2(−) | 1.10 | 6.19(9) | −0.52(9) | 4.81(14) | 0.034(11) | 4.84(14) | 0.00137(4) |

# NEUTRON OPTICS:N.WAVE-PACKET

## WAVE BEHAVIOR OF 'n'



- Total Reflection "Fermi, 1946",
- Polarization "Gukasov, 1954",
- Thin Film Interference "Maier-Leibnitz, 1962",
- Magnetic polarization/spin flipping"Drabkin, 1962"
- Prism Deflection "Landkammer/ Korpiun, 1966",
- Neutron Interferometry "Rauch, 1973",
- Supermirrors "Mezei, 1978",
- Neutron Tunneling "Refl. mode, Steyerl, 1981",
- Sagnac Effect "Werner, 1985",
- Aharonov-Bohm Effect "Collela, 1993",
- Neutron Tunneling "Ref./Trans, Polar"Maaza & al, 1996",
- Neutron Tunneling "Modelling "Ignatovich & al, 1997",
- Neutron Goos-Hanschen"de Haan & al, 2010,
- Neutron Holography "Sarenac, Pushin & al,2016".

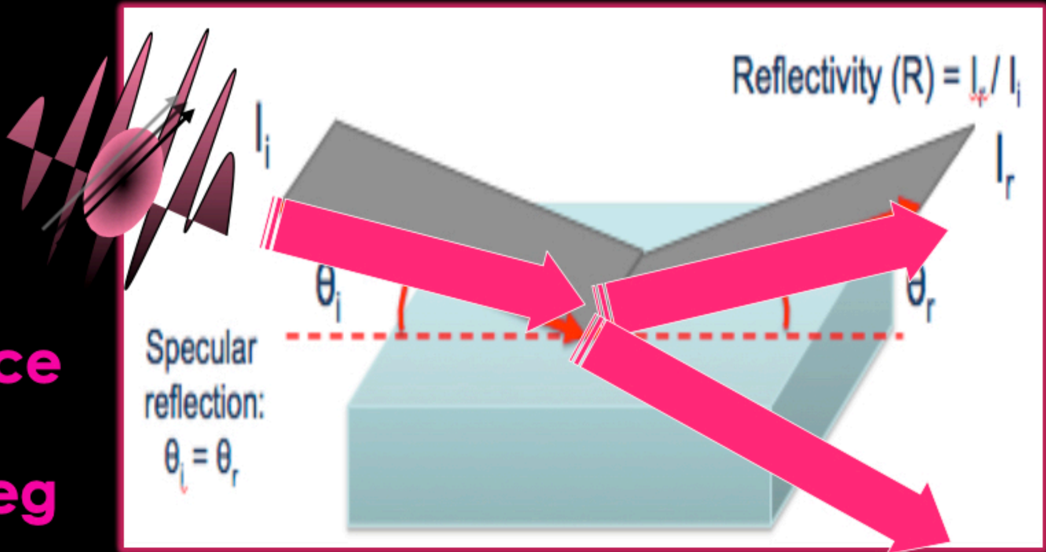
# NUCLEAR SCATTERING AMPLITUDE.

