Group delay time at the neutron reflection from multilayered resonant structures

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Outline

- *Reflection of waves and Goose – Hänchen effect*
- *Goose – Hänchen shift and group delay time (GDT)*
- *Giant positive and negative GDT the neutron refection from multi-layers structures as that was considered early*
- *Negative delay time and contradiction with causality principle*
- *More detailed calculations and solution of the paradox*
- *Conclusion*

- ***Reflection of waves and Goose – Hänchen effect***
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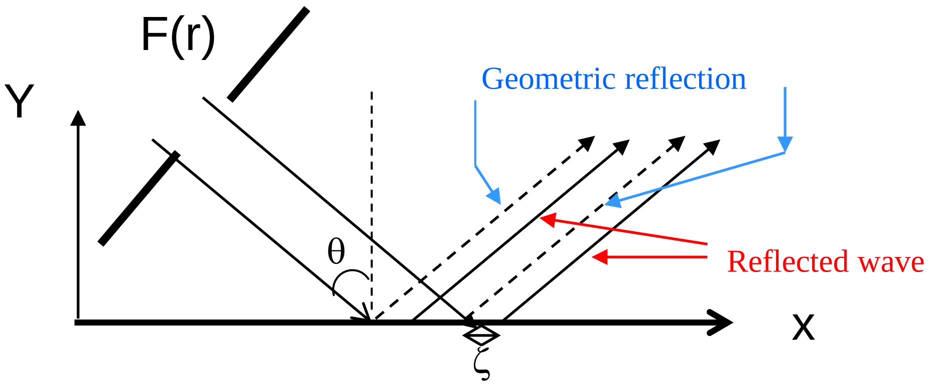
G.-H. shift. Formulation of the problem



K. Artmann, Ann. der Phys. 2, 87 (1948)

L.M. Brechovskikh, **Usp. Fiz. Nauk 50, 539 (1953)**

H. Hora, Optik 17, 409 (1960)

J. L. Carter and H. Hora. J. Opt. Soc. Am, 61, 1640, (1971)

$$A_{in}(\mathbf{r}) = A_0(\mathbf{r})\exp(i\mathbf{k}_0\mathbf{r})$$

At z = 0

$$A_{in}(x) = A_0(x)F(x)\exp(ik_{0x}x),$$

where $k_{0x} = k_0\sin(\theta)$

Our aim is to find displacement ζ

G.-H shift. Simplified solution

Fourier transform of the incoming and reflected waves

$$A_{in}(x) = \int_{-\infty}^{\infty} A_{in}(k_x)\exp(ik_x x)\,dk_x$$

$$A_R(x) = \int_{-\infty}^{\infty} A_{in}(k_x)R(k_x)\exp(ik_x x)\,dk_x$$

$$R(k_x) = |R(k_x)|\exp[i\varphi(k_x)]$$

Approximation

$$\varphi(k_x) \cong \varphi_0(k_x)_{x0} + \varphi'(k_x)_{x0}(k_x - k_{x0})$$

Solution

$$A_R(x, \cong |R(k_{x0})| \int_{-\infty}^{\infty} A_{in}(k_x)\exp[ik_x(x-\varsigma]\,dx.$$

$$\zeta = -(d\varphi/dk_x)_{x0}$$

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G.-H shift of the matter waves and its relation with the group delay time

$$k_z^2 = k_0{}^2 - k_x^2$$

$$\varsigma = -\left(\frac{d\varphi}{dk_x}\right)_{x_0} = -\left(\frac{d\varphi}{dk_z^2}\right)\frac{dk_z^2}{dk_x}$$

$$\frac{dk_z^2}{dk_x} = -2k_x$$

$$\varsigma = 2\left(\frac{d\varphi}{dk_z^2}\right)k_x$$

$$k_z^2 = \frac{2m}{\hbar^2}E_z$$

$$\varsigma = \hbar\left(\frac{d\varphi}{dE_z}\right)\upsilon_x = \tau_g \upsilon_x$$

$$\tau_g = \hbar\left(\frac{d\varphi}{dE_z}\right)$$

Group delay time
(Bohm, Wigner, 1952-55)

