Development of Iron Thin Films for Polarization Analysis of Ultracold Neutrons

2021-10-19 SPIN2021

Hiroaki Akatsuka, Masahiro Hino, TUCAN collaboration

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Introduction

- Ultra Cold Neutron (UCN)
- Neutron Electric Dipole Moment (nEDM)
- TUCAN overview
- Principle of UCN polarization measurement

Development and Evaluation of UCN polarization analyzer films

- Development of UCN polarization analyzer films
- B-H curve measurement by Vibrating Sample Magnetometry (VSM)
- Neutron reflectivity measurement

Conclusions and Outlook

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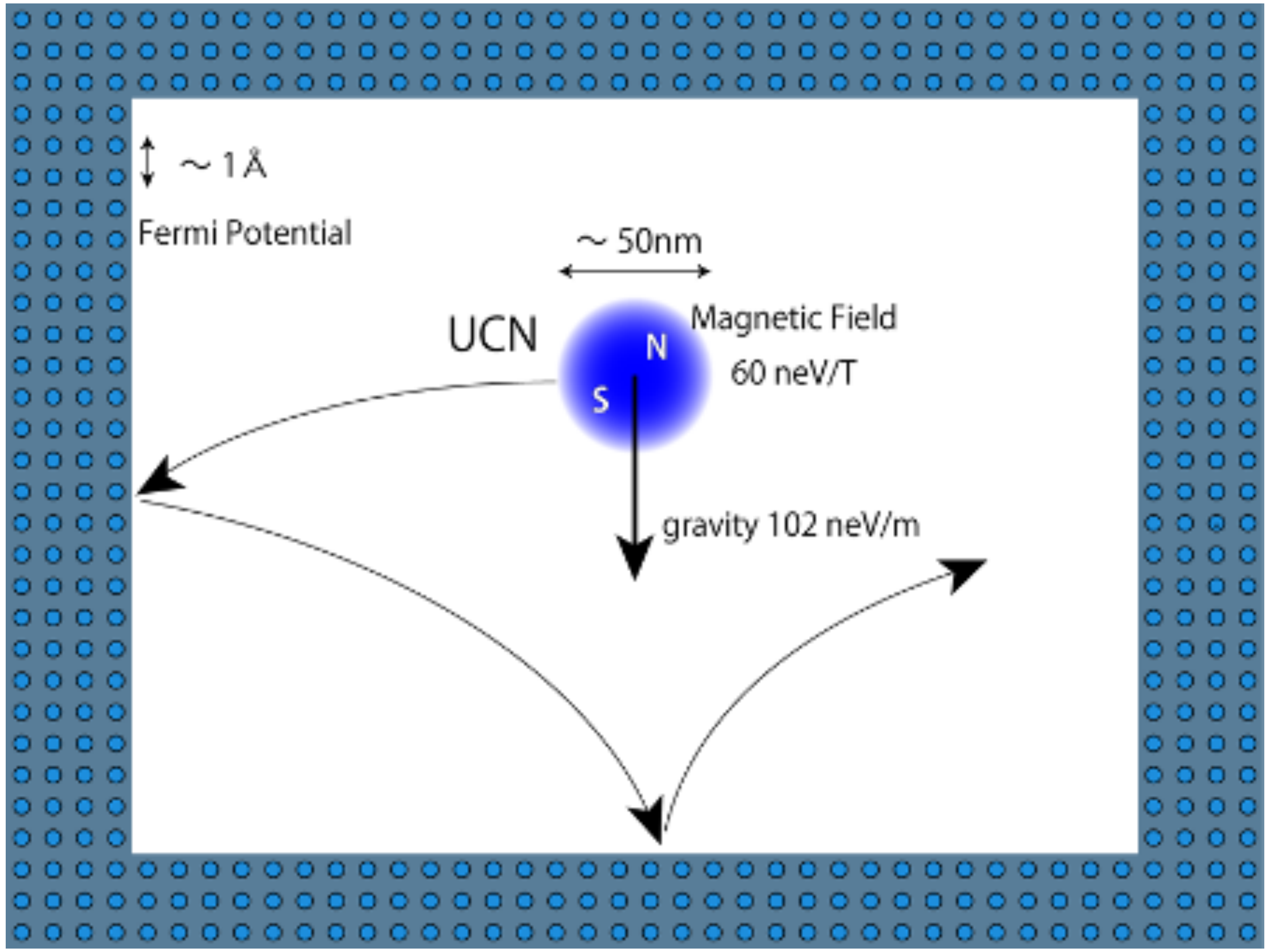
Ultra Cold Neutron (UCN)



Ultra Cold Neutron

- Energy $\lesssim 300\,\mathrm{neV}$
- velocity $\sim 8\,\mathrm{m/s}$
- wavelength $\sim 50\,\mathrm{nm}$

Major interaction on UCNs

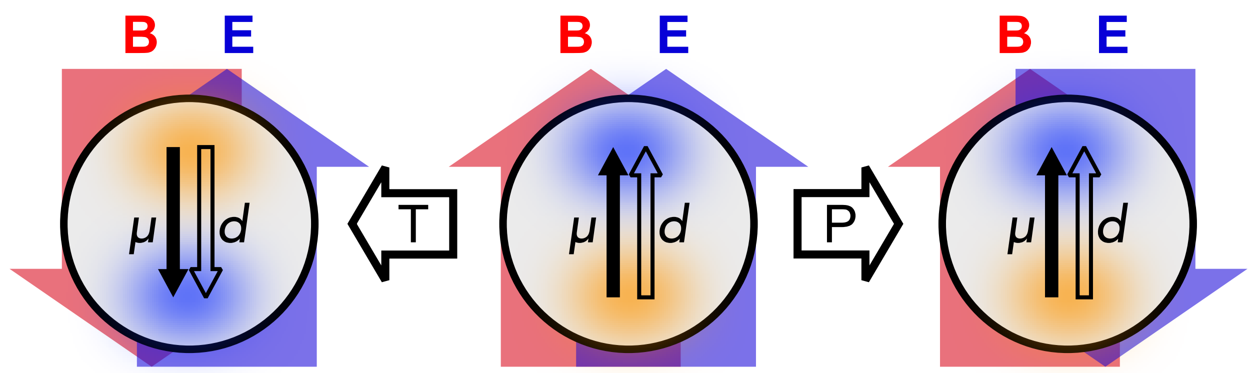
- Magnetic : μ_n= –60 neV/T
- Gravity: $m_n g$ = –102 neV/m
- Weak interaction → β-decay (n → p + e + $\bar{\nu}_e$)
- Strong interaction → Fermi potential (ex. Ni 234 neV)

Used in a variety of basic physics experiments
For example, gravity, lifetime,
neutron Electric Dipole Moment (nEDM), etc.

Confinement by matter, gravity, and magnetic field potential allows for long time (~100 s) observations.

→Longer measurement time for nEDM

Neutron Electric Dipole Moment



Neutron EDM (nEDM) violates the time-reversal (T) symmetry

- Equivalent to **CP violation** assuming CPT symmetry

Provides crucial tests of **theories beyond SM**

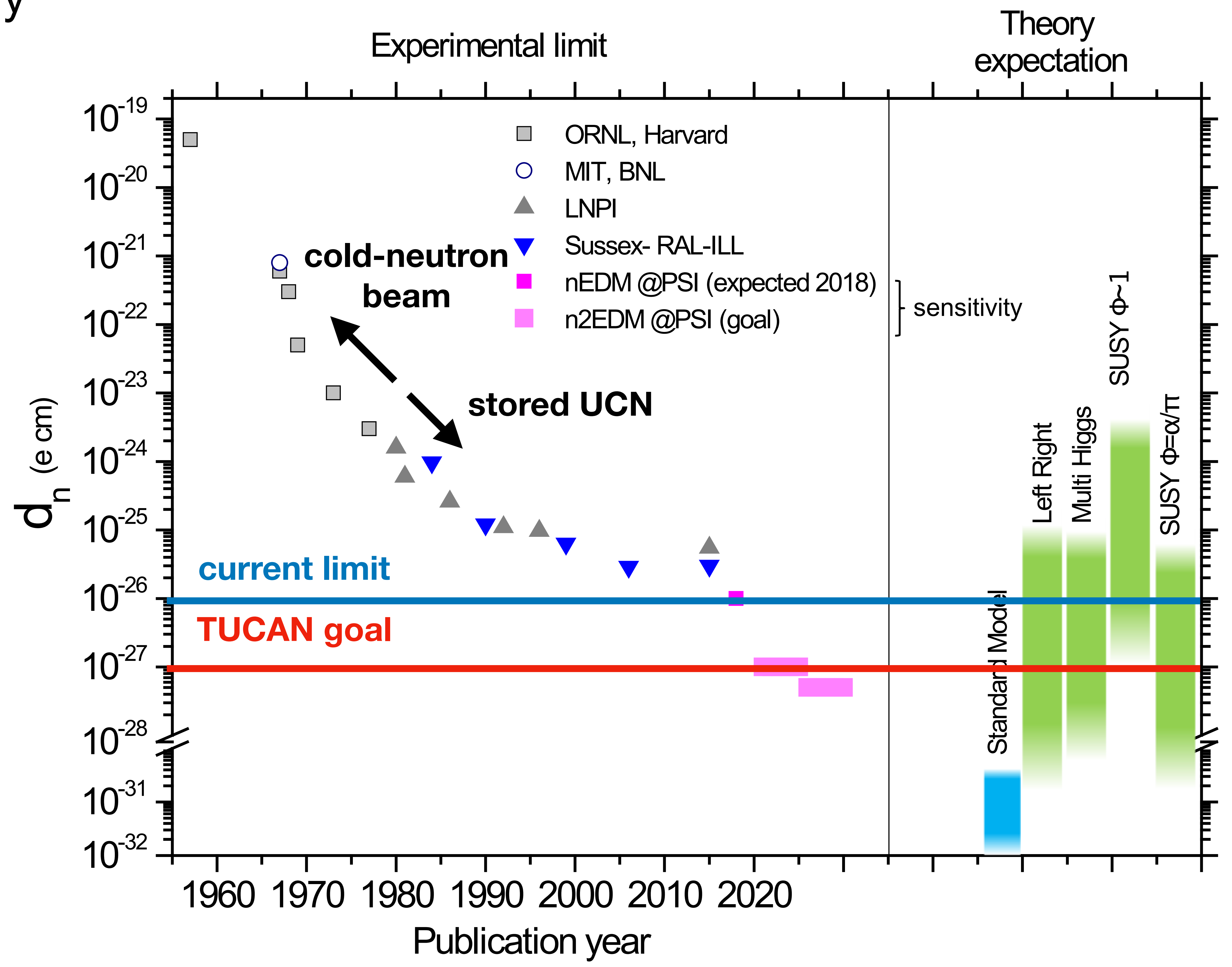
- SM : $10^{-32}\,\mathrm{e\cdot cm}$, SUSY $10^{-28} - 10^{-26}\,\mathrm{e\cdot cm}$

Today's limitation: UCN intensity

- The latest result by PSI nEDM collaboration:

$$d_n = (0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \times 10^{-26}\,\mathrm{e\cdot cm}$$

$$\rightarrow |d_n| < 1.8 \times 10^{-26}\,\mathrm{e\cdot cm}\,(90\,\%\,\mathrm{C.L})$$



Key for the next-generation nEDM measurement:
intense UCN sources !