## 3A-NEUTRON OPTICS :TOTAL REFLECTION

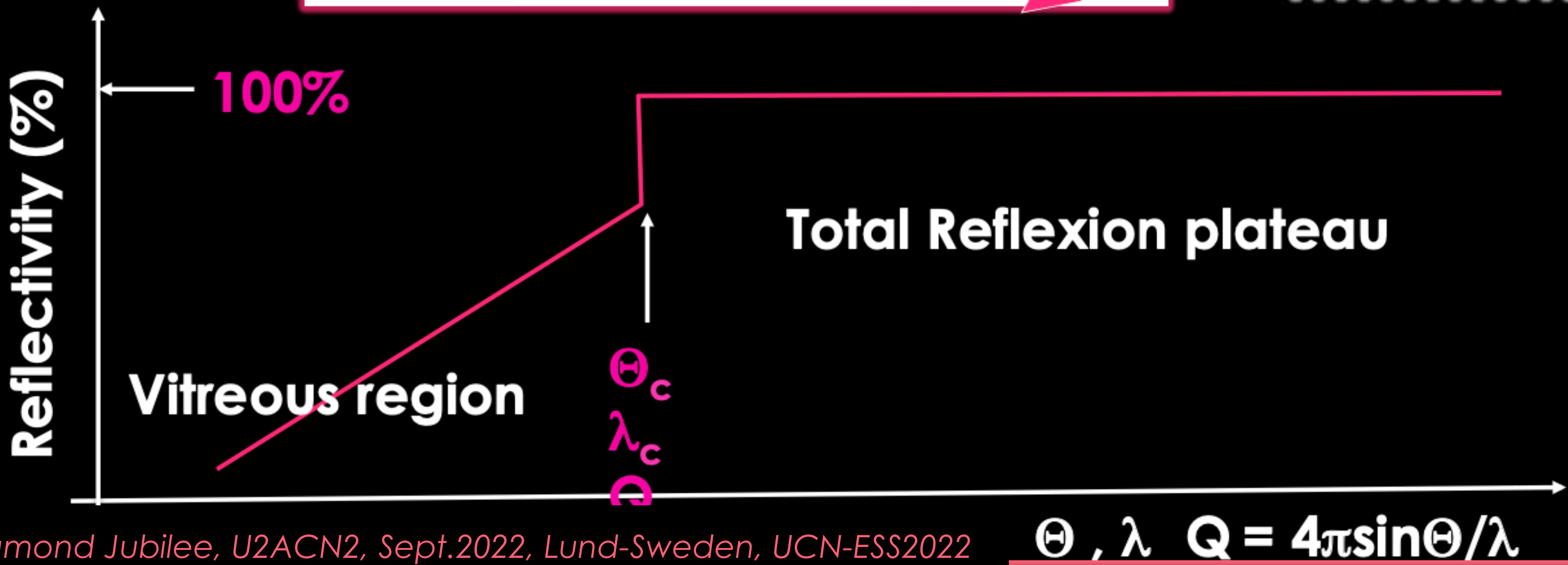
**$V_{Fermi}$ ≈ $10^{-5}$ eV, n ≈ 1**

**Grazing incidence**

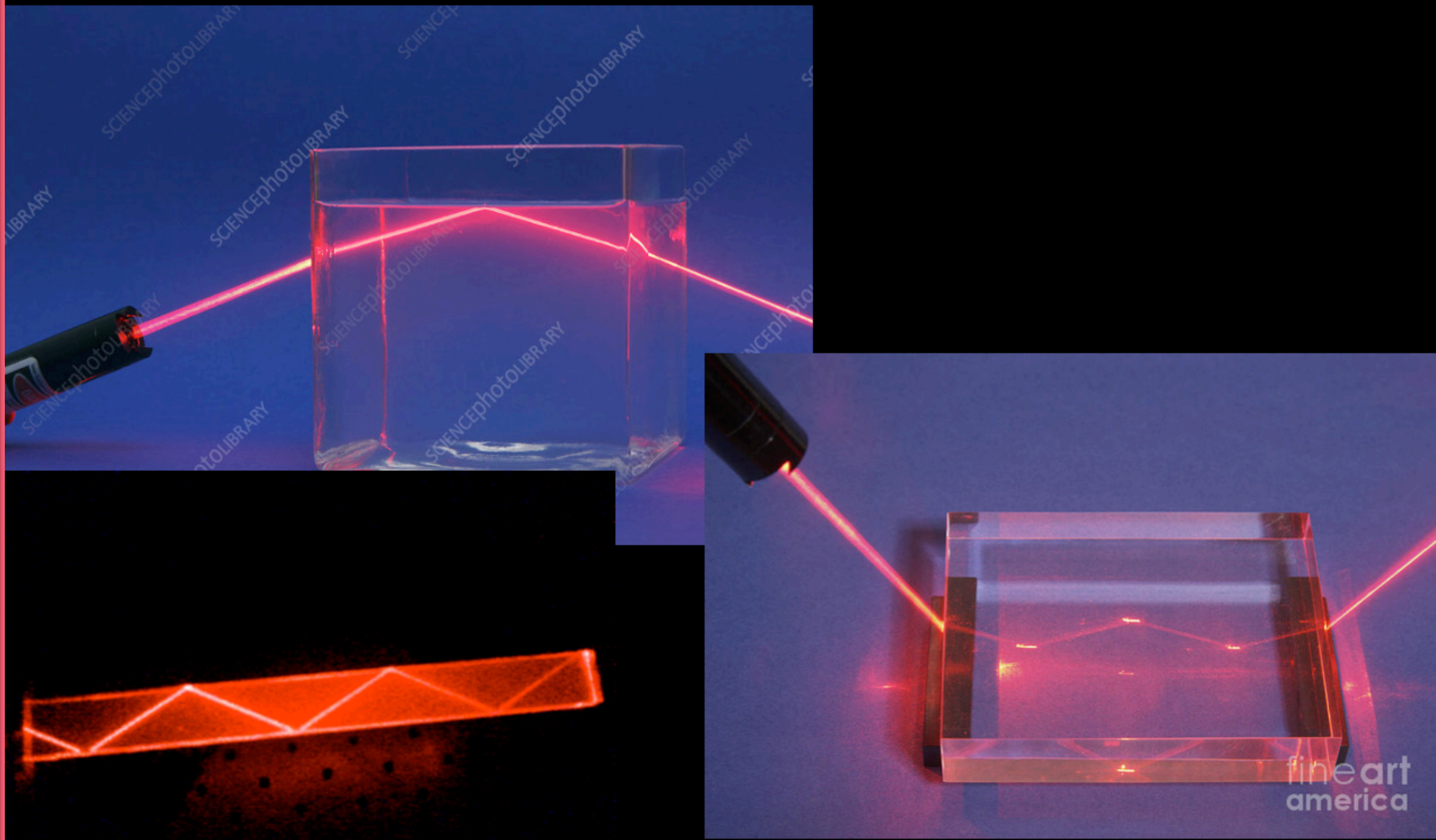
**$\Theta_i$ ≈ 1 Deg**







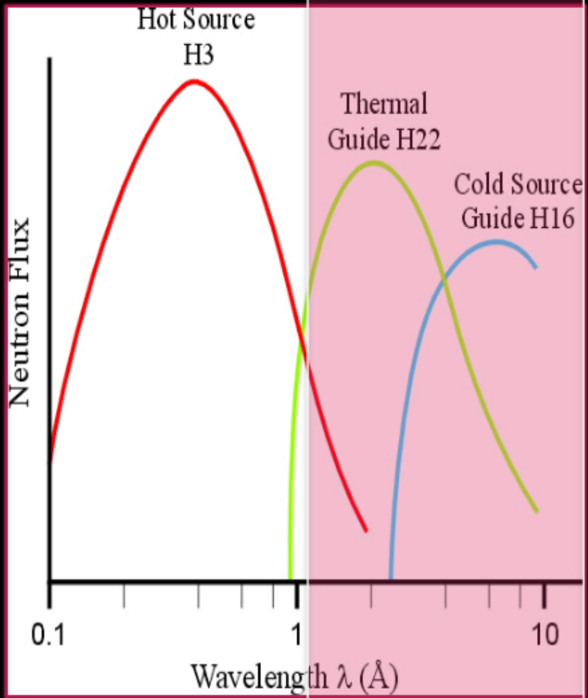
# TOTAL REFLECTION PHENOMENON

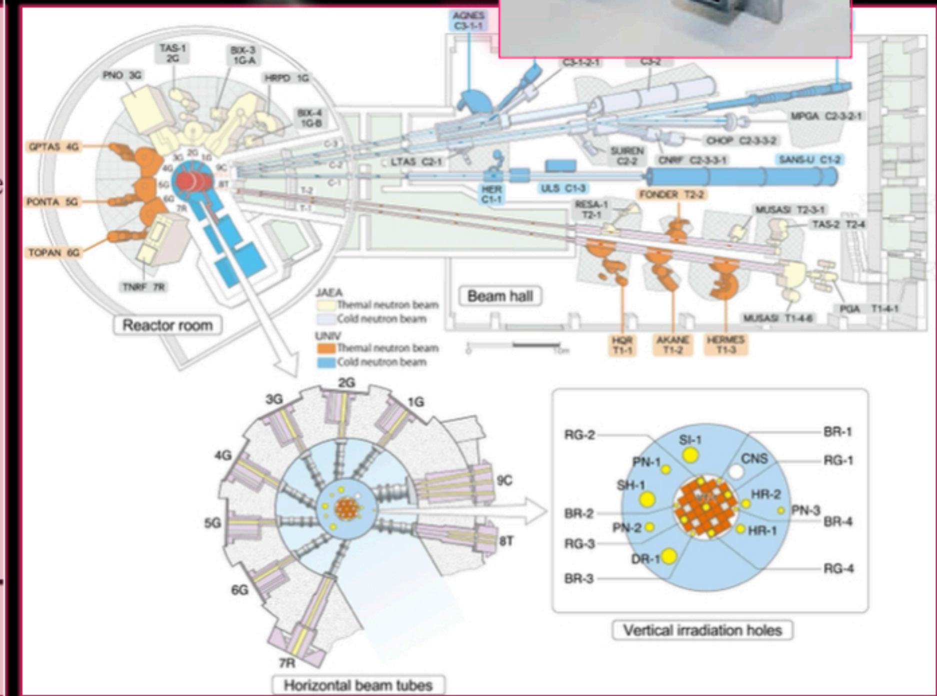


# TOTAL REFLECTION PHENOMENON

## 3A-NEUTRON OPTICS :TOTAL REFLECTION

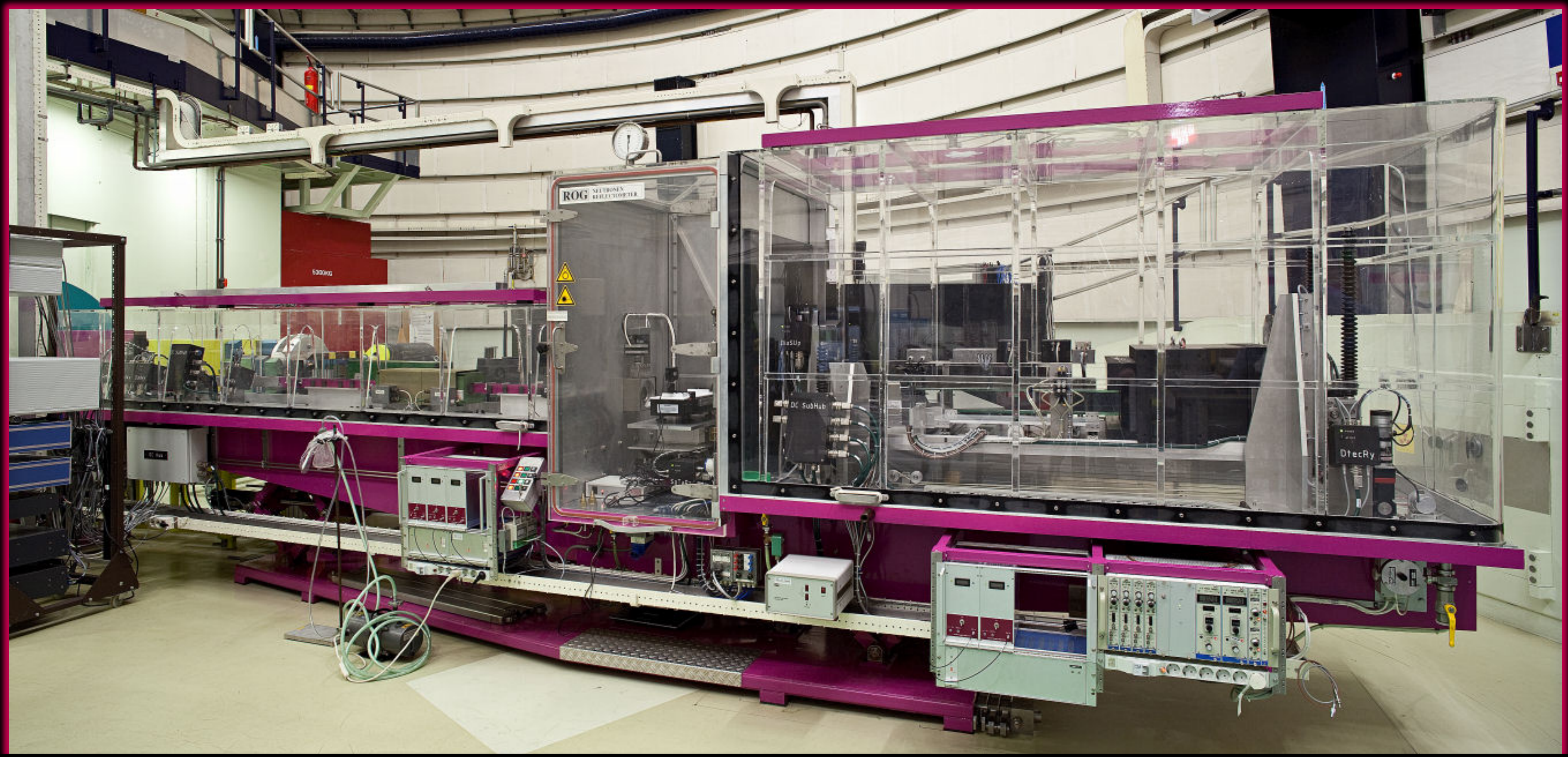
- Quantum Mechanics governed phenomena
- Maximize the reactor capabilities via n-guides



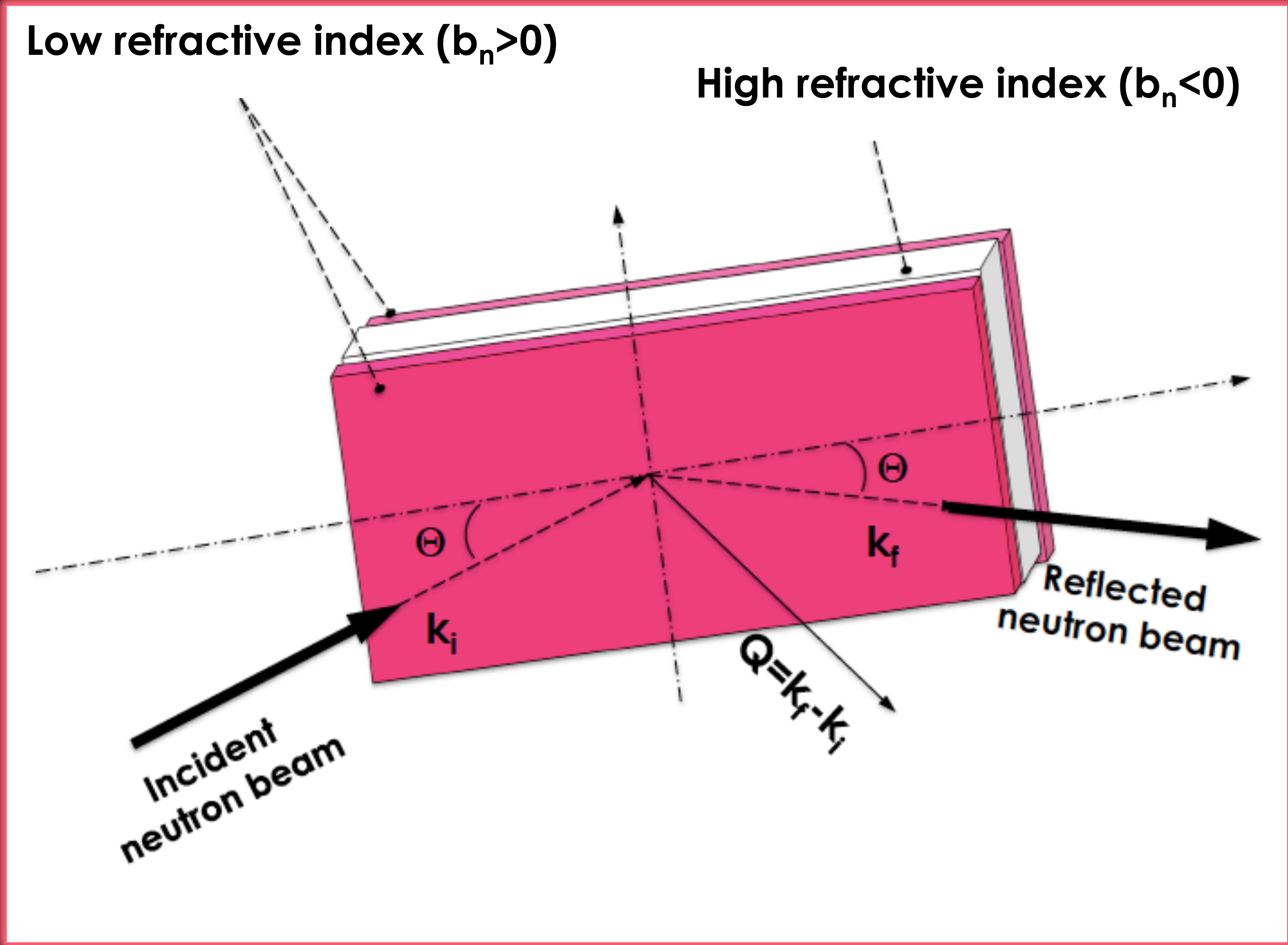



# TYPICAL NEUTRON GUIDE HALL

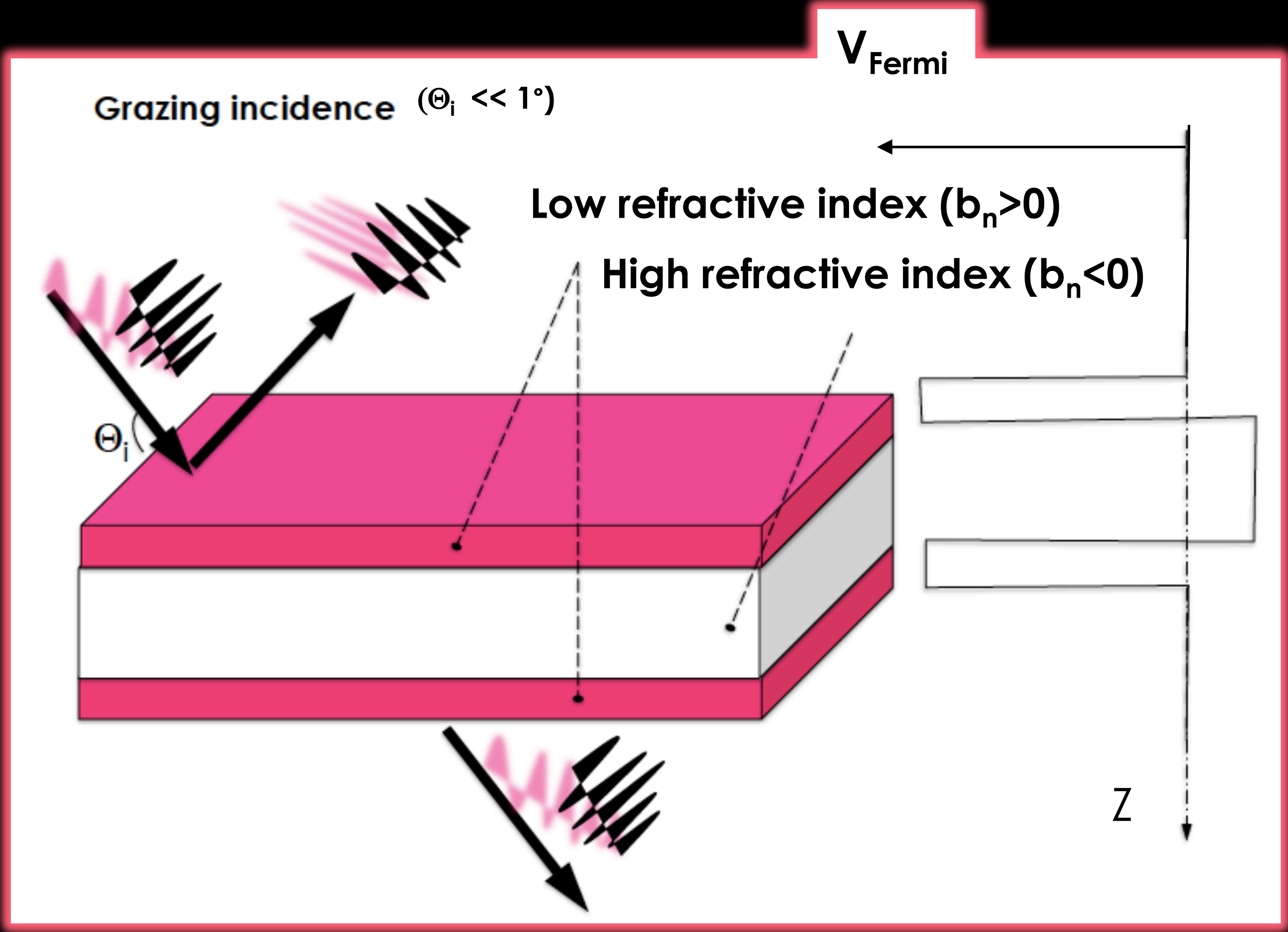
# TYPICAL NEUTRON REFLECTOMER



# FRUSTRATED TOTAL REFLECTION.



# FRUSTRATED TOTAL REFLECTION.



# OUTLINE

1- Generalities

2-Neutron lifetime,

3-Basics of neutron optics,

4A-Trapping neutron in Single Fabry-Perot nanoresonator Heisenberg uncertainty governed precision

4B-Free propogation of neutron in coupled Fabry-Perot nanoresonators with $^{10}B$