For the total reflection $\tau \approx$ **5 ÷ 7 ns**

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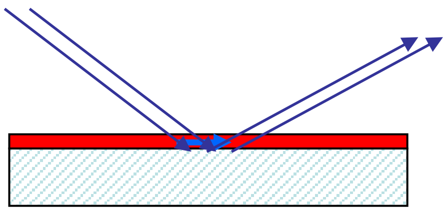
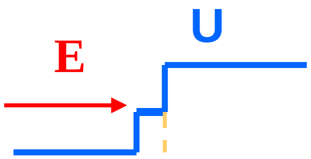
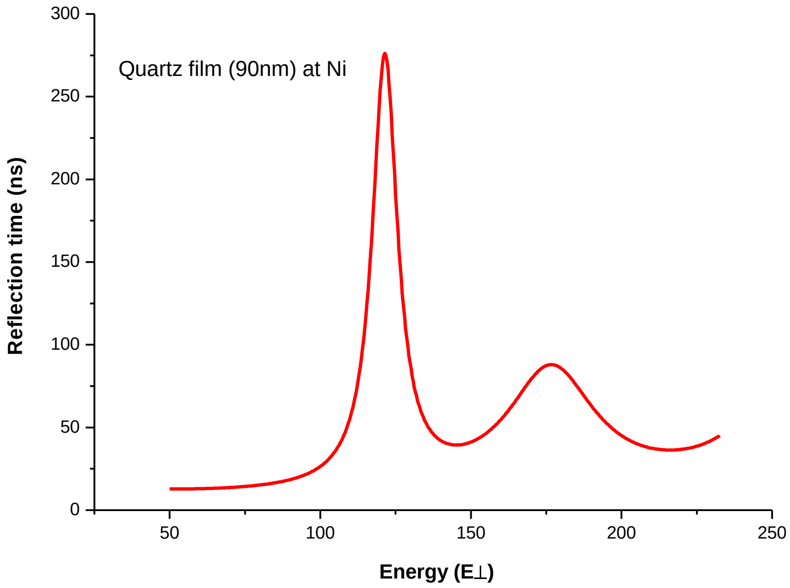
Giant delay time in reflection (and G-Ch. shift of the neutron beam)

T. Tamir, H.L. Bertoni, J.Opt.Soc.Am. 61, 1397 (1971)
V.Ignatovich, 2004

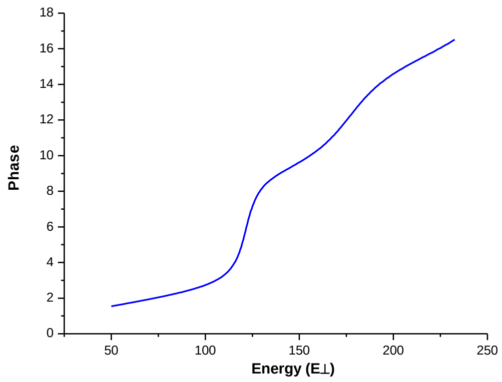
A films at the wafer (total reflection)







Group delay time at neutron reflection from quartz film (90nm) deposed at Ni substrate