Slide courtesy: B. Lauss, nEDM workshop 2017, based on NIMA 440, 471 (2000), Phys. Rev. D 92, 092003 (2015) AIP Conf. Proc. 1753, 060002 (2016)

TRIUMF Ultra-Cold Advanced Neutron

International collaboration between Japan and Canada (+US)

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TUCAN
TRIUMF Ultra Cold Advanced Neutron source

Goals of TUCAN

- **To measure the neutron electric dipole moment with an accuracy of** $10^{-27}\,\mathrm{e}\cdot\mathrm{cm}$
- **To construct the world's most intense ultra cold neutron source**

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TUCAN

TRIUMF Ultra Cold Advanced Neutron source

Overview
22/10/2021, 09:40
Parallel Session Presentation
62.The precision nEDM measurement with UltraCold Neutrons at TRIUMF

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The University of Winnipeg

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Nagoya University

UBC The University of British Columbia

RCNP

University of Manitoba

SFU Simon Fraser University Engaging the World

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Principle of nEDM measurement

Assume EDM exists

- Interaction between magnetic field B and magnetic moment μ_n , electric field d_n and EDM

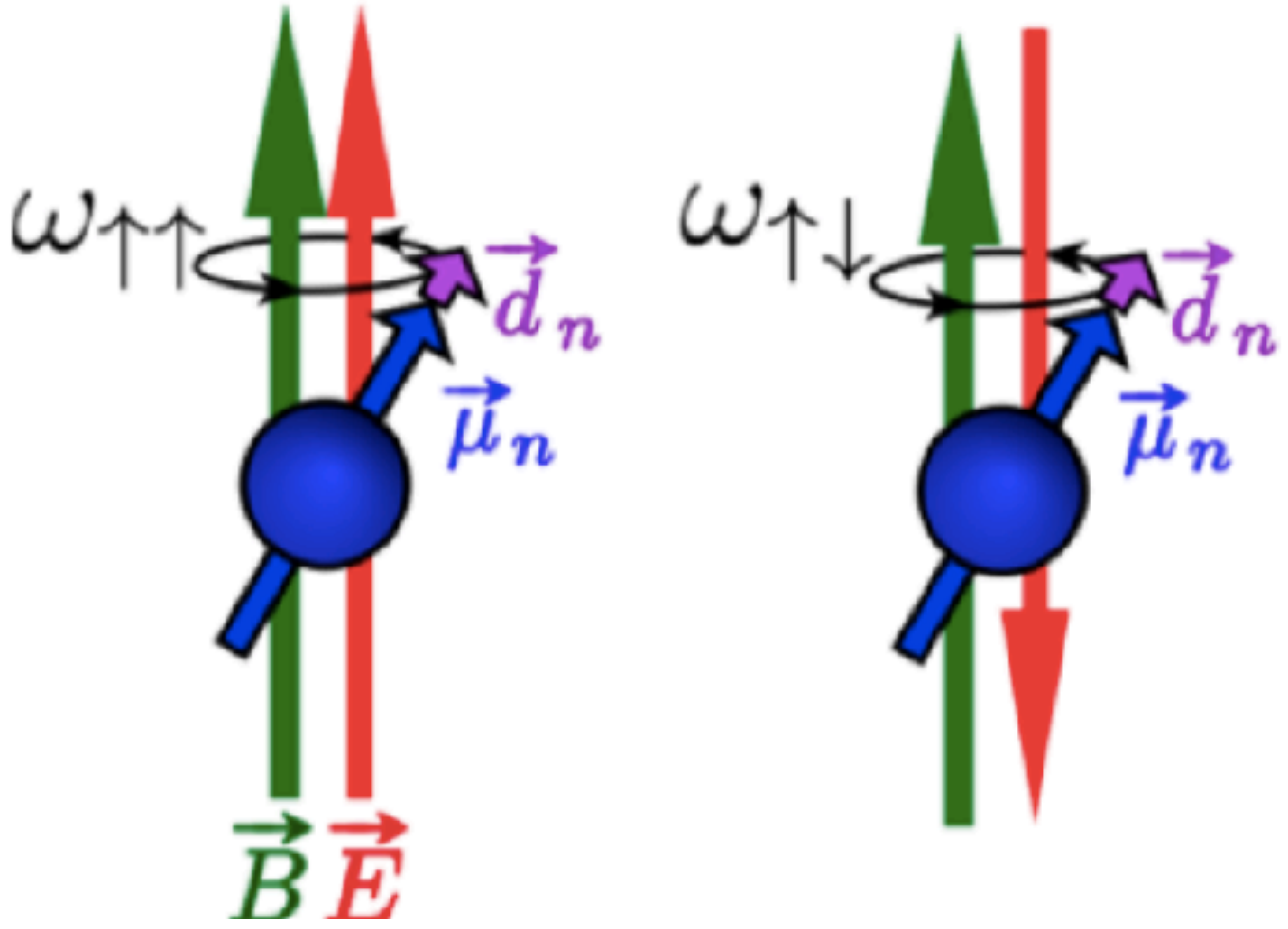
$$H = -\mu_n \cdot B - d_n \cdot E$$

- Relationship B between magnetic field and electric field E and Larmor frequency

B, E parallel (↑↑) $\quad \omega_{\uparrow\uparrow} = \dfrac{2\mu_n|B| + 2d_n|E|}{\hbar}$

B, E antiparallel (↑↓) $\quad \omega_{\uparrow\downarrow} = \dfrac{2\mu_n|B| - 2d_n|E|}{\hbar}$

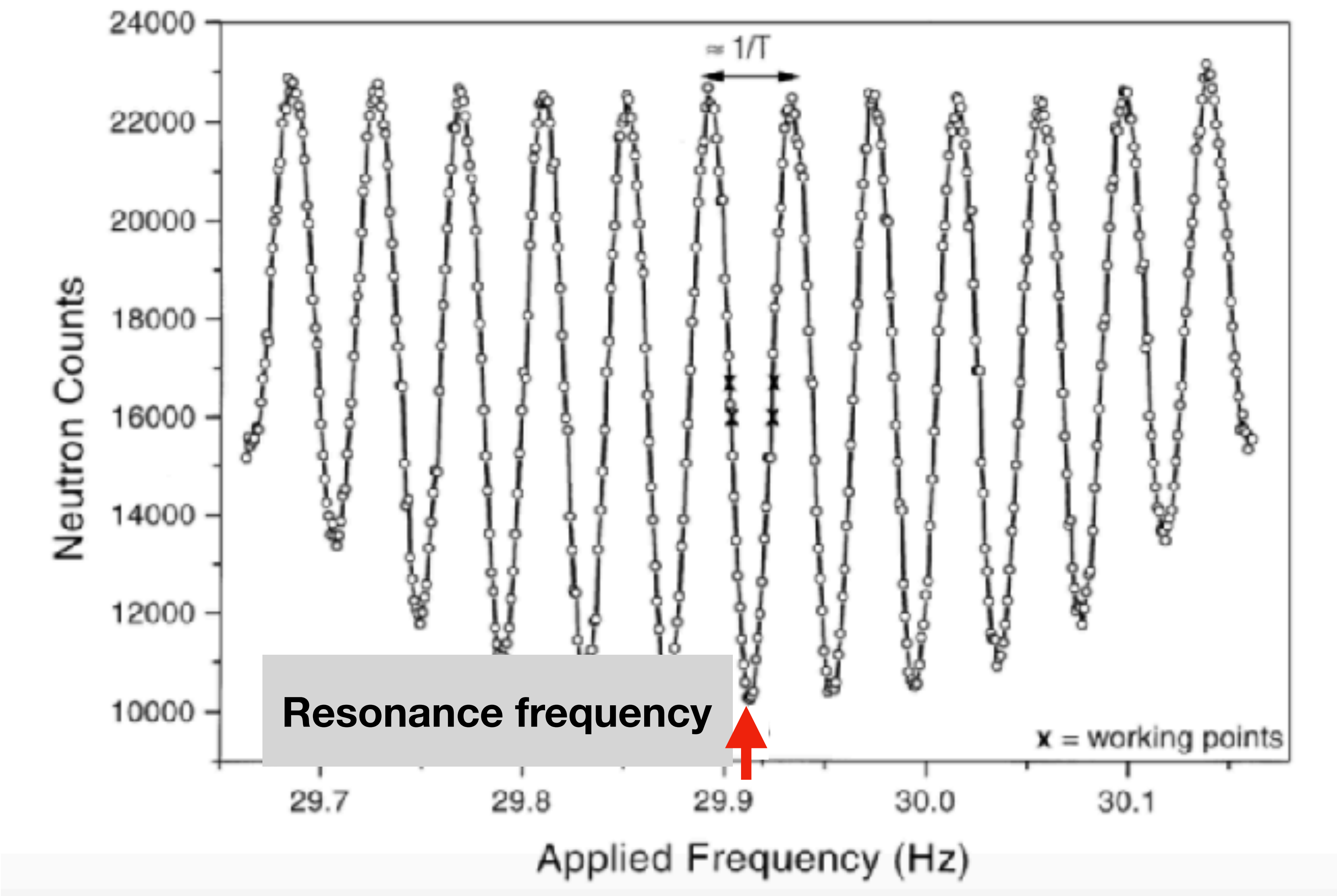
$$d_n = \frac{\hbar(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})}{4|E|}$$