5- Conclusion/Foresight

UNESCO United Nations Educational, Scientific and Cultural Organization

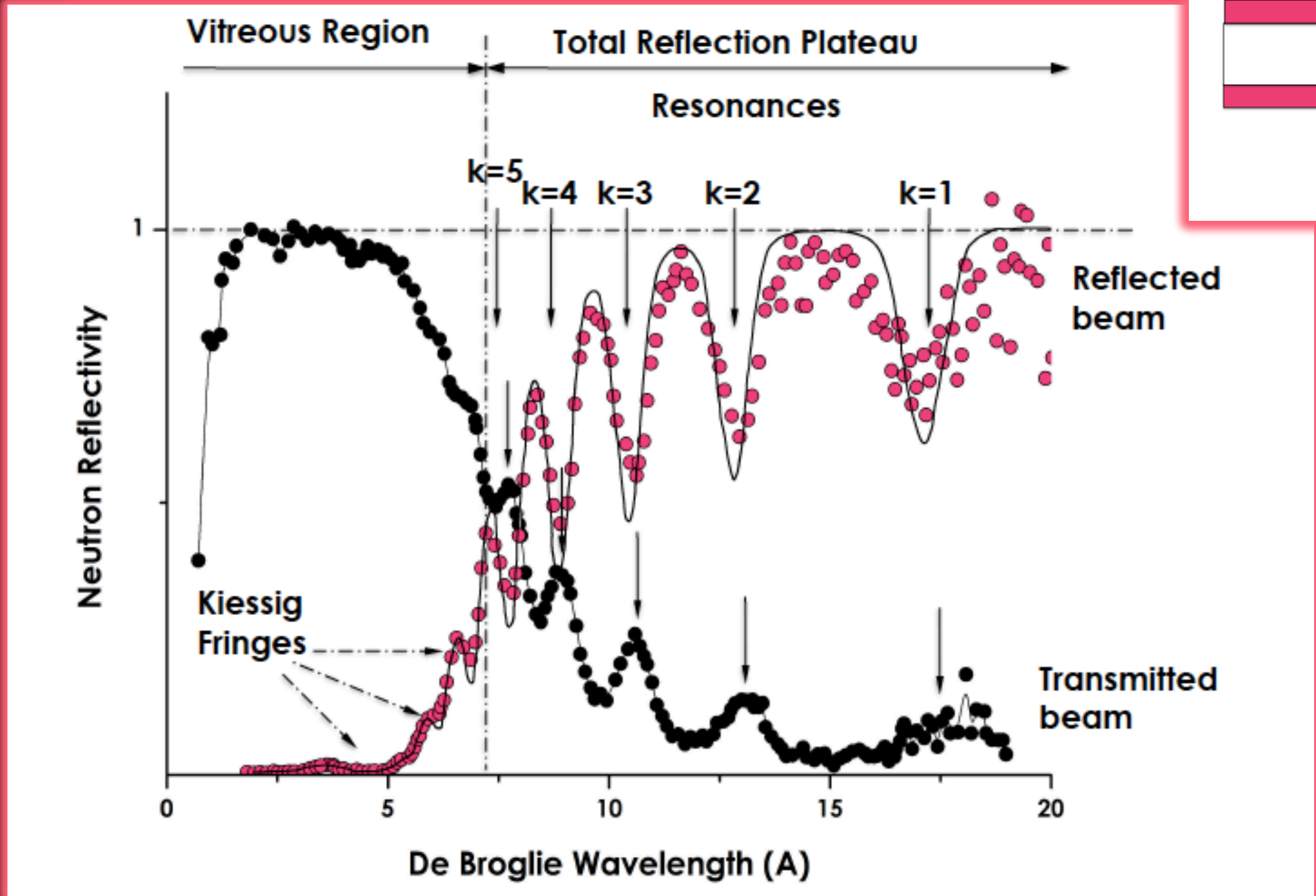
uniTwin UNESCO-UNISA Africa Chair in Nanosciences/Nanotechnology (South Africa)

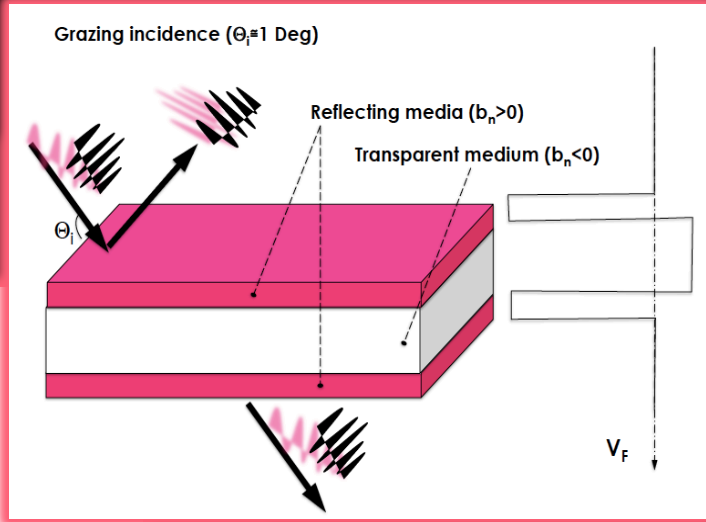
UNISA university of south africa

NRF National Research Foundation

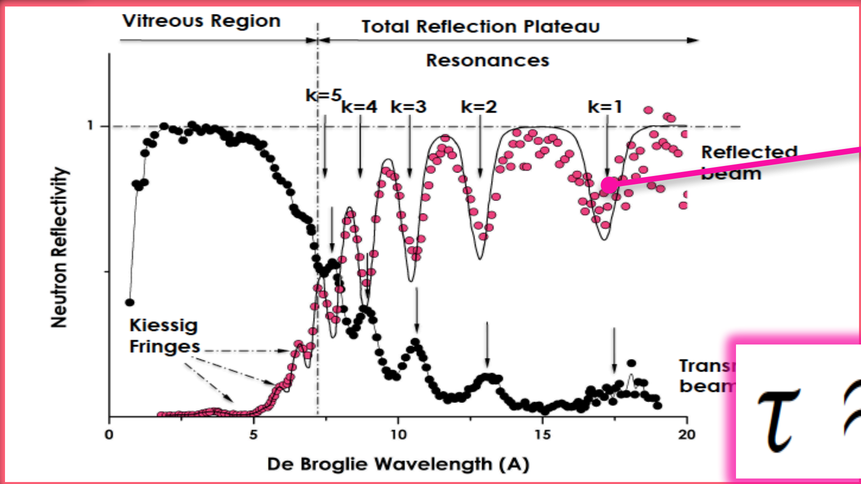
iThemba LABS Laboratory for Accelerator Based Sciences

# FRUSTRATED TOTAL REFLECTION.

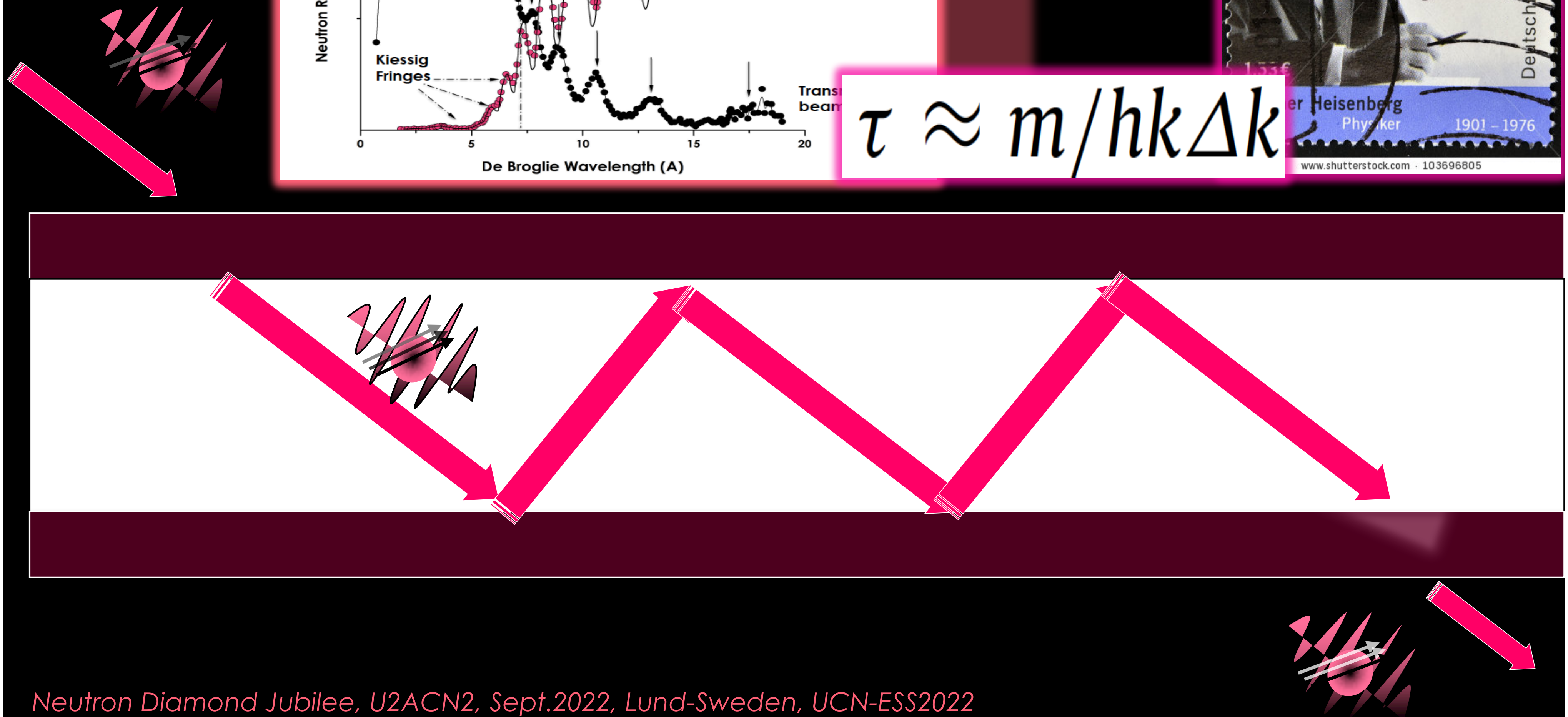


# 1-NEUTRON TRAPPING:
# NEUTRON CONFINMENT IN NANO-F.P.




$$\tau \approx m/hk\Delta k$$

# FRUSTRATED TOTAL REFLECTION.

| Resonance order $\nu$ | Resonance wavelength $\lambda_{res}$, (Å) | $\Delta\lambda_{res}$ (Å) | $k$ (Å$^{-1}$) | $\Delta k$ ($10^{-2}$ Å$^{-1}$) | Trapping time $\tau$ (ps) |
|---|---|---|---|---|---|
| 1 | 17.38 | 1.09 | 3.561 | 2.267 | 19.35 |
| 2 | 12.99 | 0.85 | 4.837 | 3.165 | 10.36 |
| 3 | 10.56 | 0.73 | 5.950 | 4.113 | 6.48 |
| 4 | 9.02 | 0.61 | 6.966 | 4.711 | 4.83 |
| 5 | 7.87 | 0.61 | 7.984 | 6.188 | 3.21 |

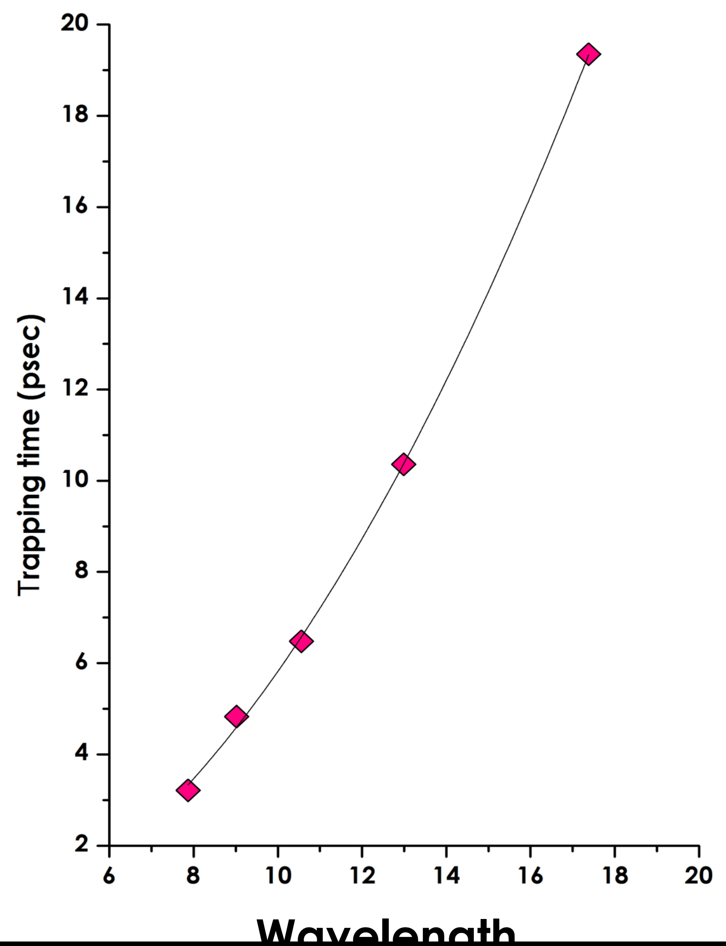
The average neutron lifetime derived from:

Beam approach was found to be $\langle \tau_n \rangle_{Beam}$ ~ 888.0 ± 2.0 s

Bottle technique of about $\langle \tau_n \rangle_{Bottle}$ ~ 879.4 ± 0.6 s

Trapping time in Fabry-Perot Nano-resonator" ± $10^{-12}$ s

# FRUSTRATED TOTAL REFLECTION.

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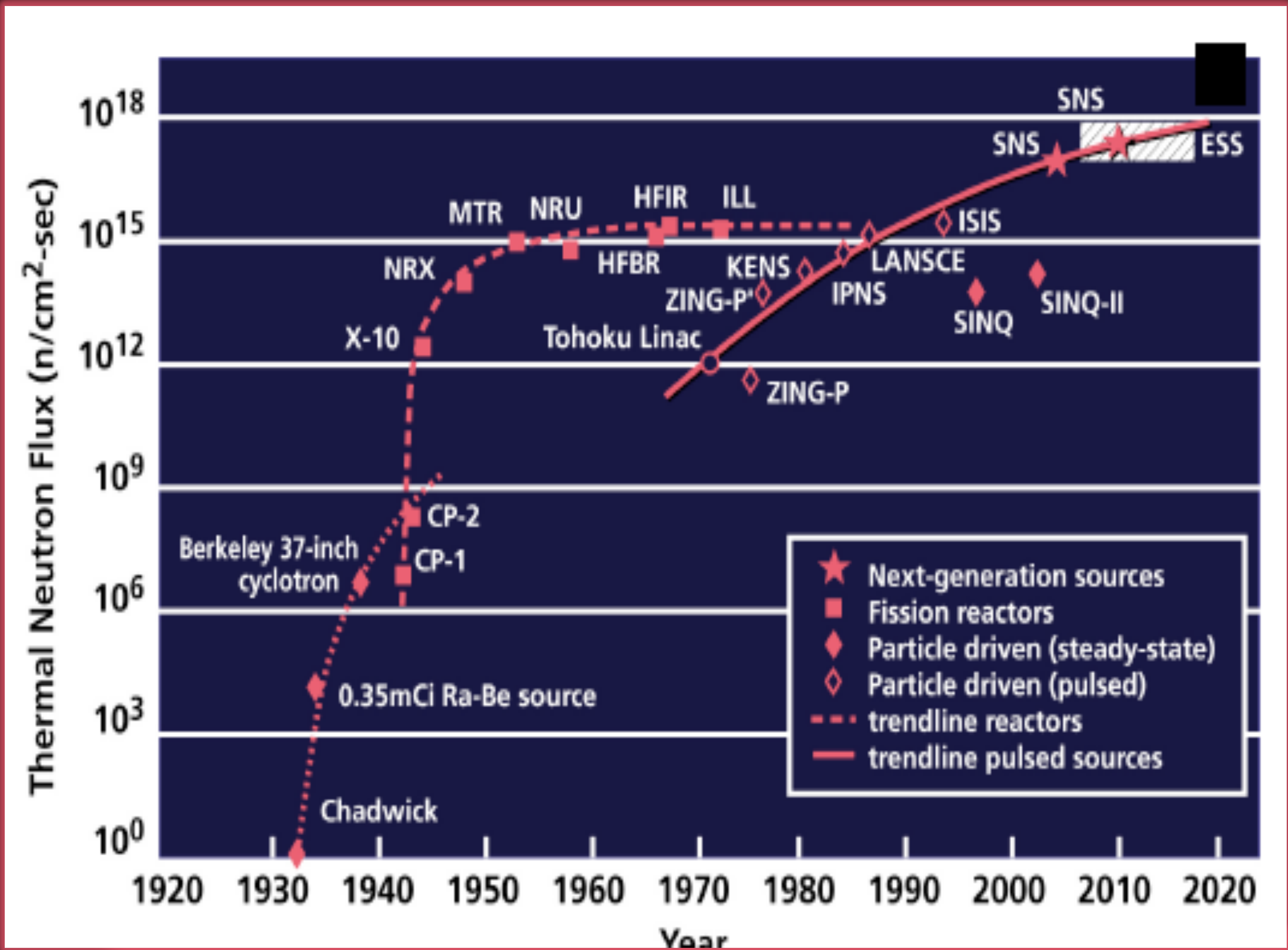
| 4 | 9.02 | 0.61 | 6.966 | 4.711 | 4.83 |

The evolution can be reasonably described by a quadratic curve $\tau_{trapping} \approx -0.084\lambda + 0.7\lambda^2$. Hence, by extrapolation, for ultra-cold neutrons with wavelength of 100 or 1000 nm, $\tau_{trapping}$ would be of 7 μs and 700,084 μs

# ULTRA-COLD NEUTRON SOURCES



# OUTLINE

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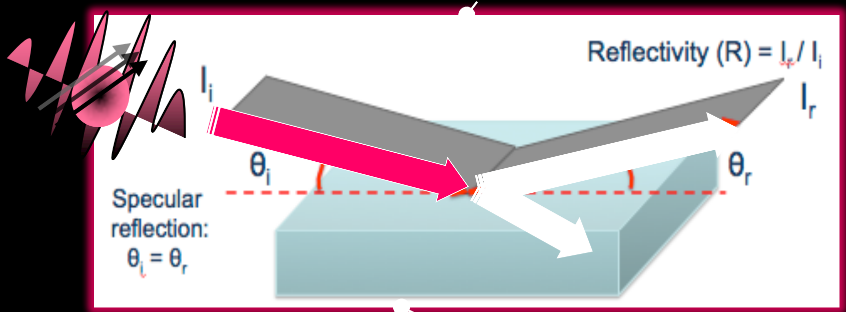
5- Conclusion/Foresight

United Nations Educational, Scientific and Cultural Organization

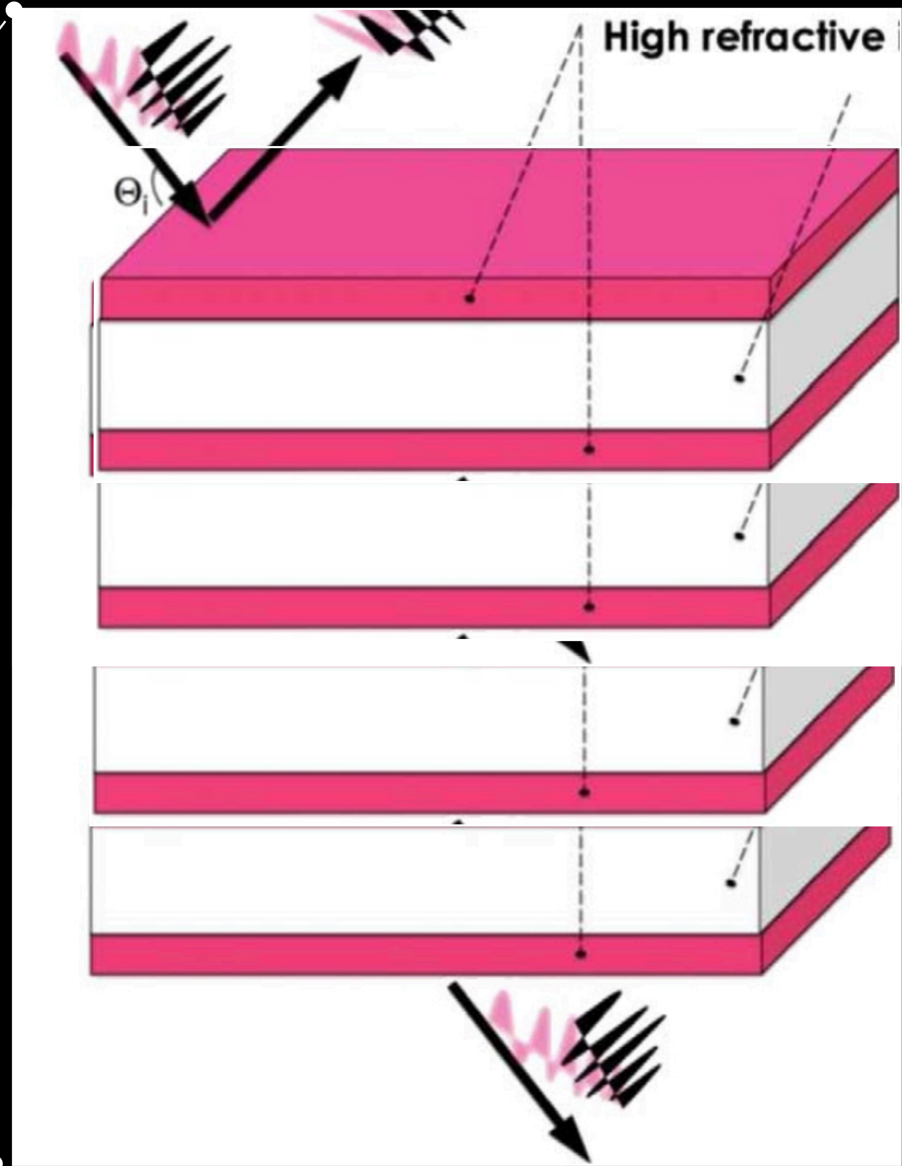
UNESCO-UNISA Africa Chair in Nanosciences/Nanotechnology (South Africa)