Phase of the reflected wave

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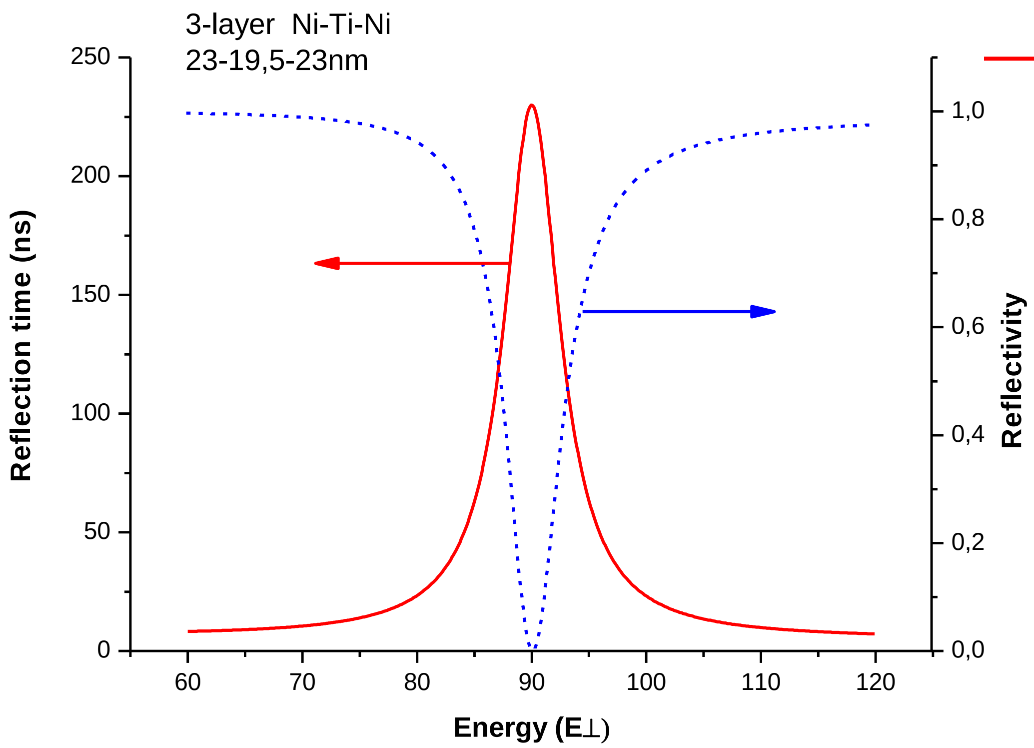
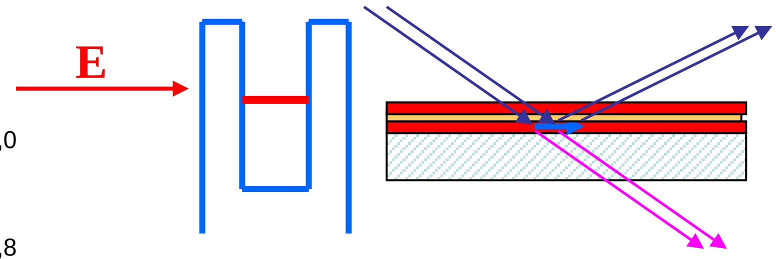
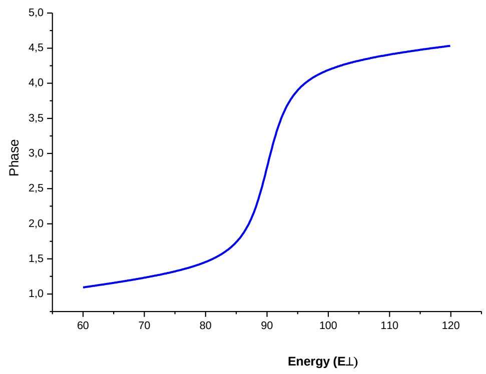
Giant delay time in reflection and G-Ch. shift of the neutron beam

Fabry-Perrot interferometer (Neutron Interference filter)







Reflection time and reflection coefficient for neutron reflection from the three layered resonant structure NiMo-Ti-NiMo. On the right – phase of the reflected wave