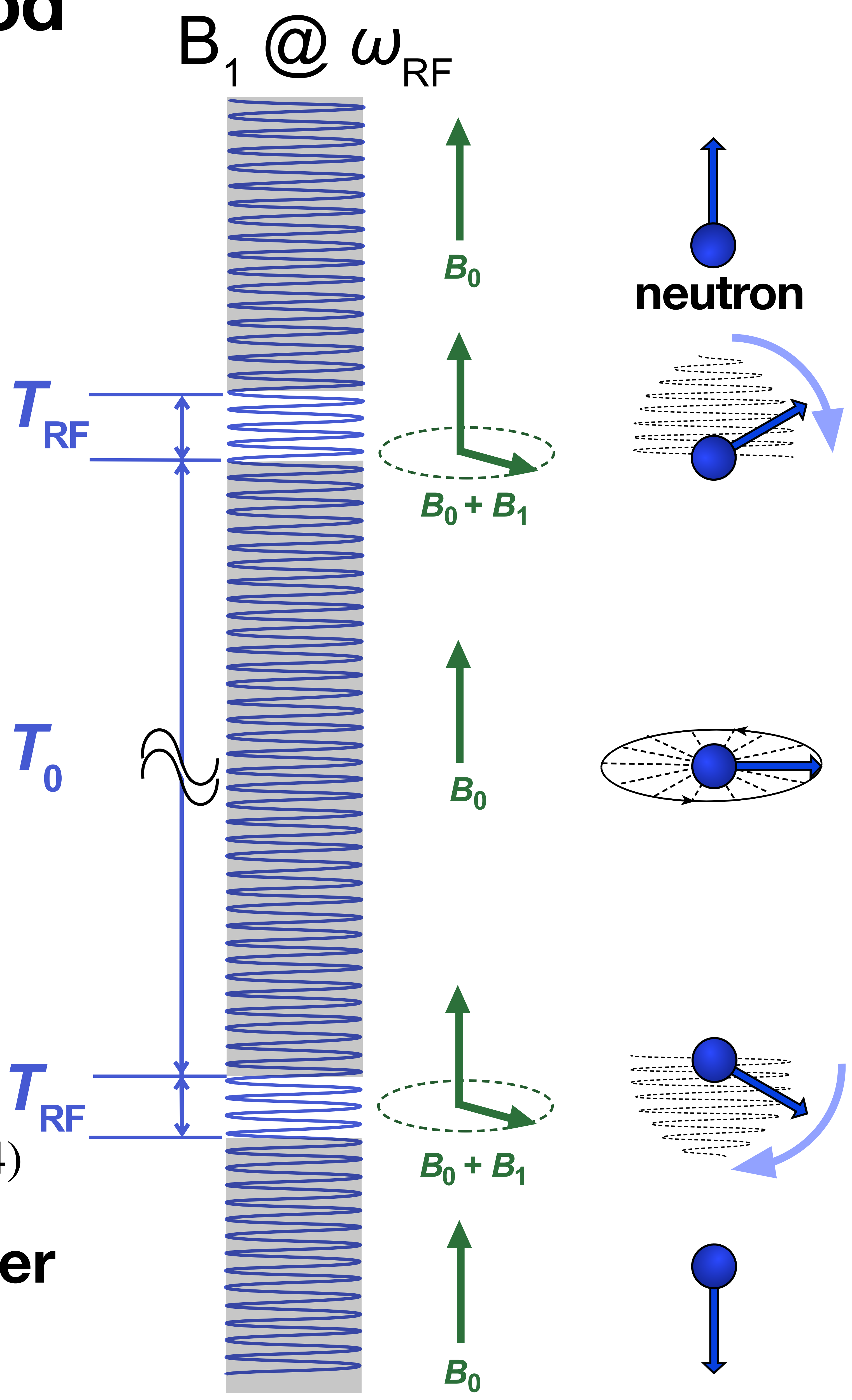
→EDM can be obtained from the Larmor frequency of the spin-polarized particle

Larmor frequency measurement by the Ramsey method

1. Neutrons are polarized in the direction of B_0 .($B_0 \sim 1\,\mu$T)
2. Apply $\pi/2$ pulse $B_1(@\omega_{RF})$ (application duration T_{RF})
3. free precession (time T_0)
4. Apply $\pi/2$ pulse $B_1(@\omega_{RF})$ (application duration T_{RF})
5. **Measure neutron polarization**
6. Repeat 1.~ 5. to obtain resonance frequency



C.A.Baker, et al, Nucl. Inst. Meth. A 736, 184 (2014)



This talk: development of the UCN polarization analyzer

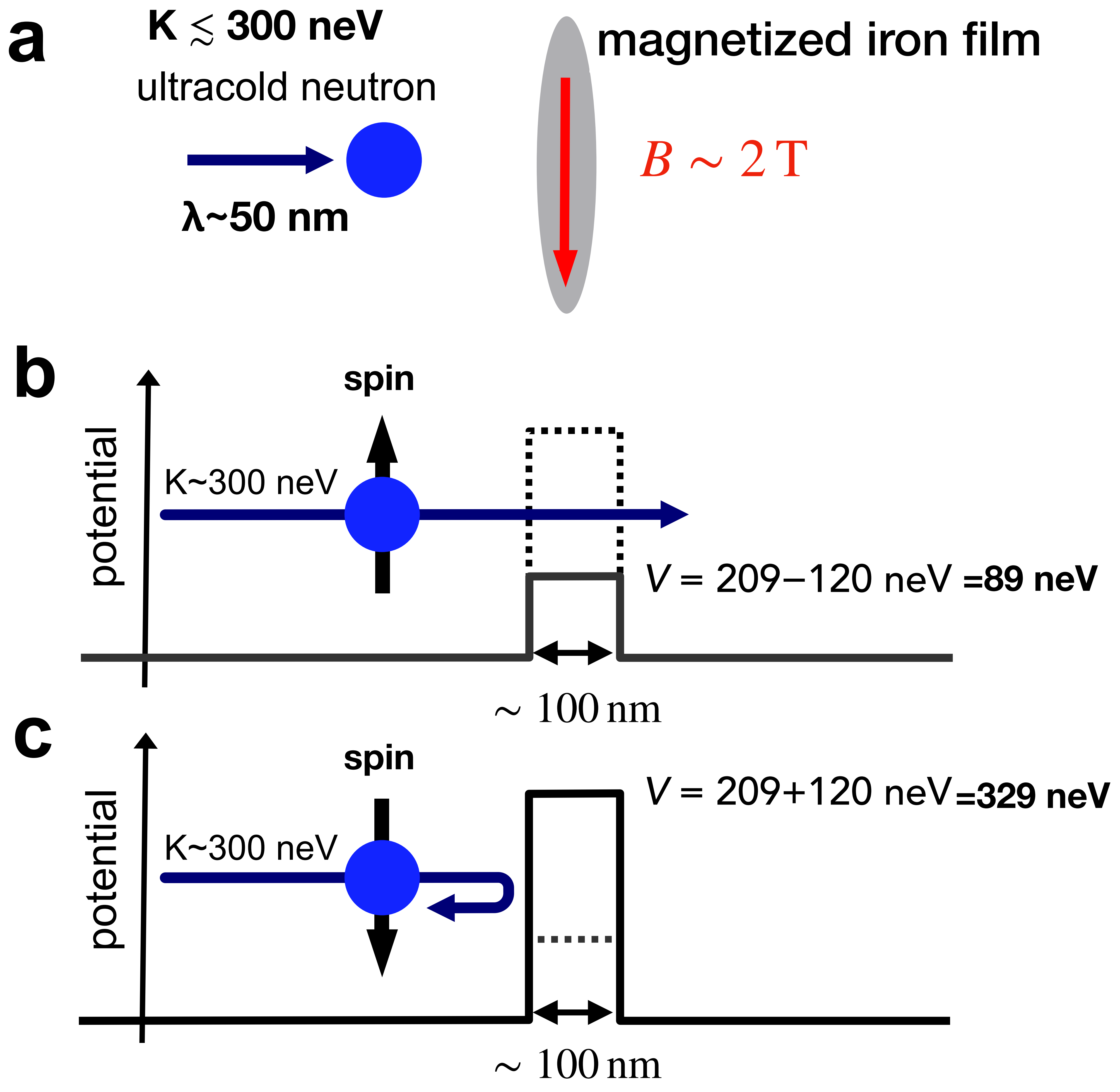
Principle of UCN spin analyzer

- UCN are polarized by a magnetized iron film
- The effective potential experienced by UCN:

$$V = V_F \pm \mu_n B = 209\,\mathrm{neV} \mp 60.3\,\mathrm{neV/T} \cdot B$$

  - Fermi potential of Fe: $V_F \sim 209\,\mathrm{neV}$
  - UCN kinetic energy $\lesssim 300\,\mathrm{neV}$

- **With ~ 2 T magnetization**
  → full separation of the UCN spin states
  → the film can be used **as a spin analyzer**

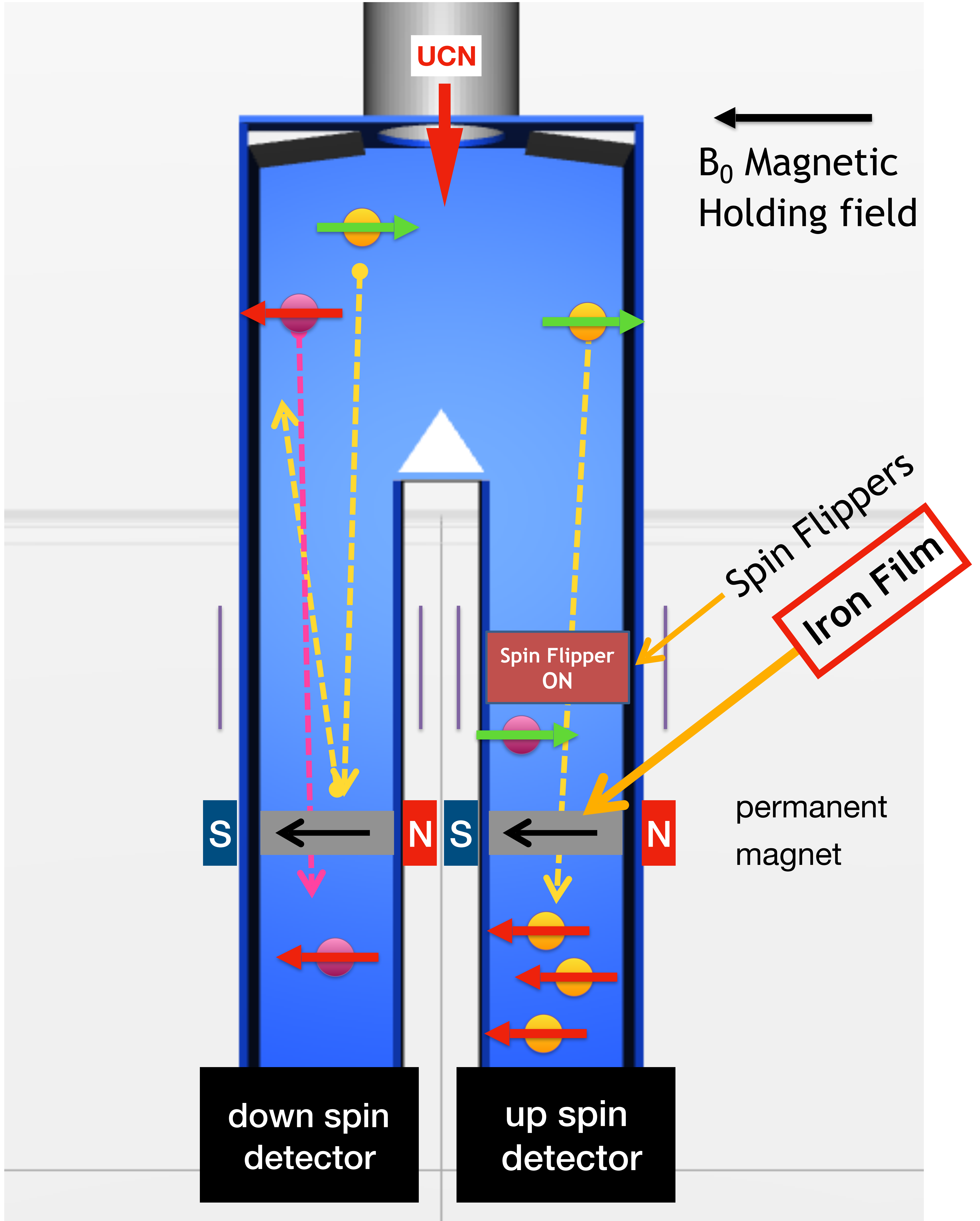


Simultaneous Spin Analyzer (SSA)

- **Simultaneous Spin Analyzer (SSA)**
  - Polarization analyzer
  - Thin Fe film in a permanent magnet: allows only a specific spin state to transmit
  - Simultaneous measurement of UCN in each spin state
    - Selection of the spin state by RF spin flipper
  - Measure the polarization from the number of UCN for each spin.