# F.P. NANO-RESONATORS COUPLING

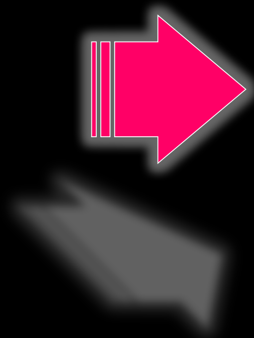
$\Theta_i \approx 1$ Deg



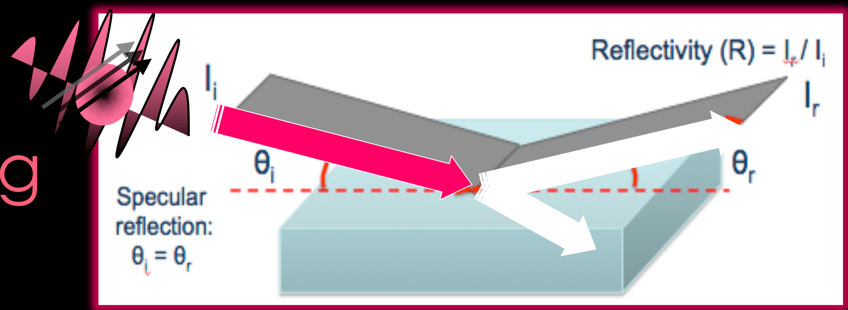

Neutron capture: $B_4C$



# NEUTRON WAVE-PACKET RESONANCE: BORON TRANSPARENCY



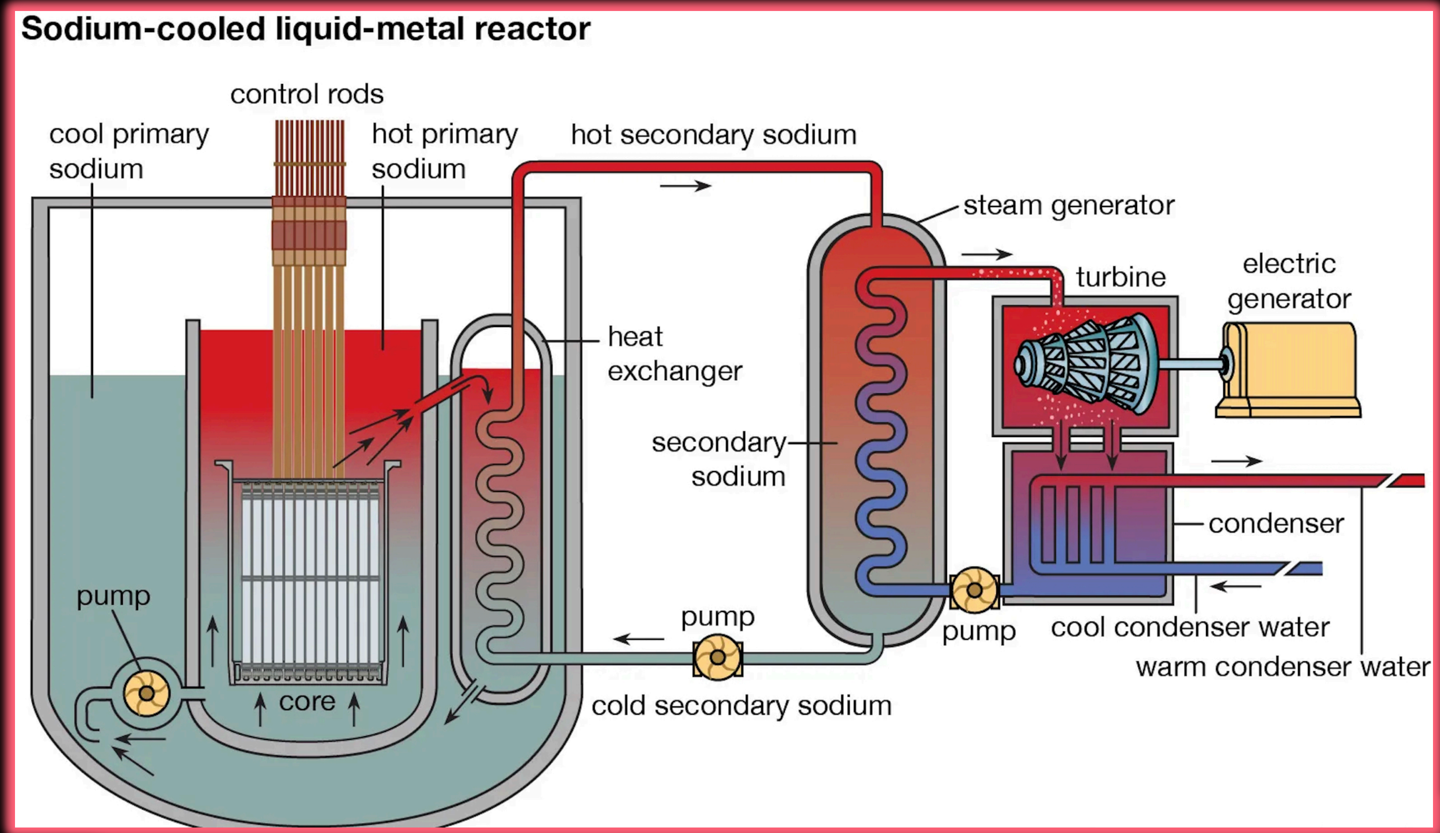
$\Theta_i \approx 1$ Deg




Neutron capture

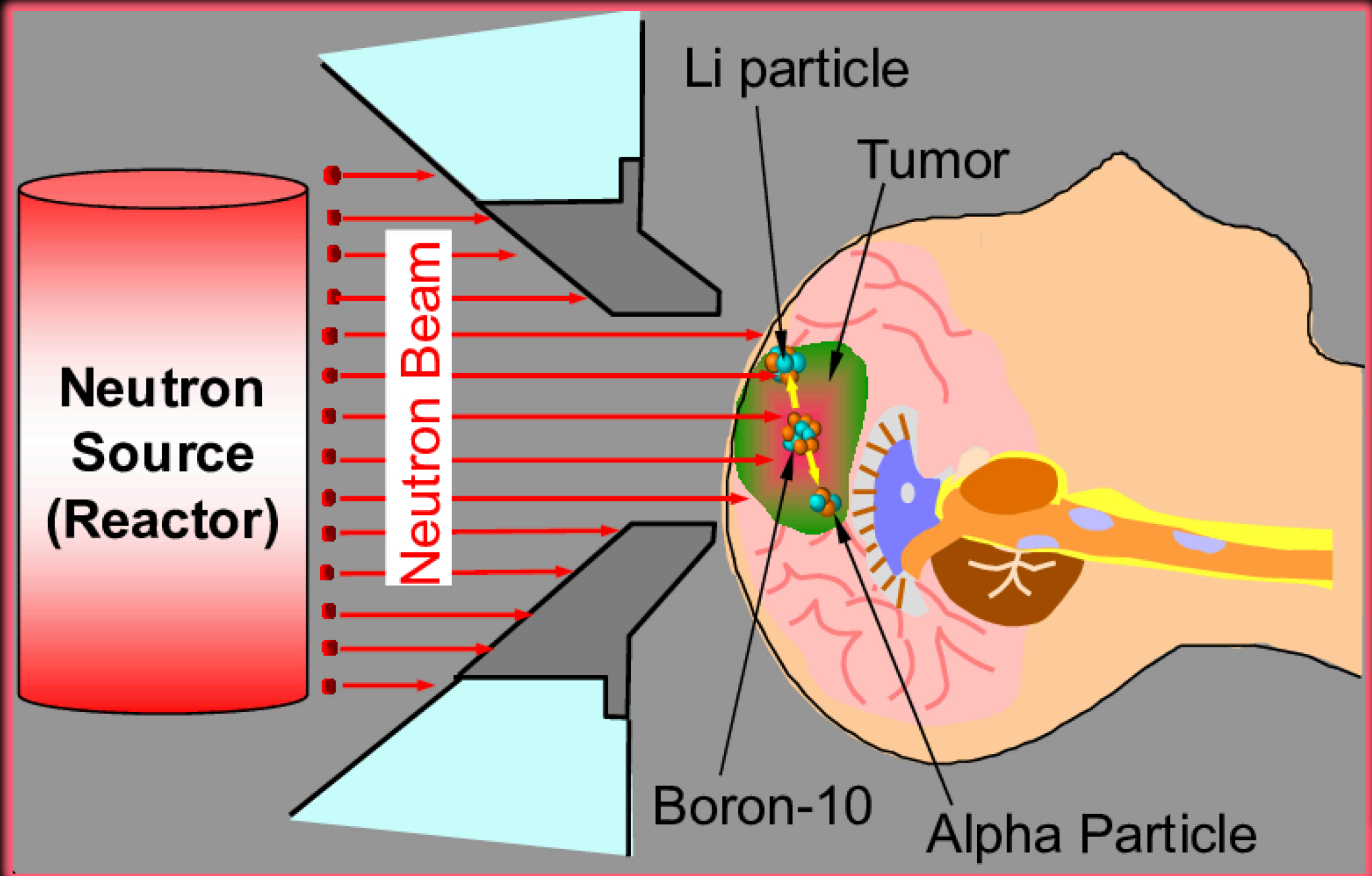
- Most important neutron absorbers: $^{10}B$ as $^{10}B_4C$ in control rods, or Boric acid as a coolant water additive in PWRs.
- Other important neutron absorbers that are used in nuclear reactors Xe, Cd, Hf, Gd, Co, Sm,, Dy, all of which usually consist of mixtures of various isotopes—some of which are excellent neutron-absorbers. These also occur in combinations such as $Mo_2B_5$, $HfB_2$, $TiB_2$,

# BORON ABSORPTION CROSS SECTION: REACTORS' BARS CONTROL




- Most important neutron absorbers: $^{10}B$ as $^{10}B_4C$ in control rods, or Boric acid as a coolant water additive in PWRs.

# BORON ABSORPTION CROSS SECTION: BORON NEUTRON CAPTURE THERAPY




$$n + {}^{10}\mathrm{B} \rightarrow {}^{7}\mathrm{Li}* + \alpha \rightarrow {}^{7}\mathrm{Li} + \alpha + \gamma \text{ (478 KeV)} + 2.31 \text{ MeV (94\%)}$$

$$\rightarrow {}^{7}\mathrm{Li} + \alpha + 2.79 \text{ MeV (6\%)}.$$

# BORON ABSORPTION CROSS SECTION: $BF_4$ NEUTRON DETECTORS

$$n + {}^{10}\mathrm{B} \rightarrow {}^{7}\mathrm{Li}* + \alpha \rightarrow {}^{7}\mathrm{Li} + \alpha + \gamma\ (478\ \mathrm{KeV}) + 2.31\ \mathrm{MeV}\ (94\%)$$

$$\rightarrow {}^{7}\mathrm{Li} + \alpha + 2.79\ \mathrm{MeV}\ (6\%).$$

# NEUTRON WAVE-PACKET RESONANCE: BORON TRANSPARENCY

Table 1. **Neutron scattering lengths and cross sections of the elements and their isotopes.**

| Column | Symbol | Unit | Quantity |
|---|---|---|---|
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| 2 | $Z$ | | atomic number |
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| 9 | $s_i$ | barn | bound incoherent scattering cross section |
| 10 | $s_s$ | barn | total bound scattering cross section |
| 11 | $s_a$ | barn | absorption cross section for 2200 m/s neutrons[2] |

(1) 1 barn = 100 $fm^2$
(2) $E = 25.30$ meV, $k = 3.494$ Å$^{-1}$, $l = 1.798$ Å

| | $Z$ | $A$ | $I(\pi)$ | $c$ | $b_c$ | $b_i$ | $\sigma_c$ | $\sigma_i$ | $\sigma_s$ | $\sigma_a$ |
|---|---|---|---|---|---|---|---|---|---|---|
| H | 1 | | | | −3.7390(11) | | 1.7568(10) | 80.26(6) | 82.02(6) | 0.3326(7) |
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| He | 2 | | | | 3.26(3) | | 1.34(2) | 0 | 1.34(2) | 0.00747(1) |
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| Li | 3 | | | | −1.90(2) | | 0.454(10) | 0.92(3) | 1.37(3) | 70.5(3) |
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| | | | | | −0.261(1)$i$ | +0.26(1)$i$ | | | | |
| | | 7 | 3/2(−) | 92.5 | −2.22(2) | −2.49(5) | 0.619(11) | 0.78(3) | 1.40(3) | 0.0454(3) |
| Be | 4 | 9 | 3/2(−) | 100 | 7.79(1) | 0.12(3) | 7.63(2) | 0.0018(9) | 7.63(2) | 0.0076(8) |
| B | 5 | | | | 5.30(4) | | 3.54(5) | 1.70(12) | 5.24(11) | 767.(8.) |
| | | | | | −0.213(2)$i$ | | | | | |
| | | 10 | 3(+) | 20.0 | −0.1(3) | −4.7(3) | 0.144(8) | 3.0(4) | 3.1(4) | 3835.(9.) |
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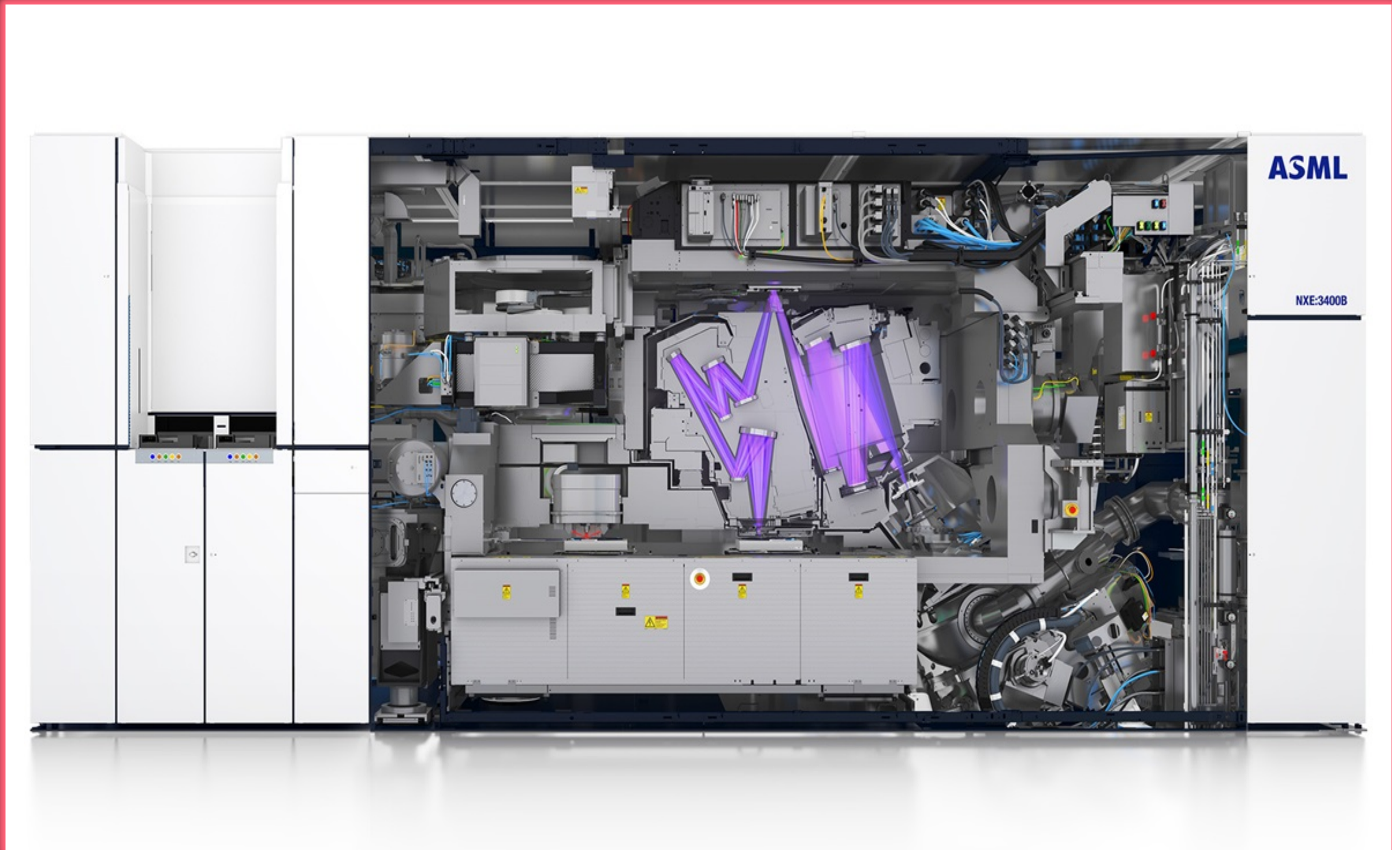
| C | 6 | | | | 6.6460(12) | | 5.550(2) | 0.001(4) | 5.551(3) | 0.00350(7) |
| | | 12 | 0(+) | 98.90 | 6.6511(16) | 0 | 5.559(3) | 0 | 5.559(3) | 0.00353(7) |
| | | 13 | 1/2(−) | 1.10 | 6.19(9) | −0.52(9) | 4.81(14) | 0.034(11) | 4.84(14) | 0.00137(4) |

**VARLEY F. SEARS**
*AECL Research, Chalk River Laboratories*
*Chalk River, Ontario, Canada K0J 1J0*

# TMSC-TAIWAN & Nano-Processors.




Водородные бомбы с использованием принципа атомного обжатия. Опытное устройство для проверки принципа атомного обжатия РДС-37.

Преимущество водородных бомб не реализуется без достаточного сжатия легкого ядерного горючего (в 10–20 раз). Энергии обычных взрывчатых веществ не достаточно для осуществления такого сжатия. Многочисленные изыскания, проводившиеся в КБ-11 в 1951–55 гг. не привели к решению проблемы создания мощных, экономичных и транспортабельных водородных бомб, обжимаемых обычными ВВ.

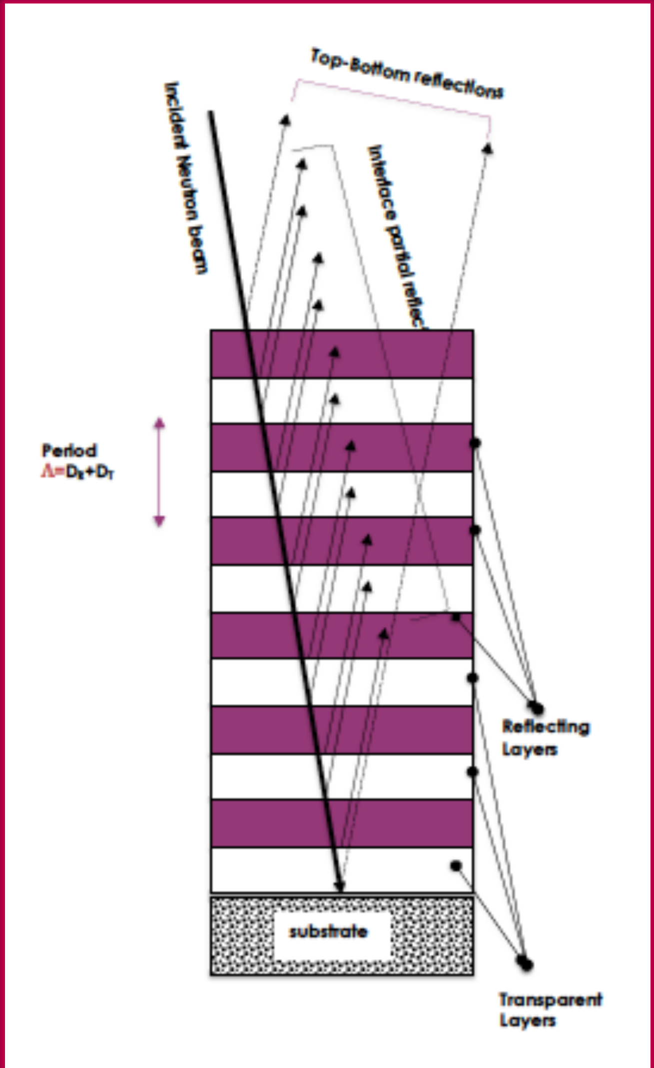
При габаритах порядка РДС-6с такие водородные бомбы оказываются даже не более экономичными, чем атомные бомбы на принципе цепной реакции.