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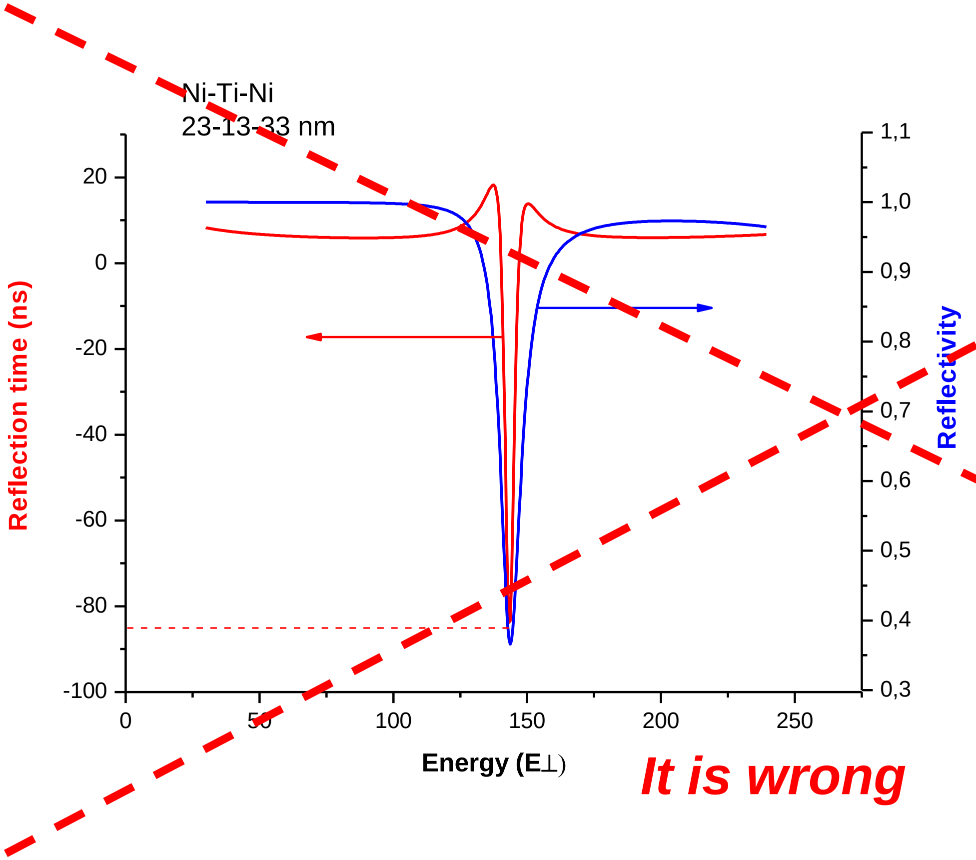
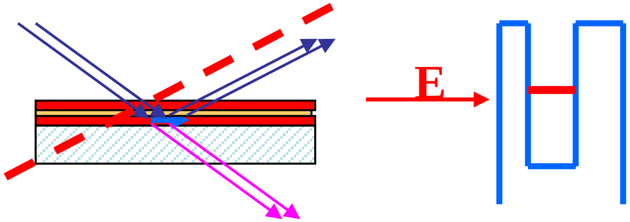
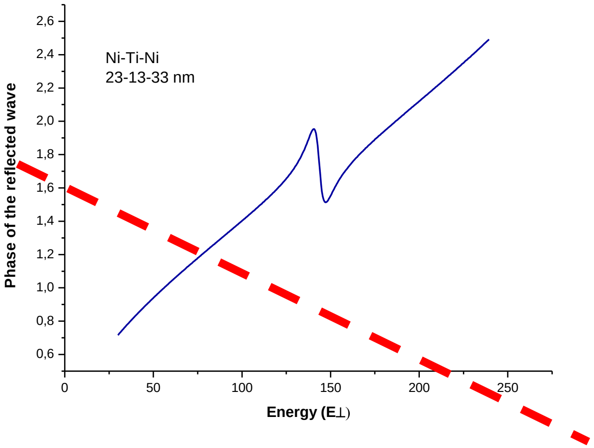
Giant negative group delay time







Group reflection time and reflection coefficient for the asymmetric three-layered resonant structures NiMo-Ti-NiMo