- **Requirements on the polarization films for the SSA**
  - Large saturation magnetization ($\sim 2\,\mathrm{T}$) (for high efficiency of spin analysis)
  - Saturate with a low magnetic field ($\lesssim 10\,\mathrm{mT}$)
    - Low leakage field
    - Compact device
  - Small absorption of UCN

S. Afach, et al, Euro. Phys. Jour. A 51, 143 (2015)



nEDM spectrometer

Under development

- **beam in 2022**
- **commissioning in 2023**
- **start measurement in 2024**

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Development of polarization analysis film

Iron thin films were prepared using an ion beam sputtering system (IBS) at KURNS

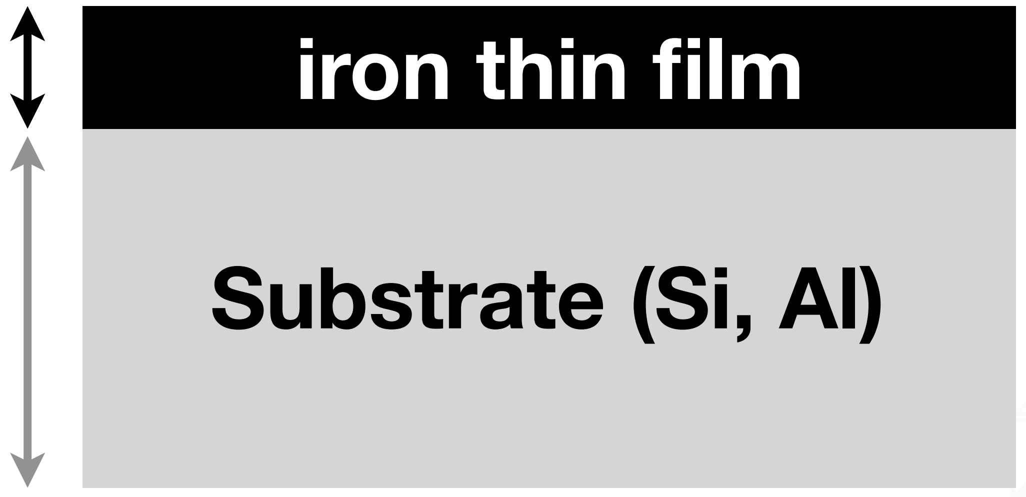
Produced sample

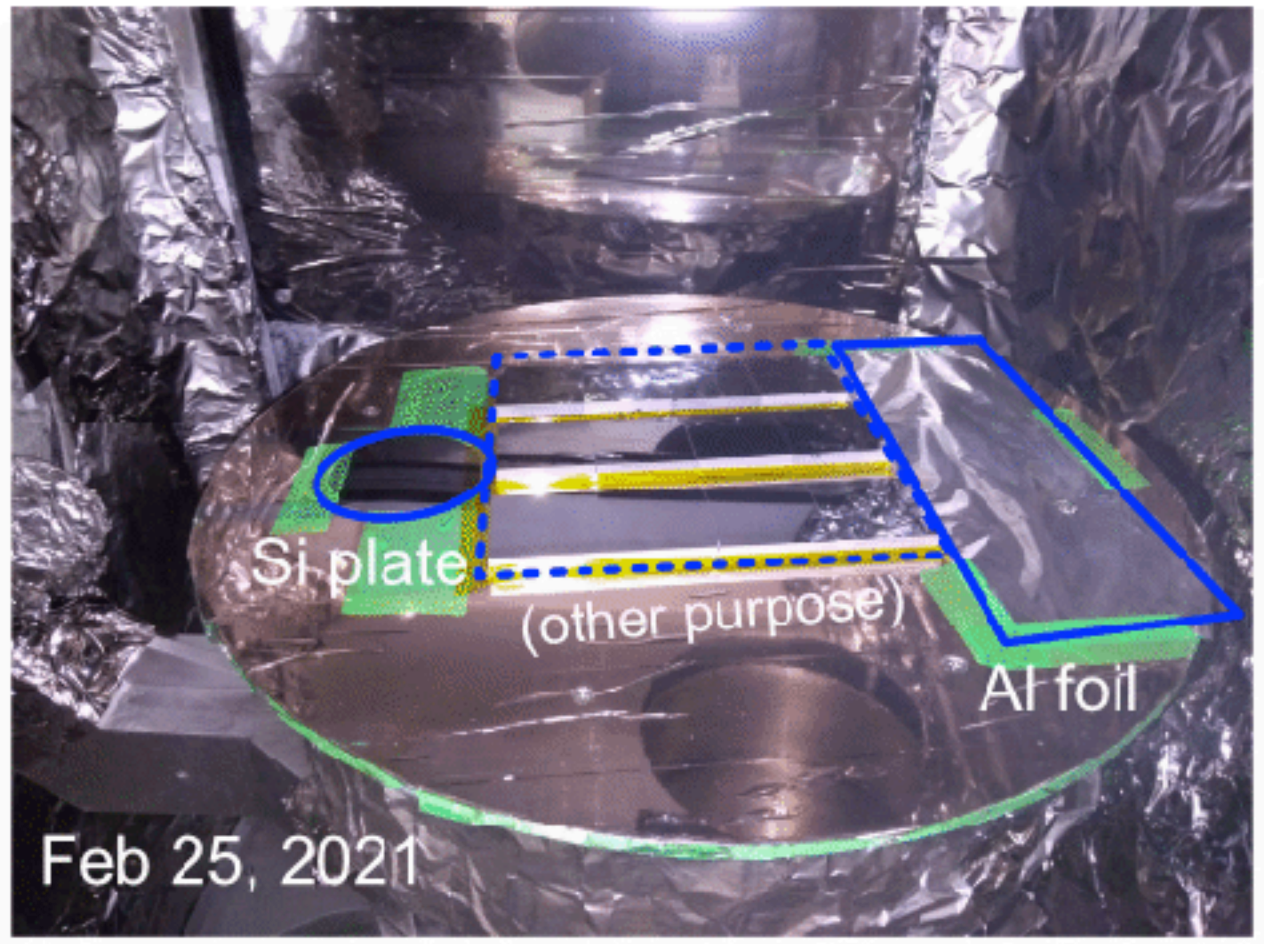
Iron thin film

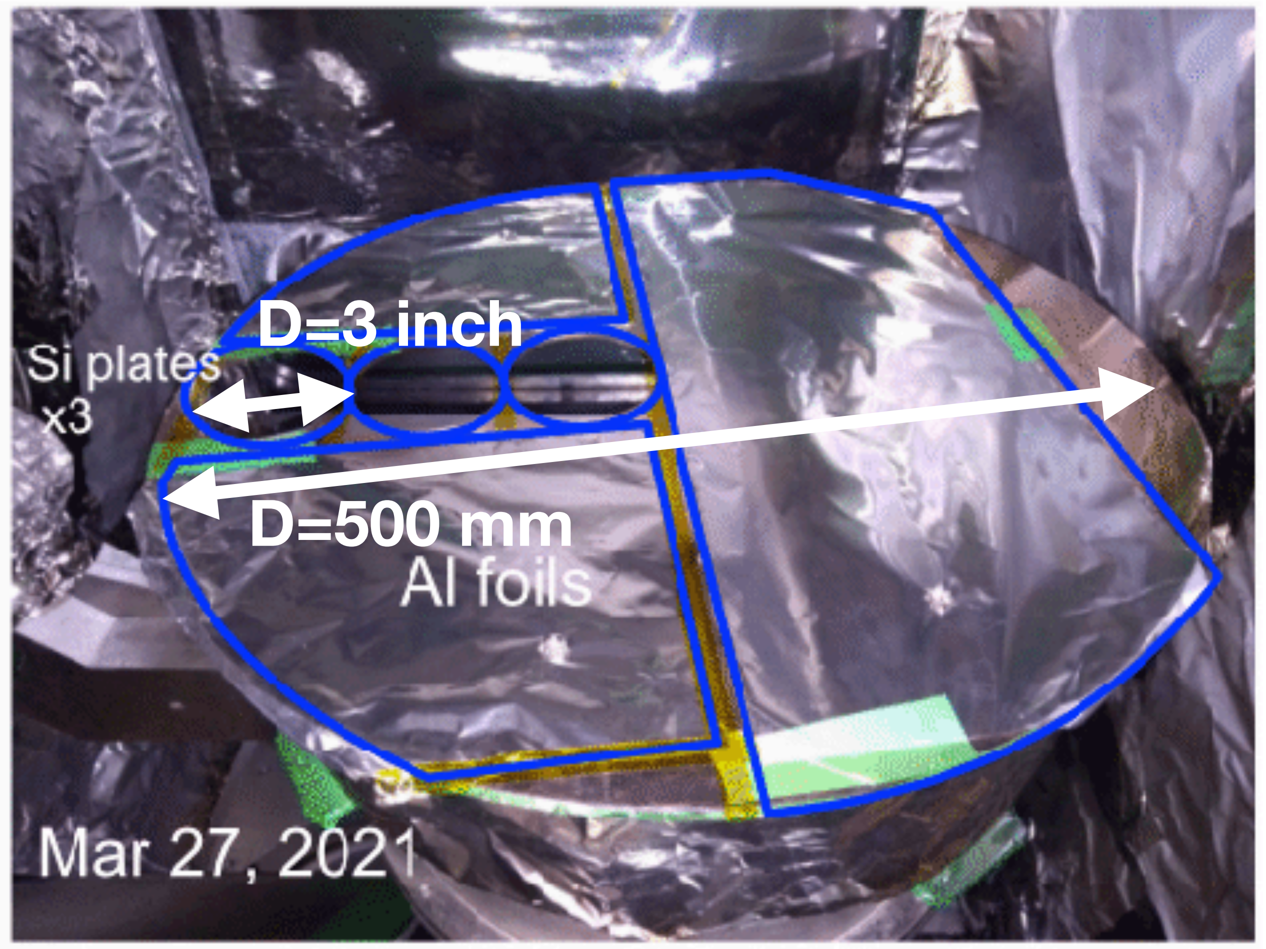
- thickness : 30, 50, 90 nm

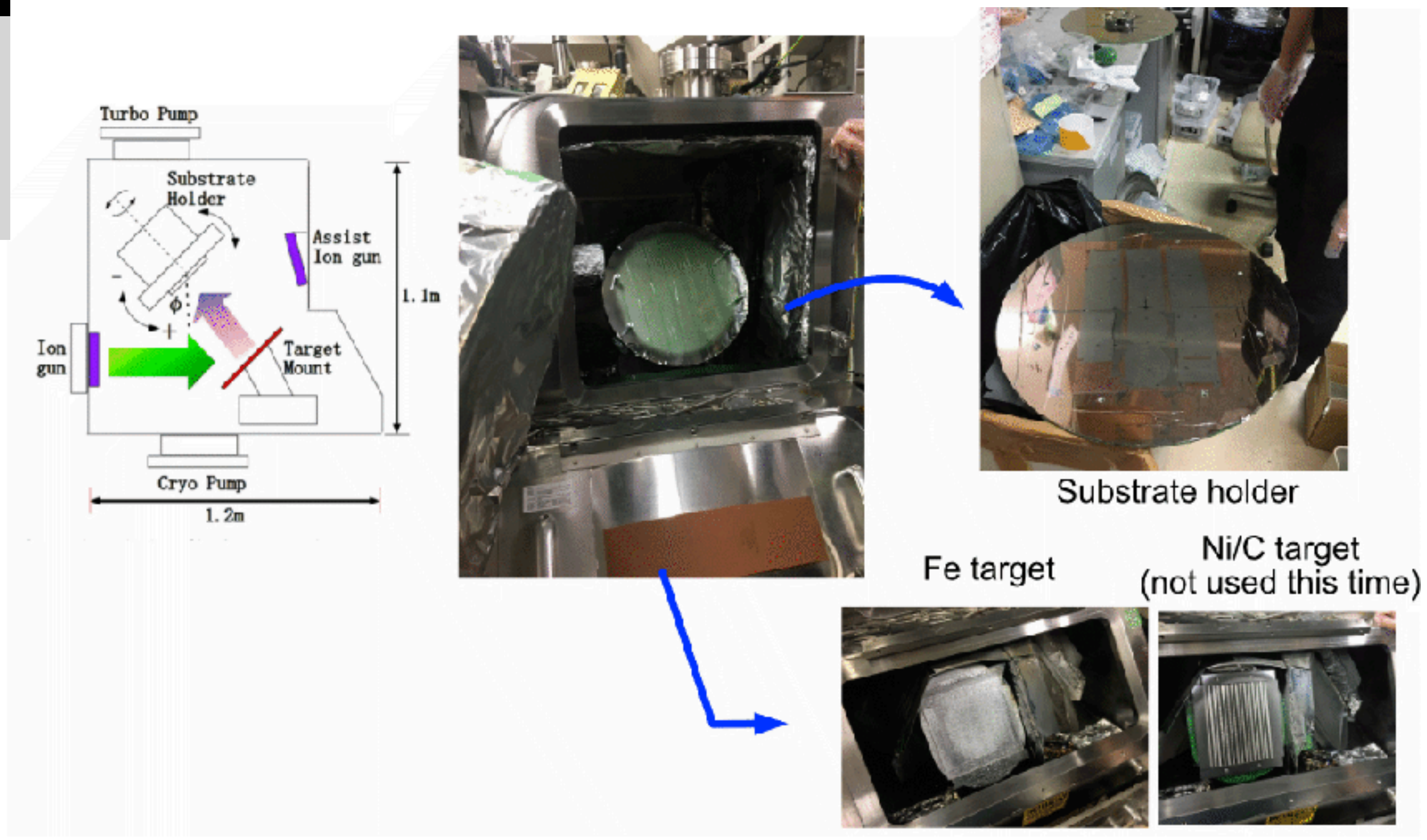
Substrates

- Si (thickness $380\ \mu$m)
- Al (thickness $25\ \mu$m)