Для получения высоких [illegible] использовать совершенно нов[illegible] обжатие», т.е. сжатие водород[illegible] гии взрыва вспомогательной а[illegible]

В 1951, 1952 и 1954 гг. в С[illegible] пытаний водородных бомб, в т[illegible] была испытана бомба мощност[illegible] 1954 г. была испытана трансп[illegible] ностью 14 млн тонн. Столь вы[illegible] нашему мнению, с большой [illegible] тельствуют о применении атом[illegible]

Расчет мощности опытн[illegible] проведенный на электронной [illegible] ления прикладной математики [illegible] 1,9 млн тонн.

# NEUTRON WAVE-PACKET RESONANCE: BORON TRANSPARENCY




Bragg diffraction: $2\,\Lambda\,\sin\Theta_i \approx k\lambda$

Kiessig & resonance condition:
$L_{total}\,Q_{max} \approx k'2\,\pi$

# NEUTRON WAVE-PACKET RESONANCE: BORON TRANSPARENCY



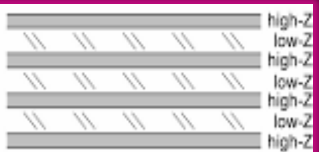
Resonance conditions:

Zeldovich-Vinogradov equation (X-Rays)

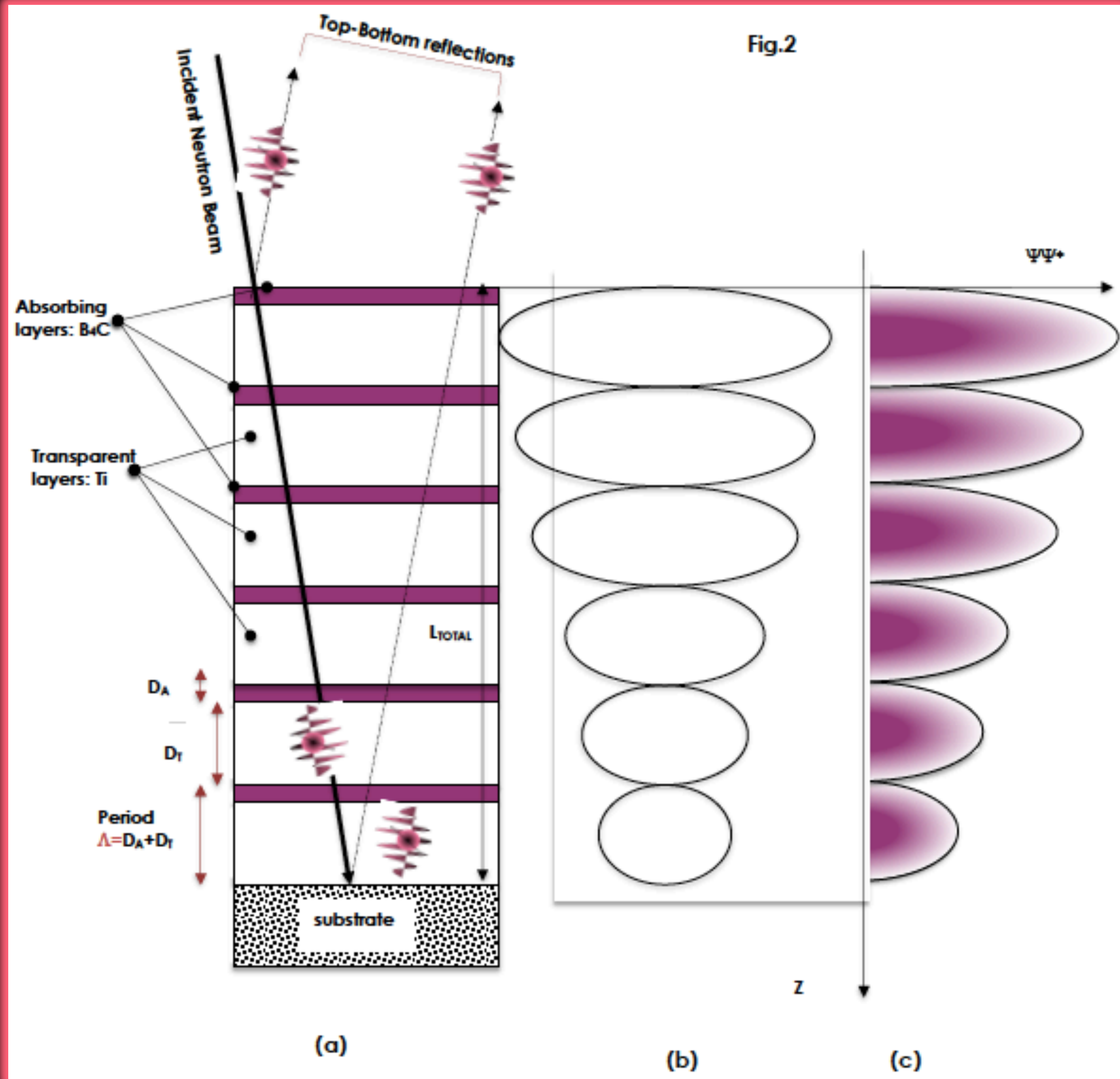
$$\Gamma = \frac{\Delta t_H}{\Delta t_H + \Delta t_L} = \frac{\Delta t_H}{d} \quad (4.7)$$

$$\tan(\pi \Gamma_{opt}) = \pi \left[ \Gamma_{opt} + \frac{\beta_L}{\beta_H - \beta_L} \right] \quad (4.8)$$

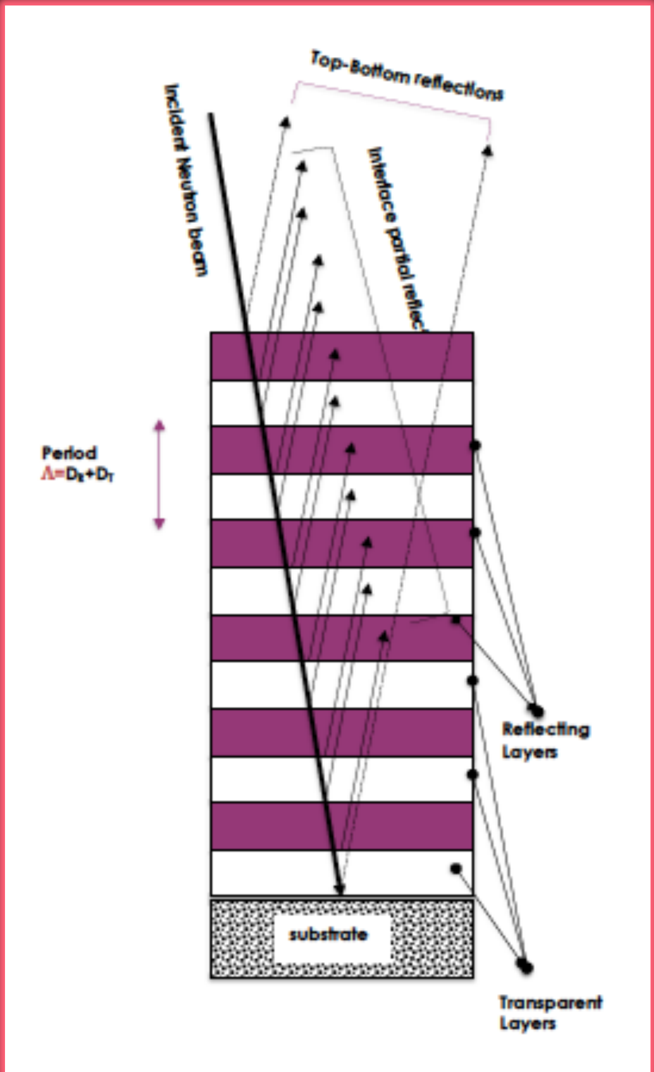
(Vinogradov and Zeldovich, 1977)
(also see Borrmann, 1941)

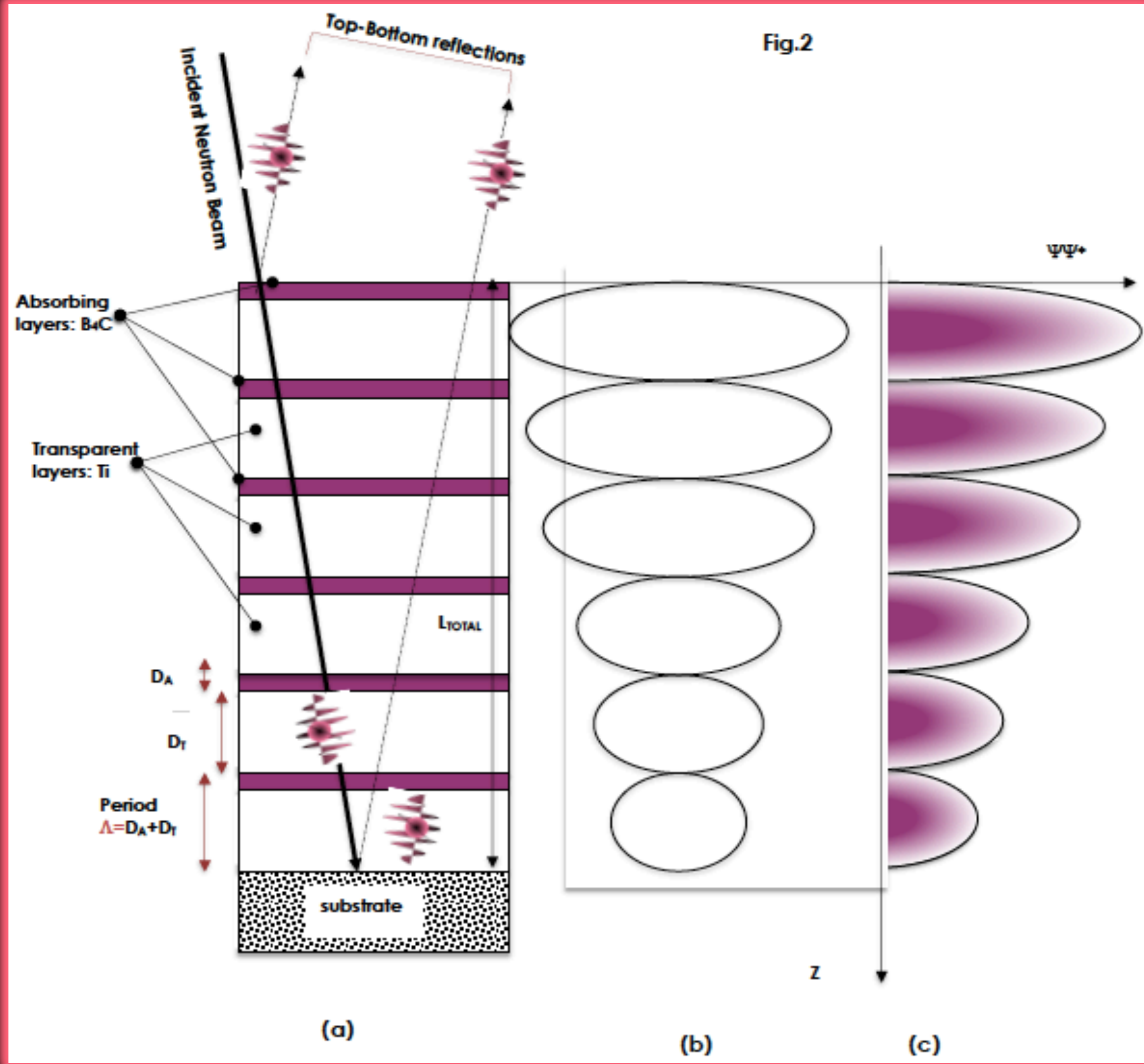



- Sharp interfaces needed for scattering
- Thin high-Z layer to minimize absorption
- Low-Z layer best as a "spacer"