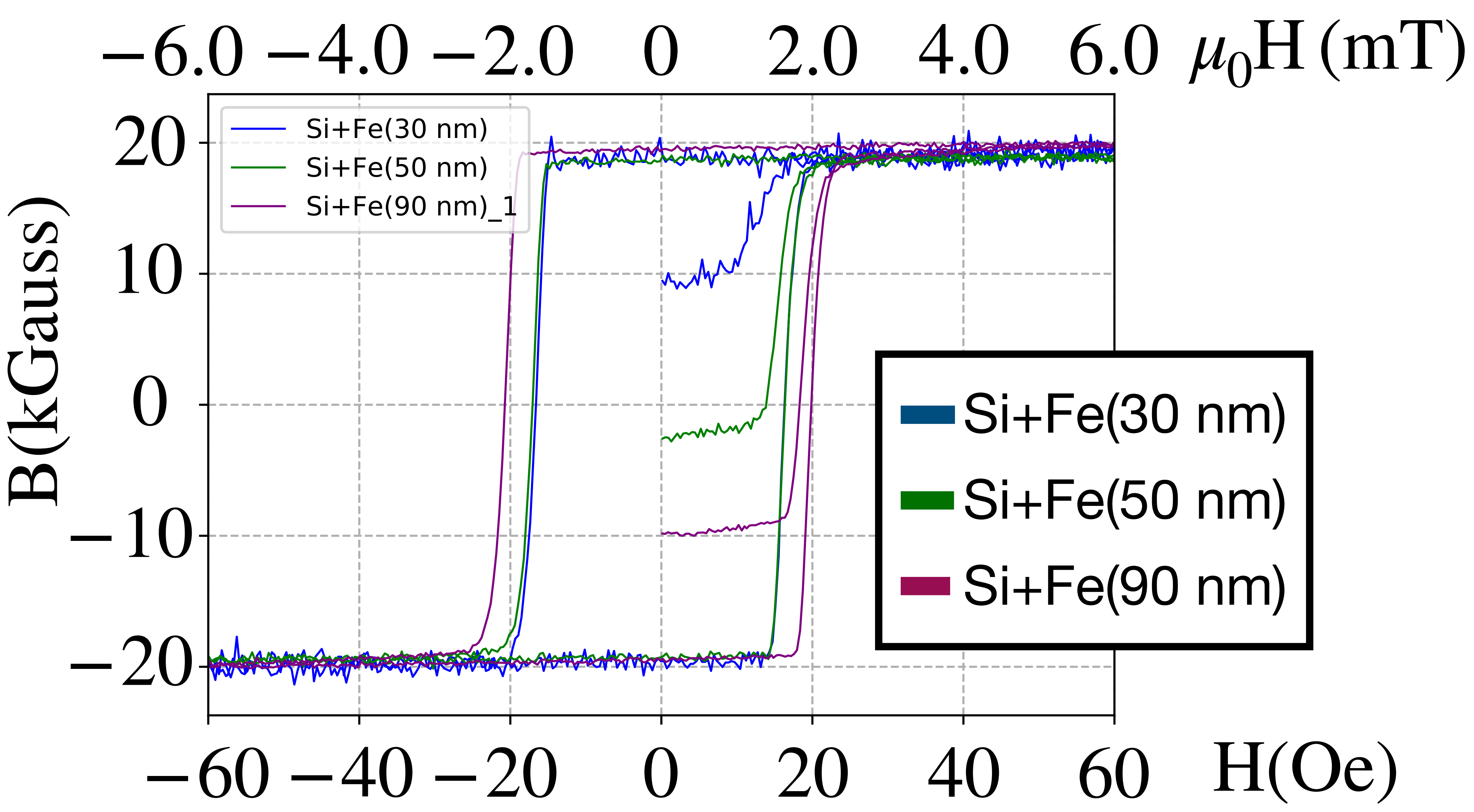


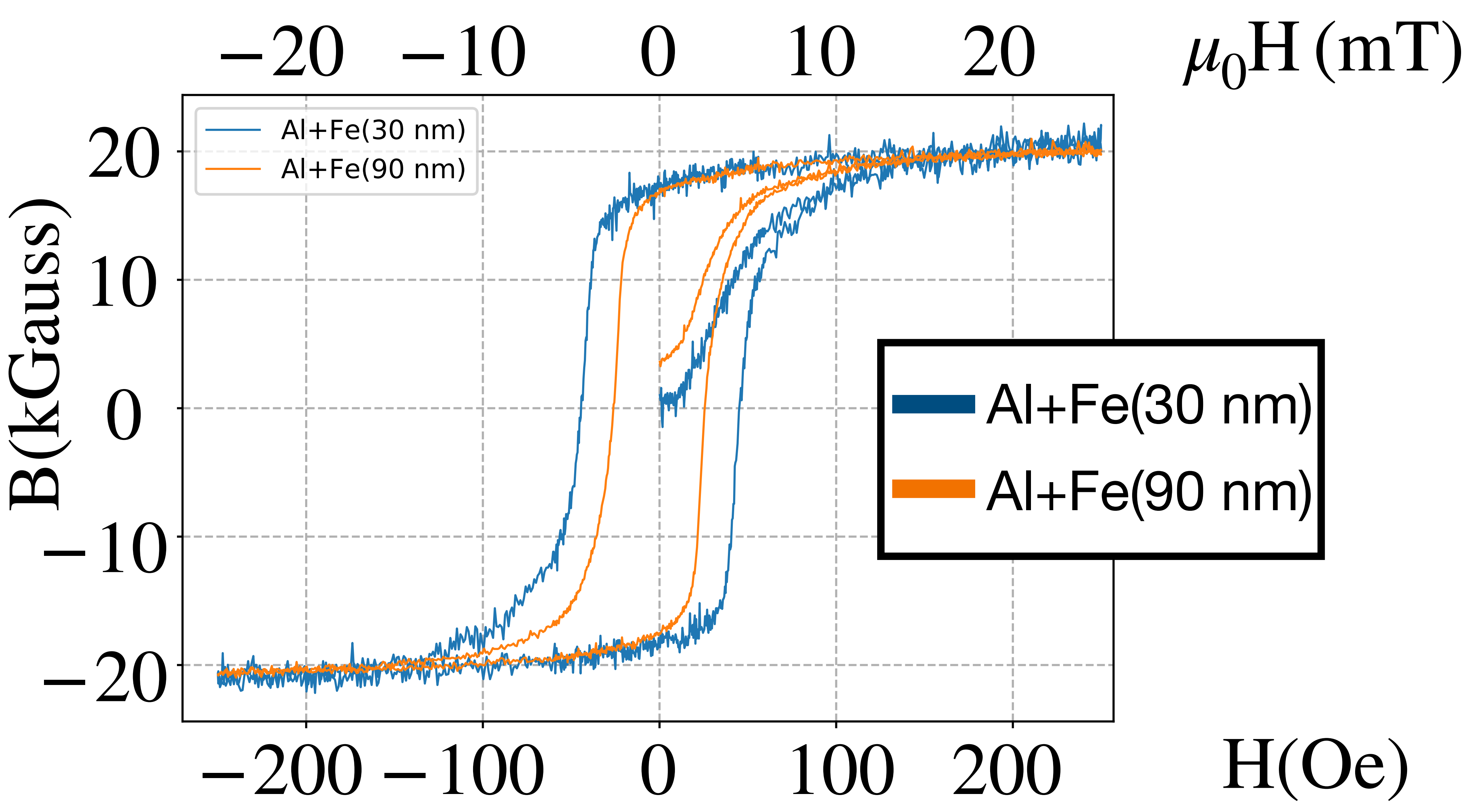




M. Hino et al, Nucl. Inst. Meth. A 797, 265 (2015)

Hysteresis curve measurement





H_c: Intersection of BH curve and B=0, H_s:H corresponding to 95% of B_{sat}

sample	Hc(Oe)	Hs(Oe)	μ0Hs(mT)
Si+Fe(30 nm)	16.5	29.8	2.98
Si+Fe(50 nm)	16.7	24.5	2.45
Si+Fe(90 nm)	20.3	45.5	4.55

sample	Hc(Oe)	Hs(Oe)	μ0Hs(mT)
Al+Fe(30 nm)	45.0	159	15.9
Al+Fe(90 nm)	25.8	134	13.4

- BH curves of each sample were measured by Vibrating Sample Magnetometry (VSM)
- **Samples saturates with low magnetic fields (requirements : $\mu_0 H_s \lesssim 10\,\mathrm{mT}$)**
  - $\mu_0 H_s \lesssim 5\,\mathrm{mT}$ (Si substrate)
  - $\mu_0 H_s \lesssim 15\,\mathrm{mT}$ (Al substarte)

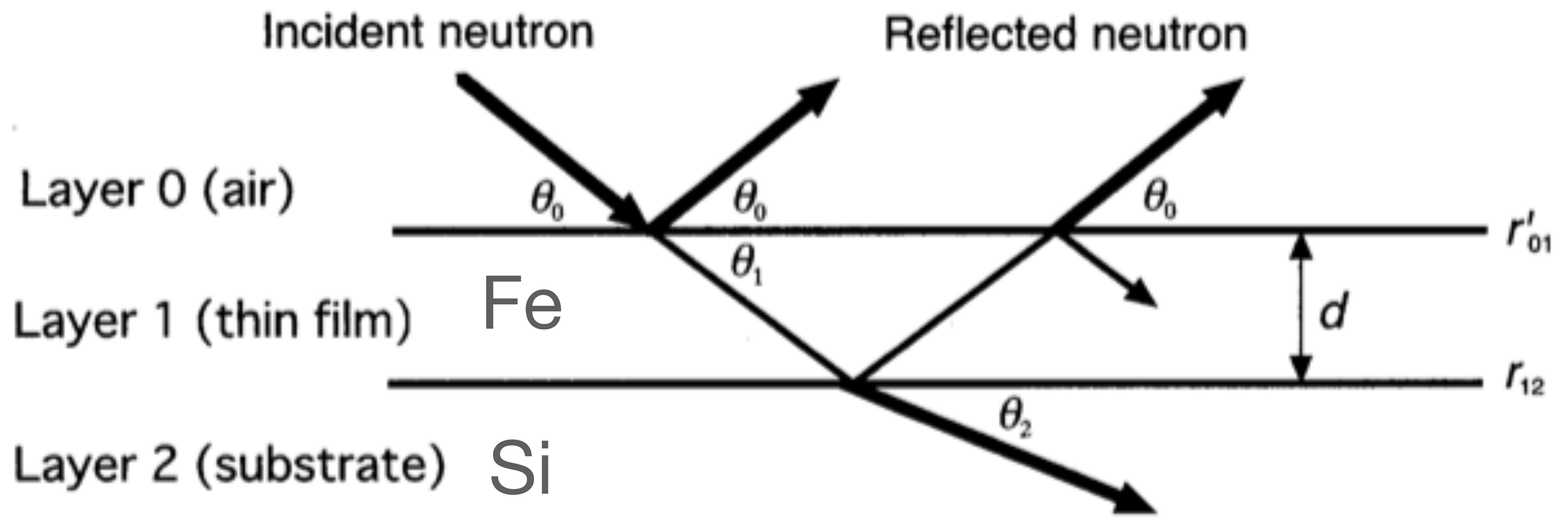
Neutron reflectometry

- Cold neutrons (wavelength $0.2 \sim 1\,\mathrm{nm}$) are injected to a sample and the reflectivity is measured.

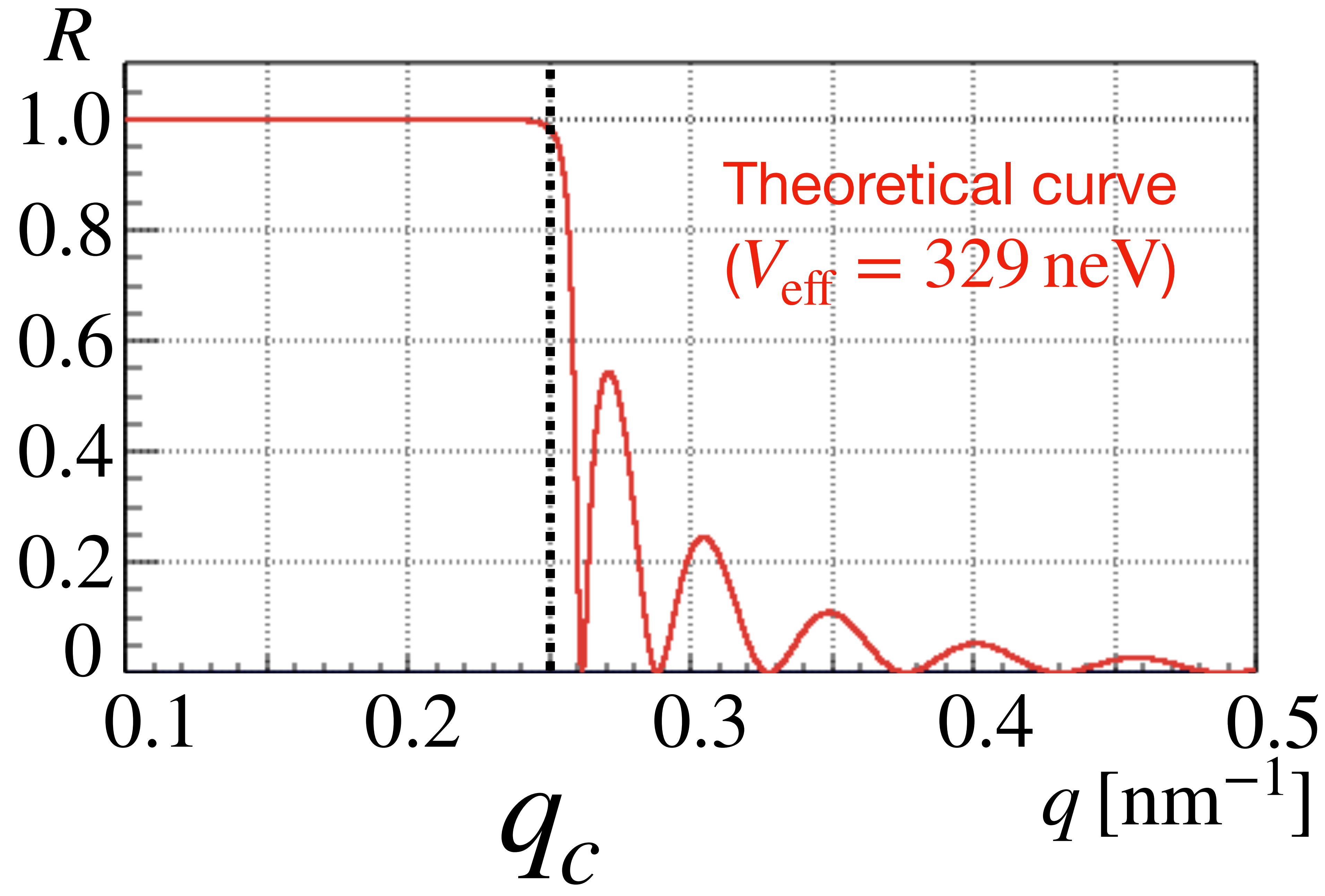
- From the reflectivity profile as a function of wave vector transfer $q = 4\pi \sin\theta_0/\lambda$, the critical value q_c can be determined.

- From the critical value q_c, the magnetic potential experienced by the neutron can be extracted.