# NEUTRON WAVE-PACKET RESONANCE: BORON TRANSPARENCY



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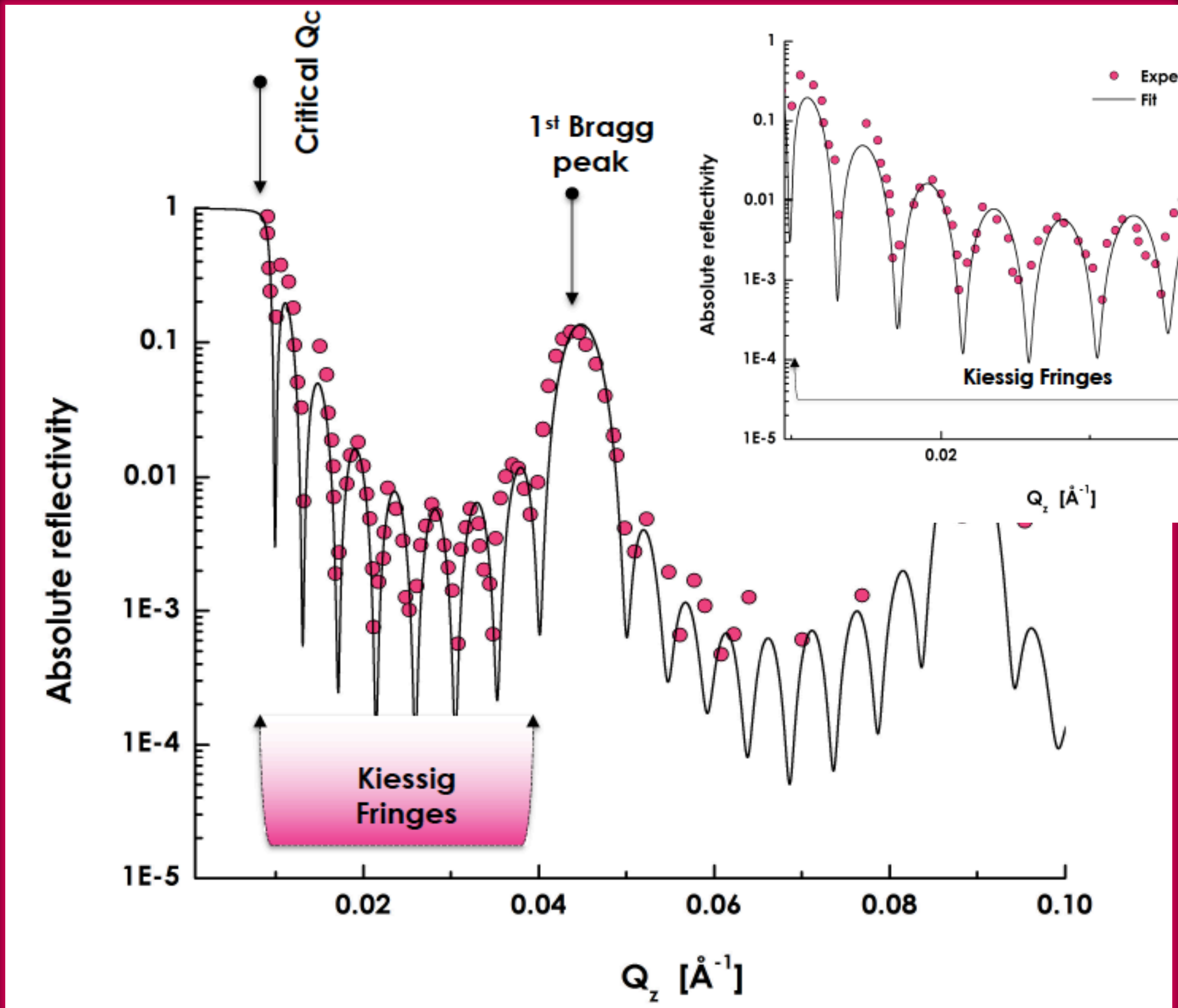
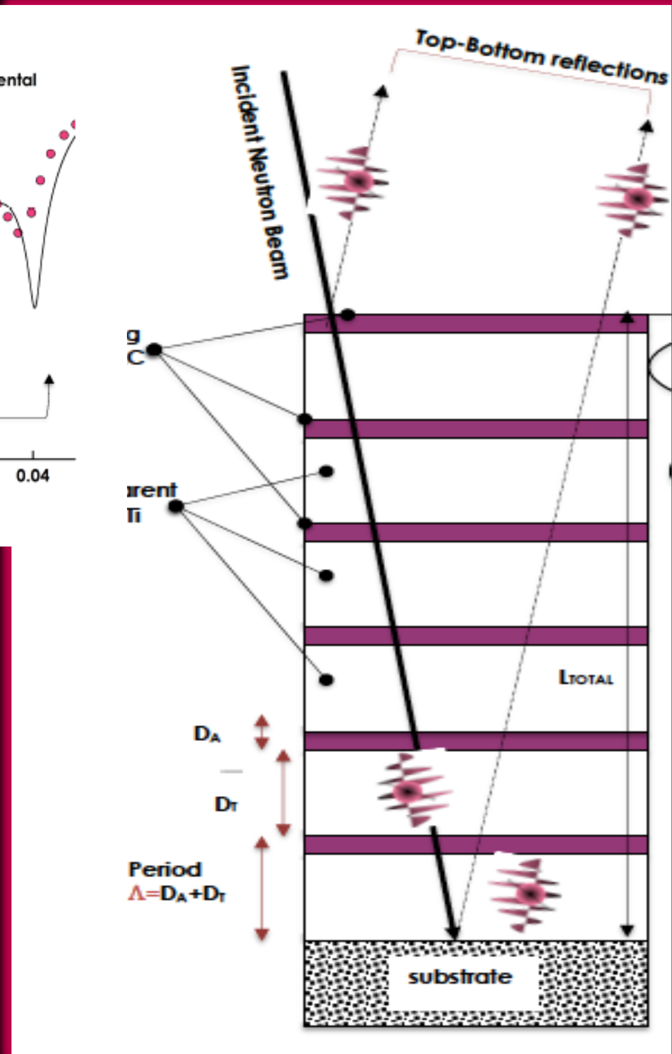



Cold Neutron Physics Workshop- Webinar ESS, Lund-Sweden 21-05-2021

# NEUTRON WAVE-PACKET RESONANCE: BORON TRANSPARENCY

***Untersuchungen zur Totalreflexion von Röntgenstrahlen*** [1]

***Von Heinz Kiessig***

(Mit 30 Figuren)

**Einleitung**

Nachdem der Nachweis erbracht worden war, daß au… Röntgenstrahlen sich meßbar brechen und reflektieren l… sind in den letzten Jahren zahlreiche Arbeiten gemacht w… die sich mit dem quantitativen Studium dieser Ersche… befassen.[2]) Das Ziel dieser Arbeiten war fast ausschließ… die Messung des Brechungsindex in Abhängigkeit von der Wellenlänge und den Materialien, um die Dispersionskurve für Röntgenstrahlen aufstellen zu können. Es zeigte sich, daß die Drude-Lorentzsche Dispersionstheorie nicht nur qualitativ anwendbar ist, sondern auch quantitativ die Verhältnisse gut wiedergibt. Da für Röntgenstrahlen der Brechungsindex $n$ kleiner als 1 ist, aber nur wenig von 1 abweicht, setzt man üblicherweise

$$n = 1 - \delta$$

und gibt immer nur den Wert $\delta$ an. Es lautet dann die Lorentzsche Dispersionsformel

$$\delta = \frac{e^2}{2\pi m} \sum \frac{N_K}{\nu^2 - \nu_K^2},$$

wobei

$\nu$ die Frequenz der einfallenden Strahlung,

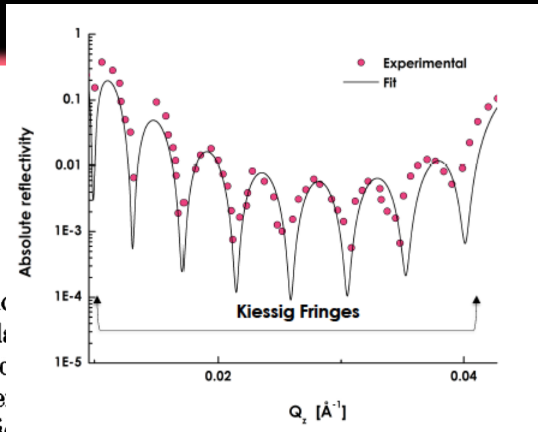
$\nu_K$ die Eigenfrequenzen der Elektronen und

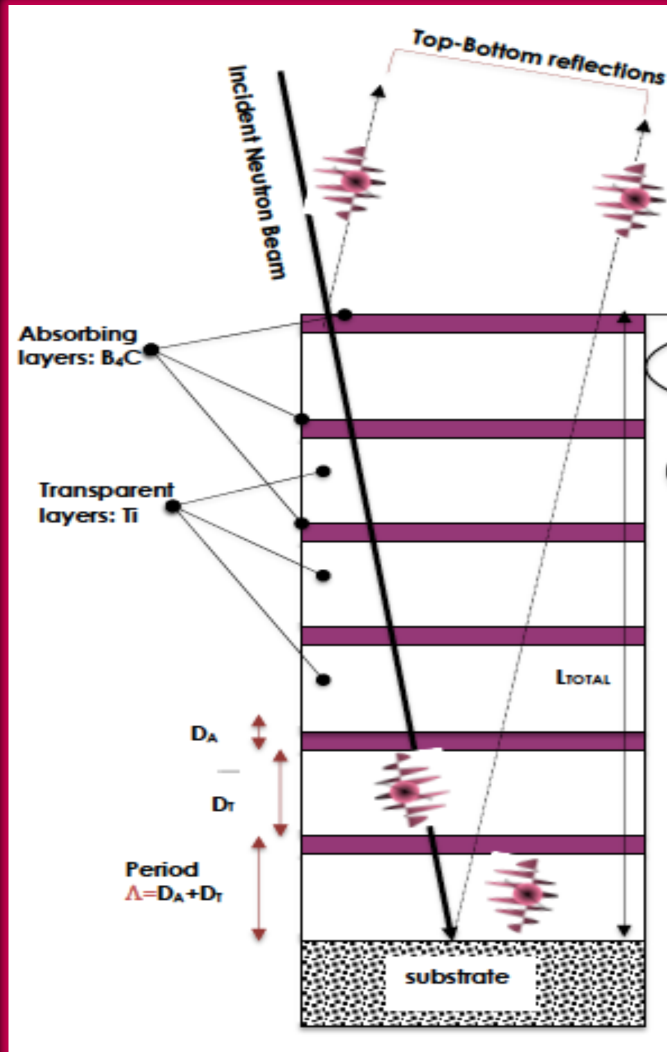
$N_K$ die Anzahl der Elektronen mit der Eigenfrequenz $\nu_K$ in dem Einheitsvolumen bedeutet.

Die Summe ist über alle Eigenfrequenzen zu erstrecken.

1) Dissertation der Technischen Hochschule München.

2) Zusammenfassende Darstellungen über das vorliegende Material



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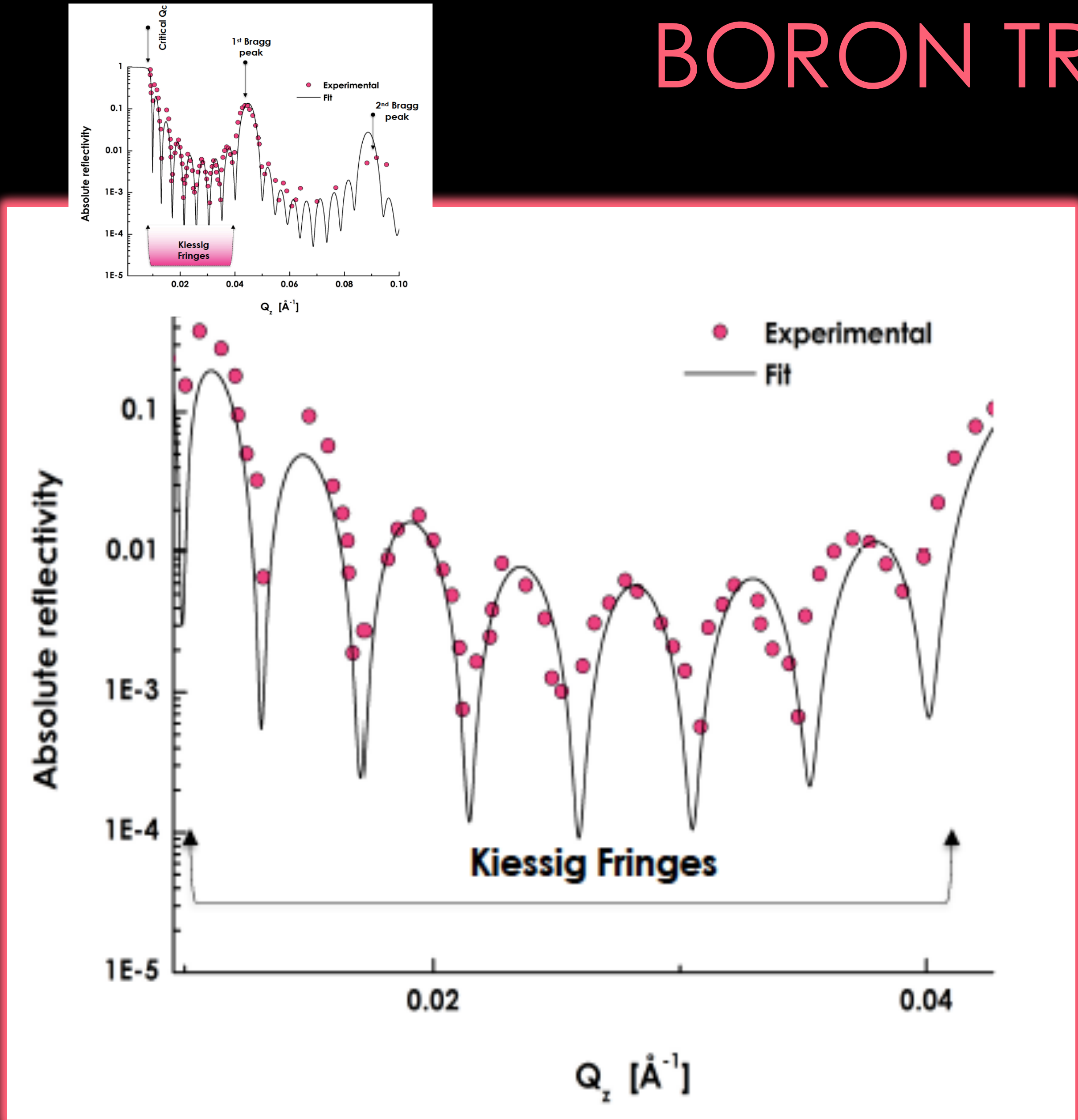