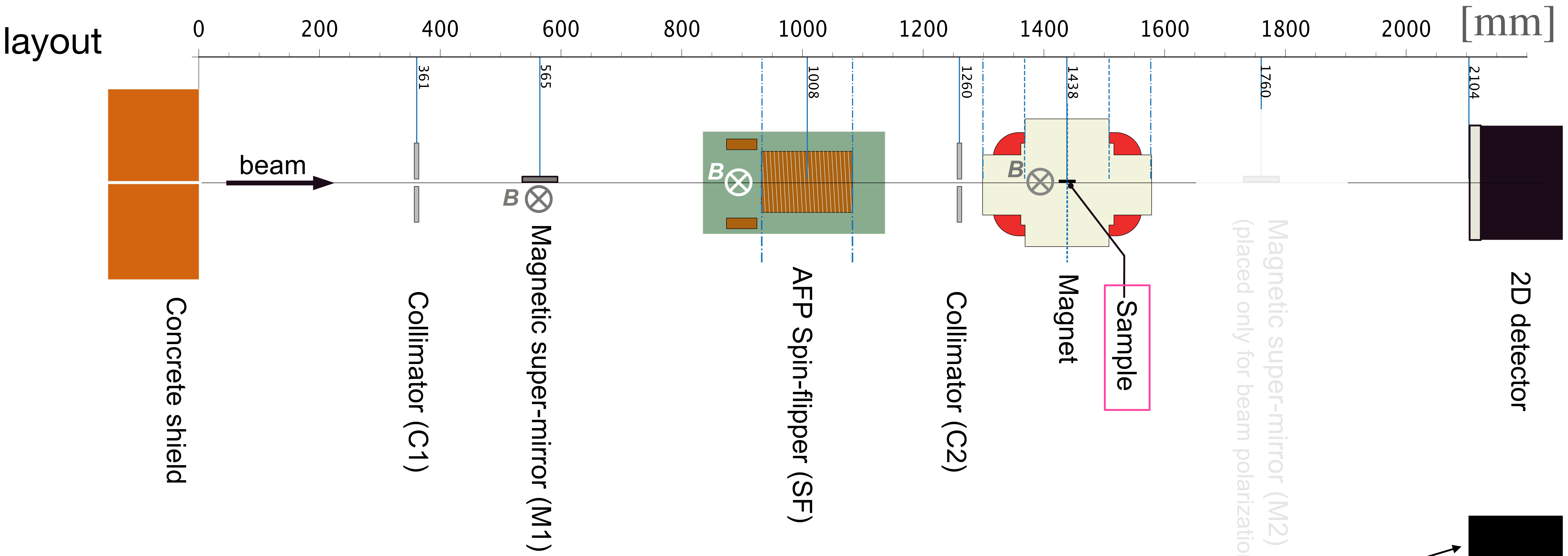
$$V_{\mathrm{eff}} = \frac{\hbar^2 q^2}{8 m_n} \qquad (m_n : \mathrm{neutron\ mass})$$

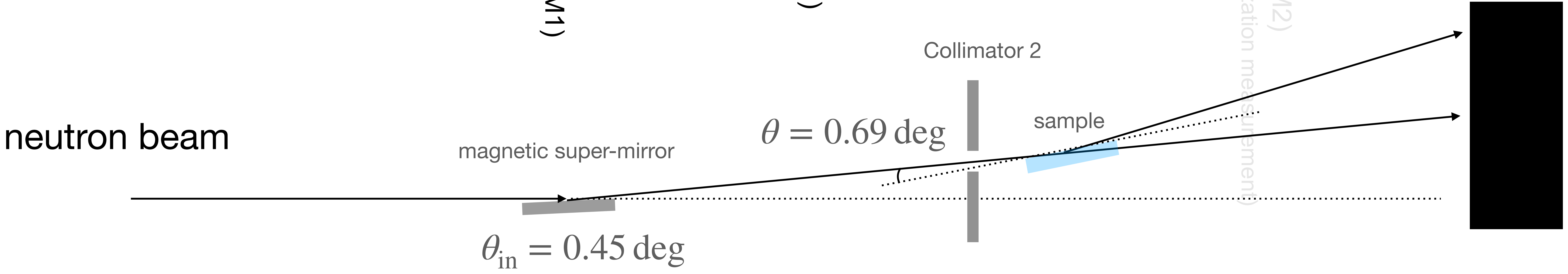


Journal of the Neutron Science Society of Japan "Ripples" Vol.18, No.4, 2008 Principle of neutron reflectometry Naoya Torikai and Masayasu Taketa



Neutron reflectivity measurement Setup (J-PARC/MLF BL05)





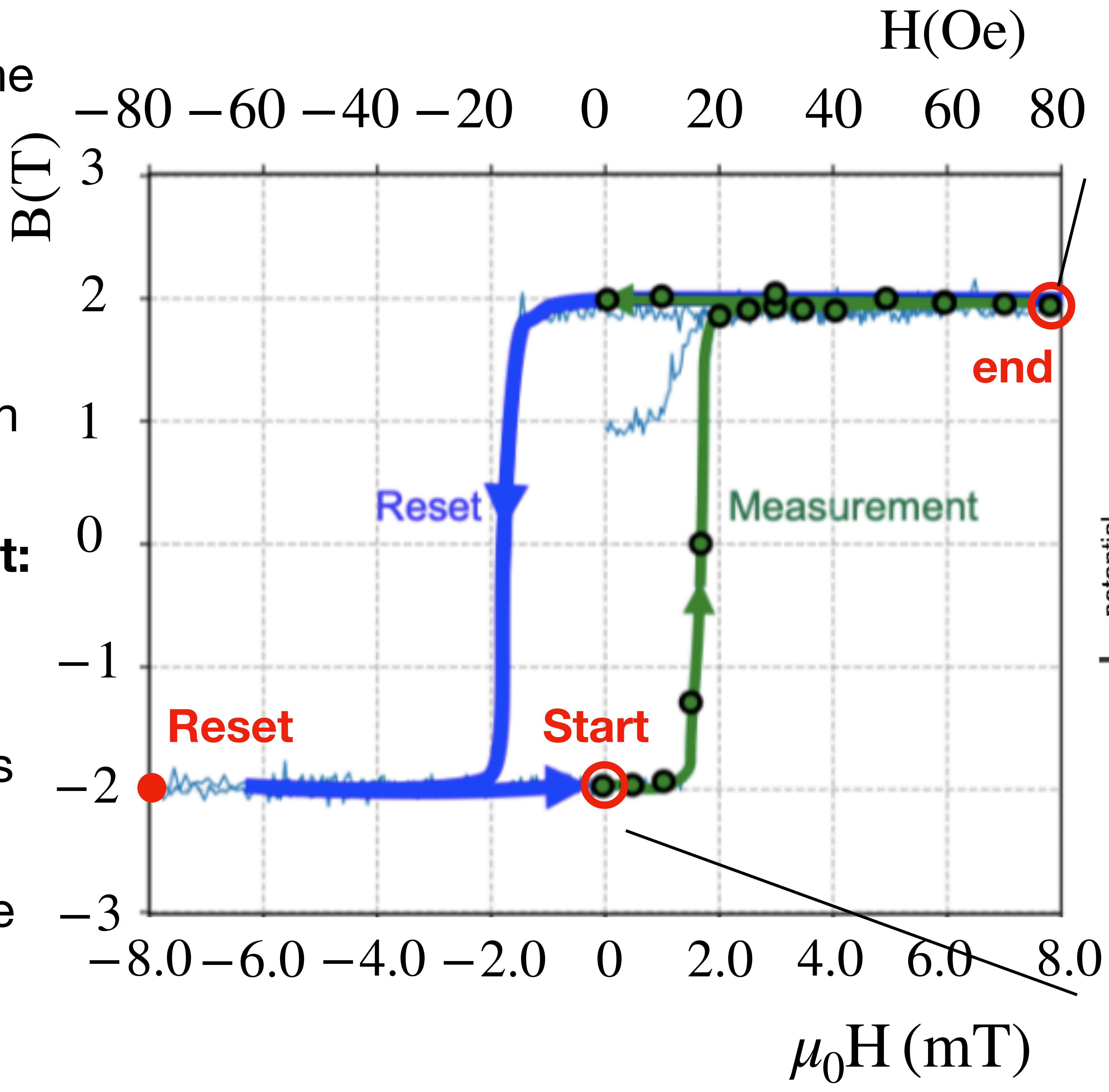
Reflectivity measurement of the sample

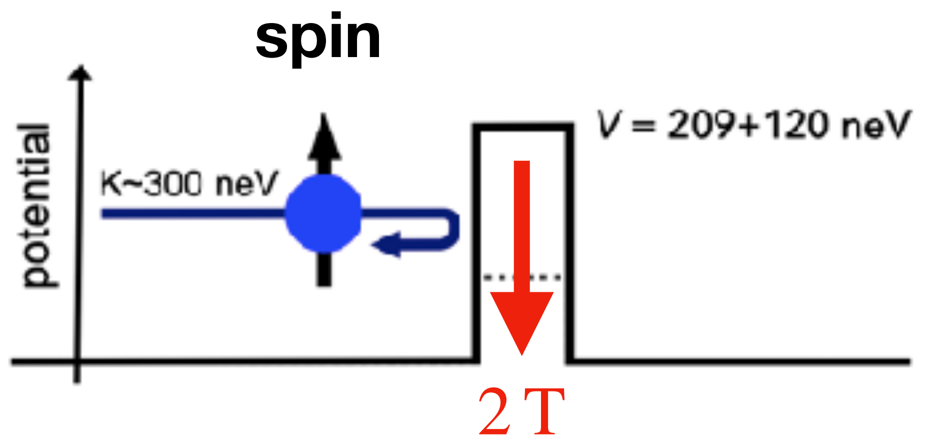
Measurement procedure:

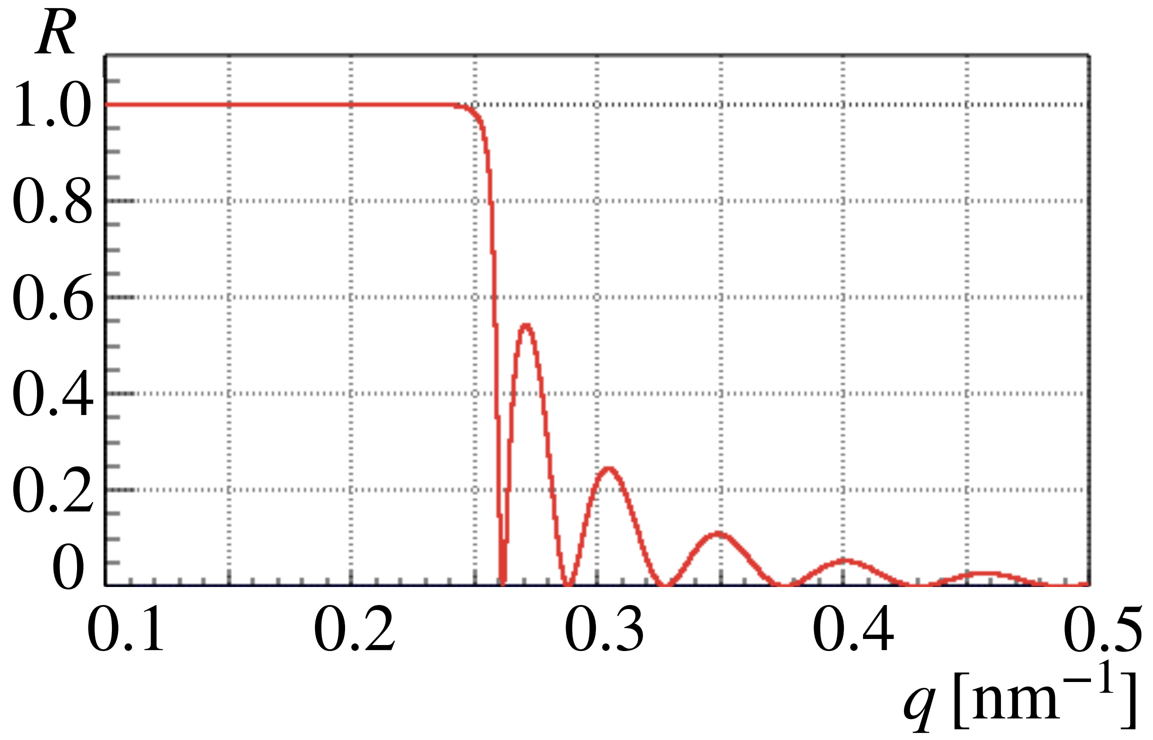
1. A magnetic field of $-8\,\mathrm{mT}$ was applied to the sample. (Reset)
2. The reflectivity R was measured while increasing the applied magnetic field.
   - The effective potential was determined from the reflectivity with the spin flipper on and off.

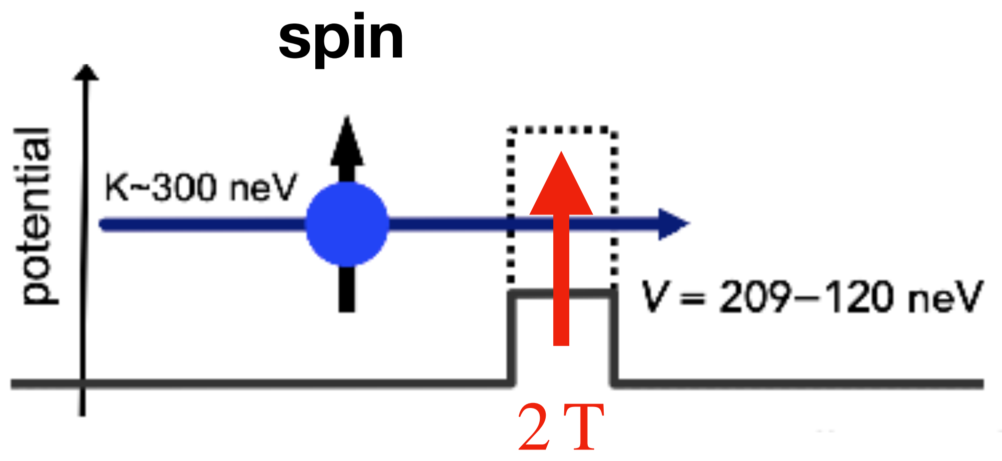
How to extract physical properties of interest:

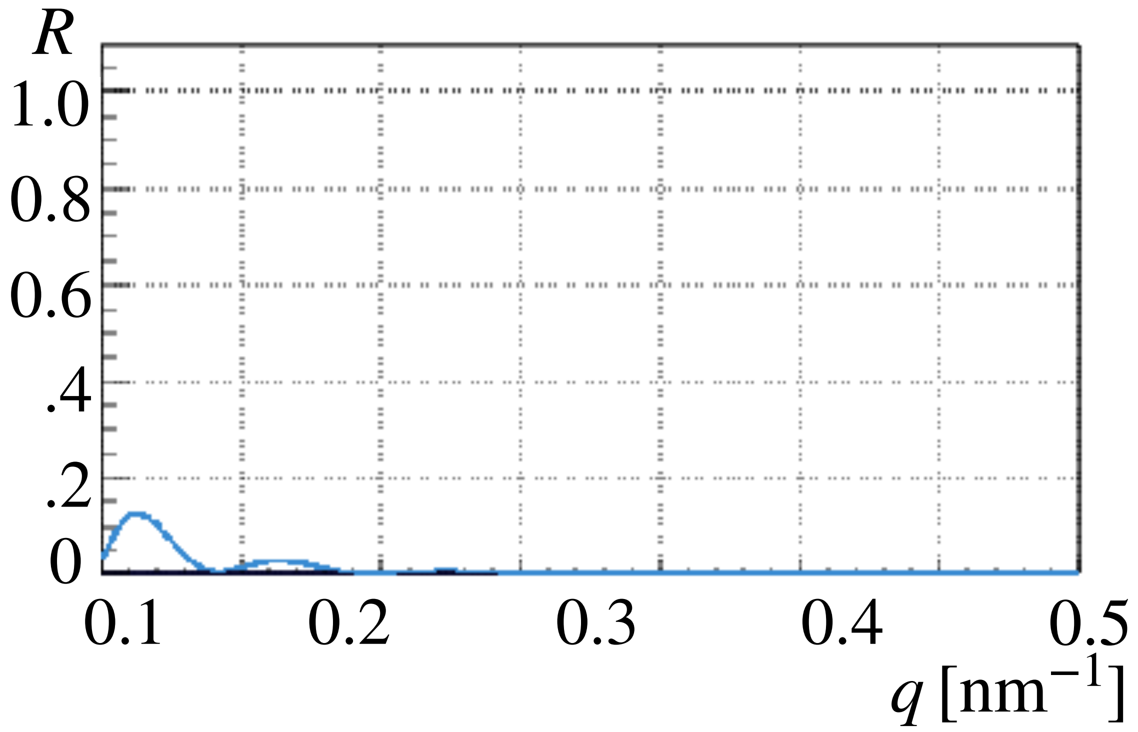
- The critivcal value q_c of the reflectivity profile R(q)
  → The potential V_{eff} experienced by neutrons at saturation
- From the magnetic field at which the effective potential V_{eff} rises
  →Magnetic field required to saturate the film











Neutron reflectivity measurement results

Fe 90 nm + Si substrate
(Neutrons incident in each spin states
Reflectivity R_{down}, R_{up})

- Fitted with a function which takes into account the beam polarization
- Fitting results

  Reflectivity critical value : $q_c = 0.251(9)\,\mathrm{nm}^{-1}$

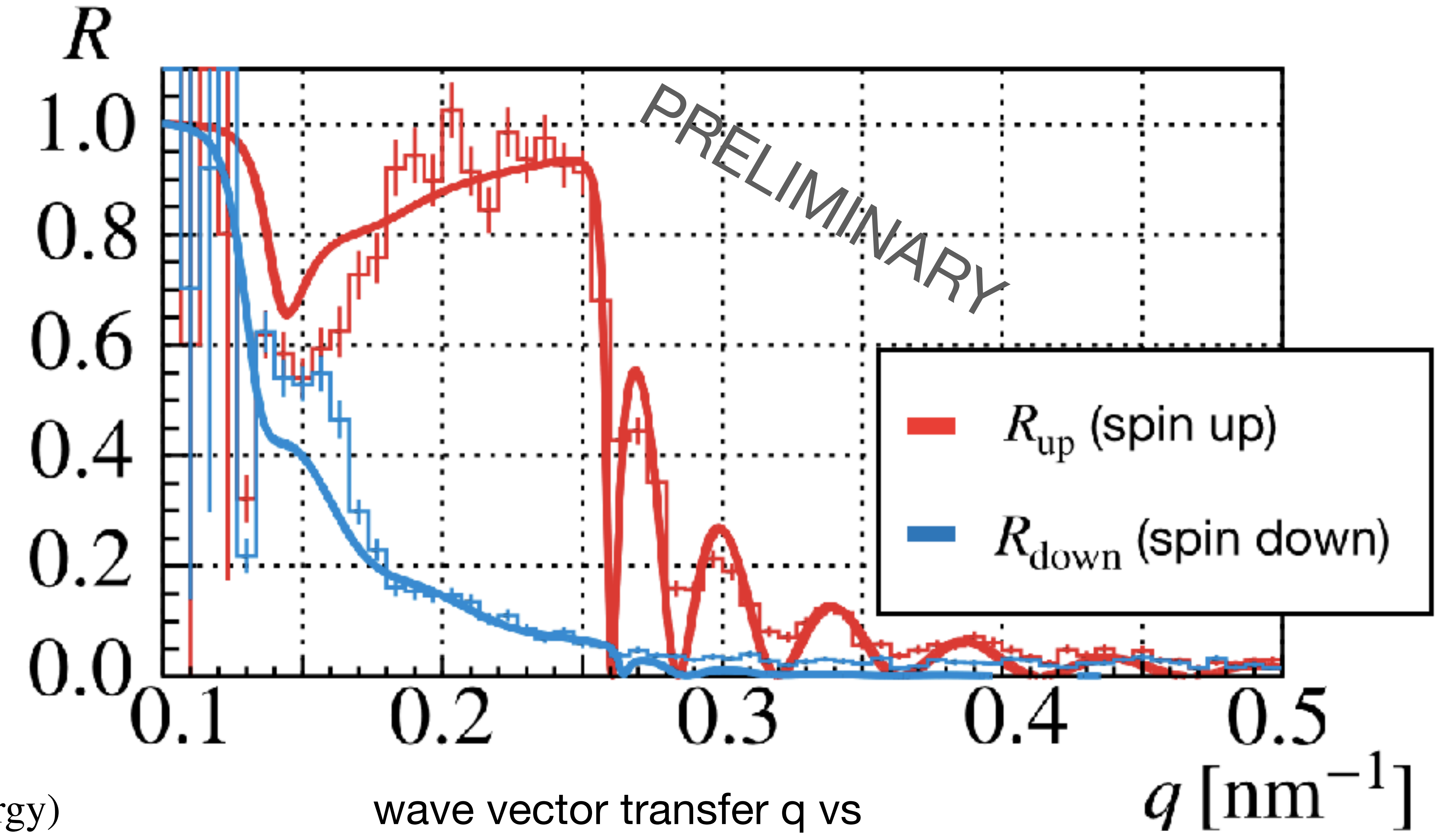
  $\leftrightarrow V_{\mathrm{eff}} = 328.5(4)\,\mathrm{neV}$

  (requirements: $V_{\mathrm{eff}} > 300\,\mathrm{neV} \gtrsim E_{\mathrm{UCN}}$) (E_{UCN} : UCN energy)

  $\leftrightarrow$ Fe magnetization $1.980(7)\,\mathrm{T}$

  when 8 mT is applied

  (requirements : $\mu_0 \mathrm{H} \lesssim 10\,\mathrm{mT}$)
- **Enough saturation magnetization obtained to polarize UCN at sufficiently low magnetic field**



wave vector transfer q vs
Spin-up reflectivity R_{up},Spin-down reflectivity R_{down}
when 8mT is applied.

Details are still under analysis.

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Conclusion and outlook

- Development of UCN polarization analyzer for TUCAN
- Reflectivity measurement of the sample (Fe+Si substrate)
  - $V_{\mathrm{eff}} \sim 324\,\mathrm{neV}$ (requirements: $V_{\mathrm{eff}} \gtrsim 300\,\mathrm{neV} \gtrsim E_{\mathrm{UCN}}$), when 8 mT is applied. (requirements: $\mu_0\mathrm{H} \lesssim 10\,\mathrm{mT}$)
- **Successfully produced films that can be used for UCN polarization analysis**
- **Evaluation with UCNs are planned in spring 2022.**

Acknowledgements

Thank you for your attention!

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