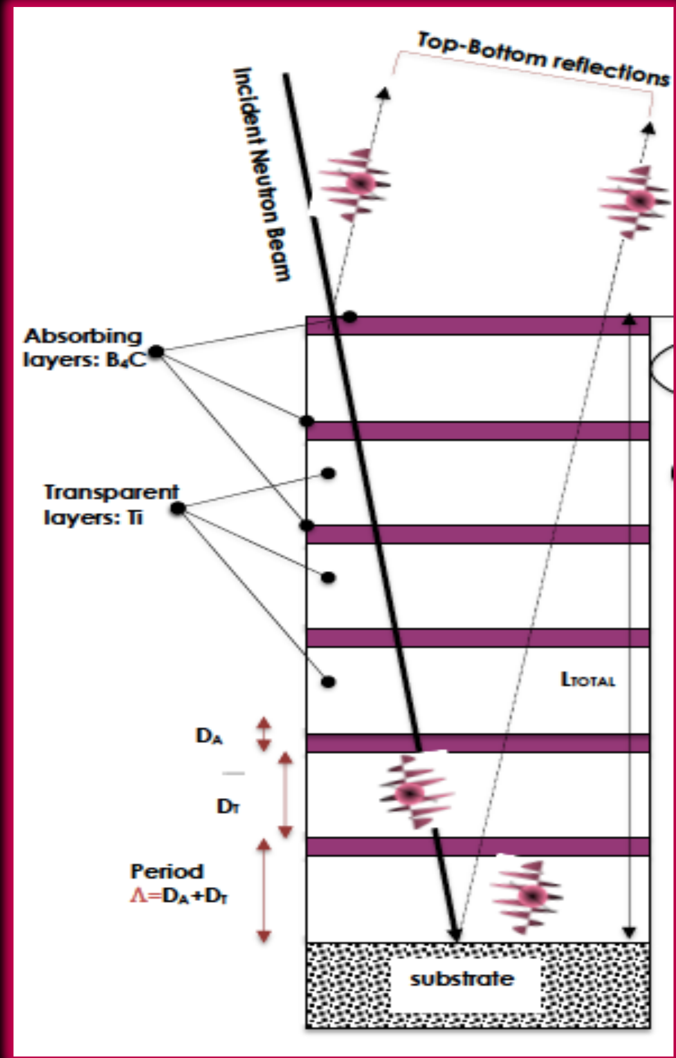

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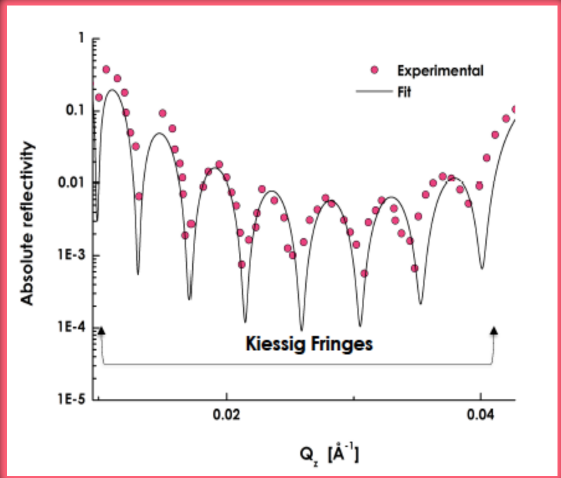
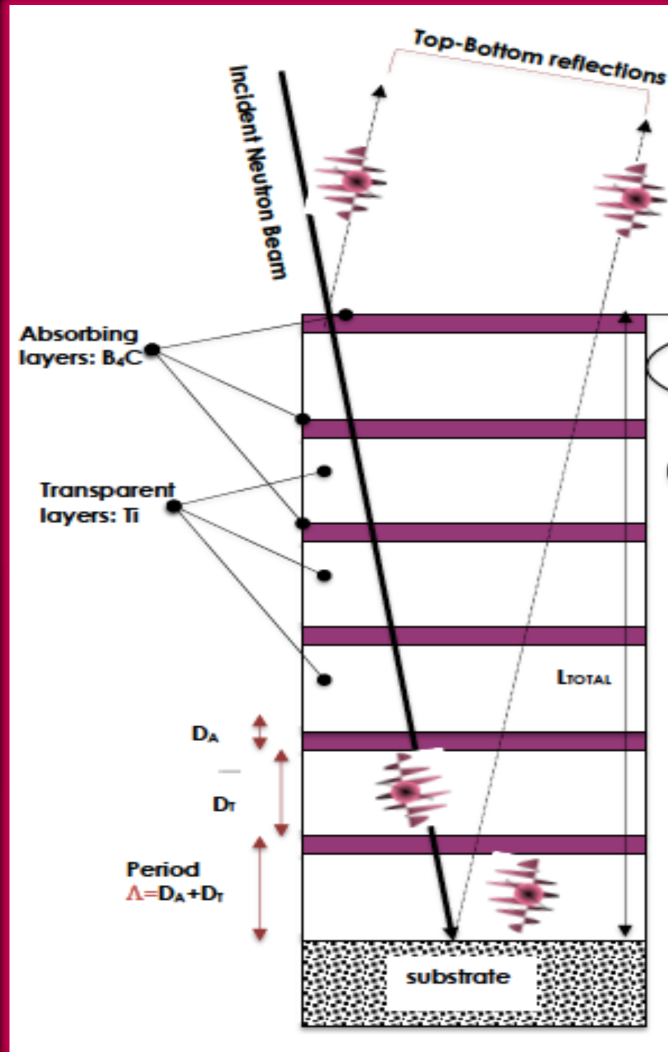


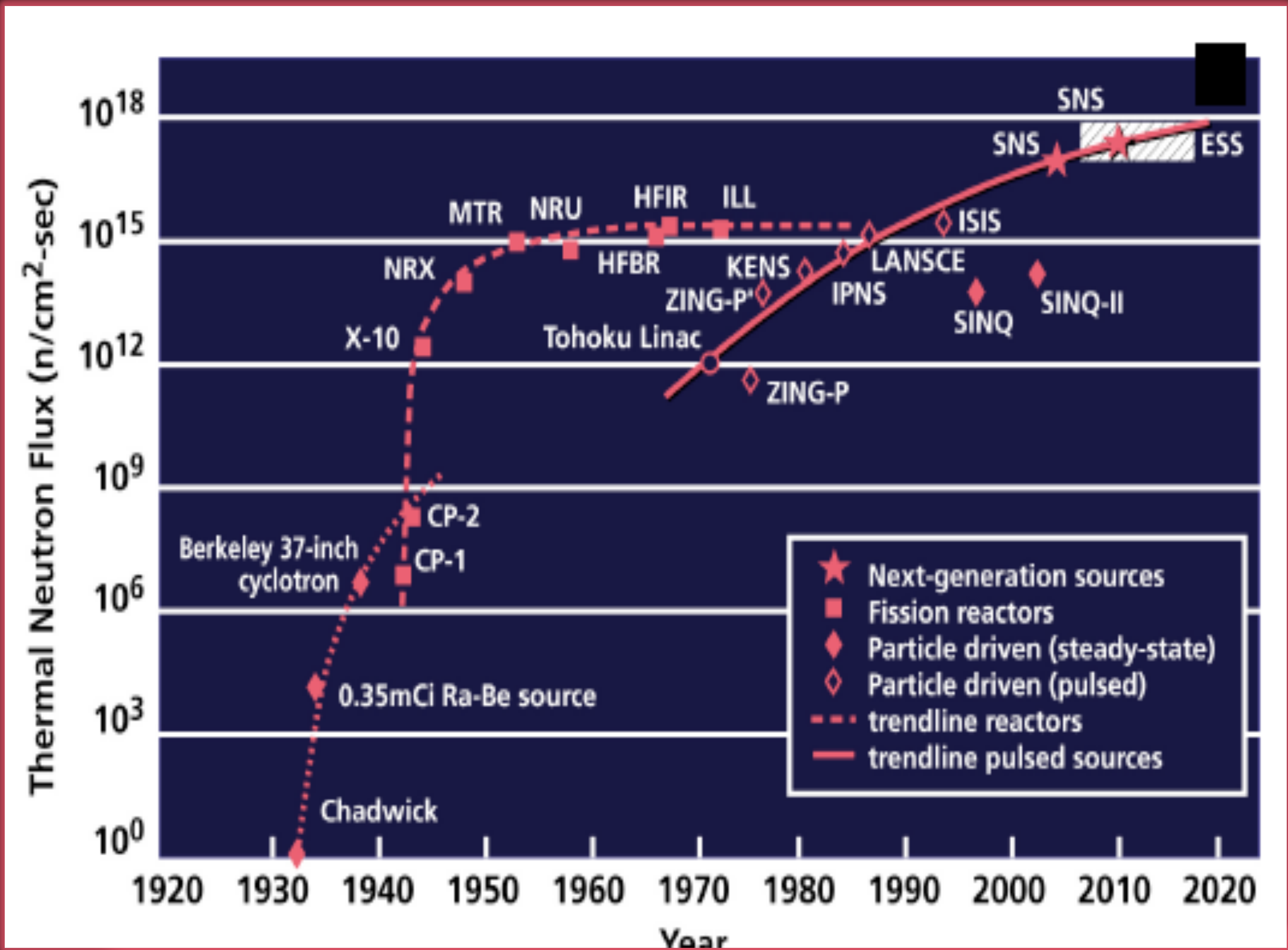

$\Theta_i \approx 1$ Deg


$D_{eff} \approx D_{B4C}/\sin\Theta$

$D_{eff} \approx 200$nm



# ULTRA-COLD NEUTRON SOURCES



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- Organization of Women in Science for the Developing World, Trieste-Italy.
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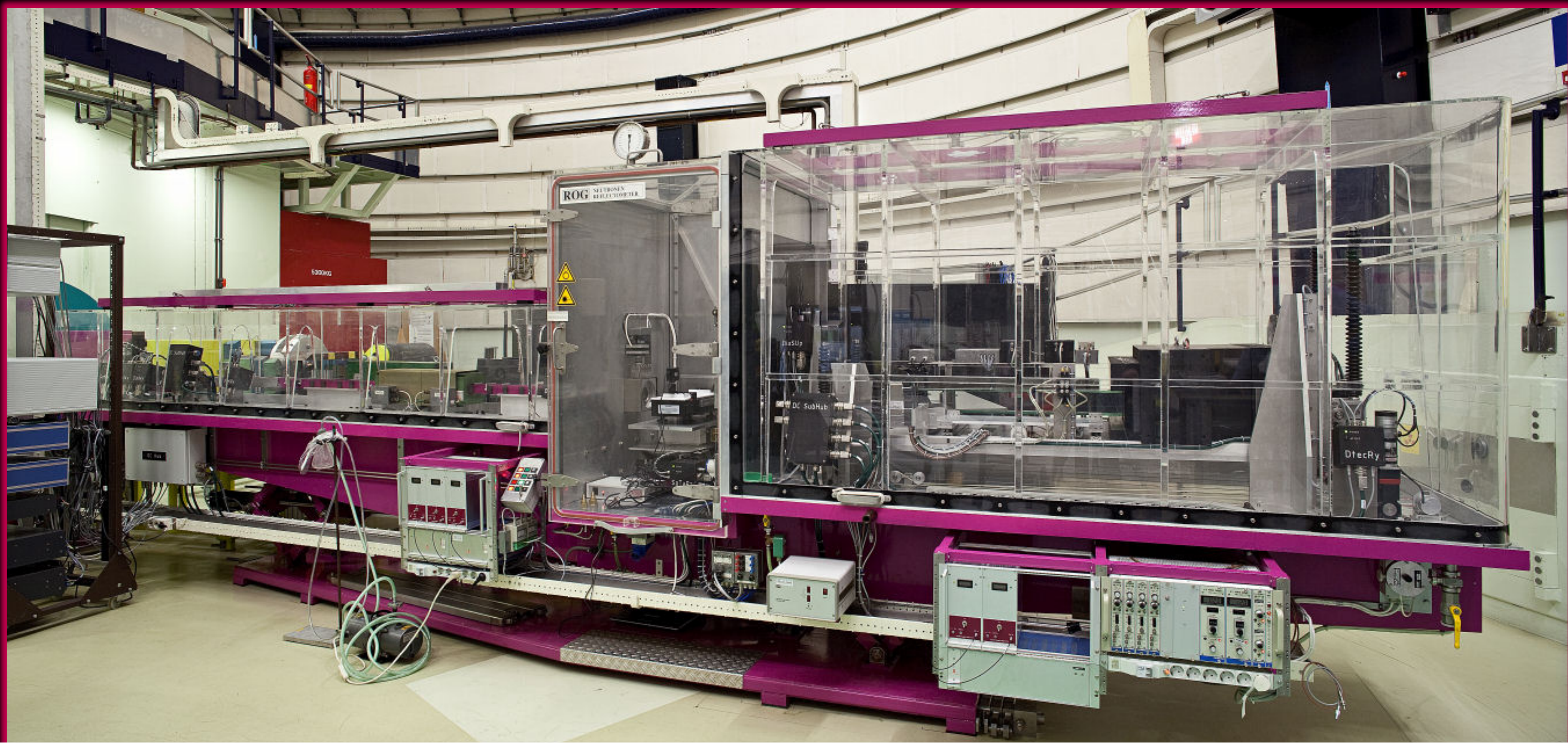
# TYPICAL NEUTRON GUIDE HALL/ REFLECTOMER



# FRUSTRATED TOTAL REFLECTION.

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**Observation of Quasibound States of the Neutron in Matter**

K.-A. Steinhauser, A. Steyerl, and H. Scheckenhofer
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(Received 29 February 1980)

Quasistationary states of ultracold neutrons have been observed in a double-hump potential barrier. This potential barrier was created by sandwiching a thin film of aluminum between two thin copper films. Measurements of reflection from and transmission through such composite films displayed clear resonances. The resonance positions and widths are in agreement with calculations.

The average neutron lifetime derived from:

Beam approach was found to be $\langle \tau n \rangle_{Beam}$ ~ 888.0 ± 2.0 s

Bottle technique of about $\langle \tau n \rangle_{Bottle}$ ~ 879.4 ± 0.6 s

Steyerl & al,Trapping in Fabry-Perot Nano-resonator" ± $10^{-6}$ s

Trapping in Fabry-Perot Nano-resonator" ± $10^{-12}$ s