Phase of the reflection wave

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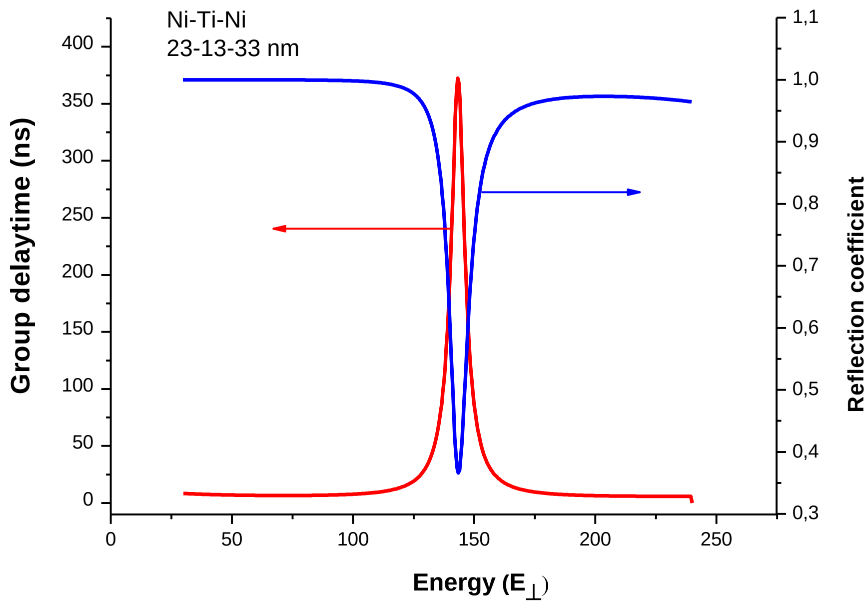
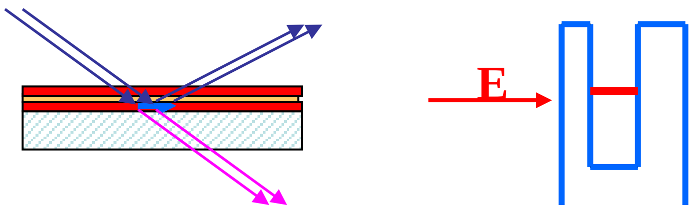
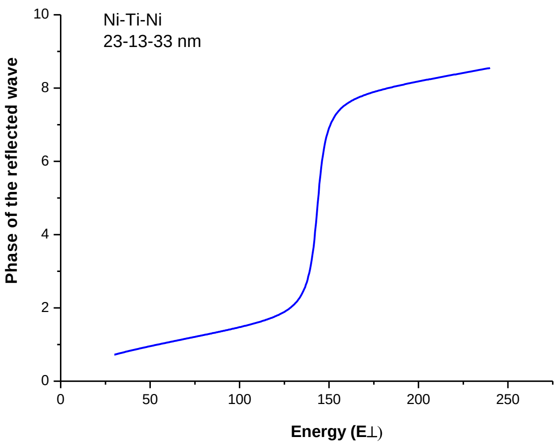
Giant POSITIVE group delay time





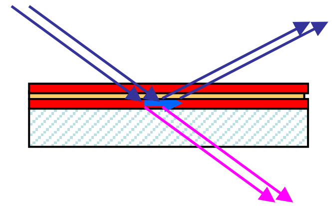


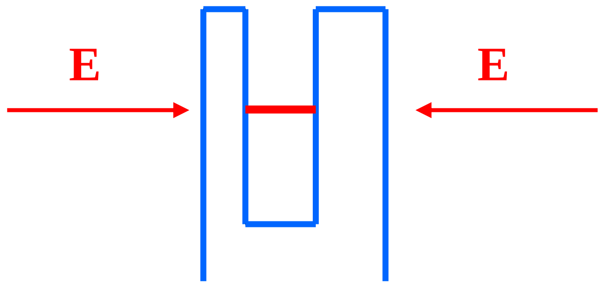
Group reflection time and reflection coefficient for the asymmetric three-layered resonant structures NiMo-Ti-NiMo

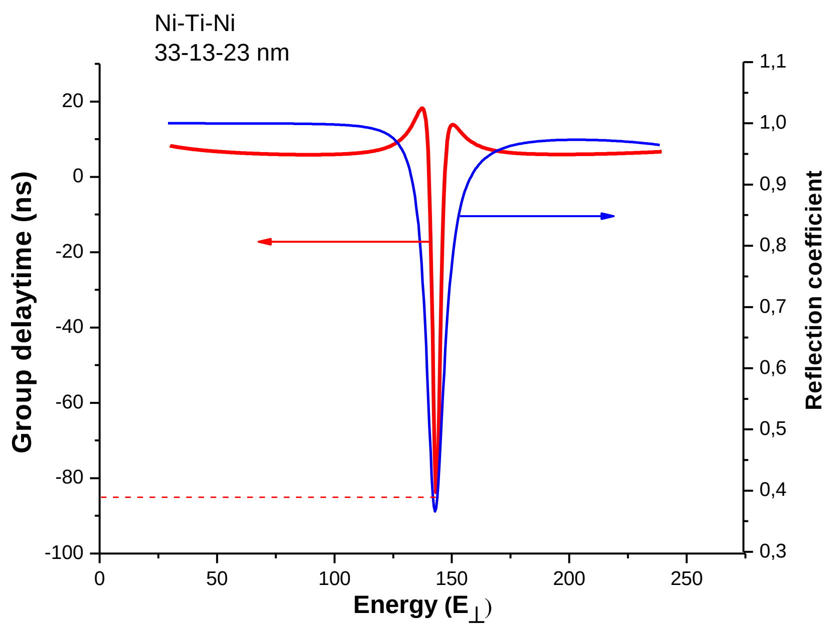
Phase of the reflection wave

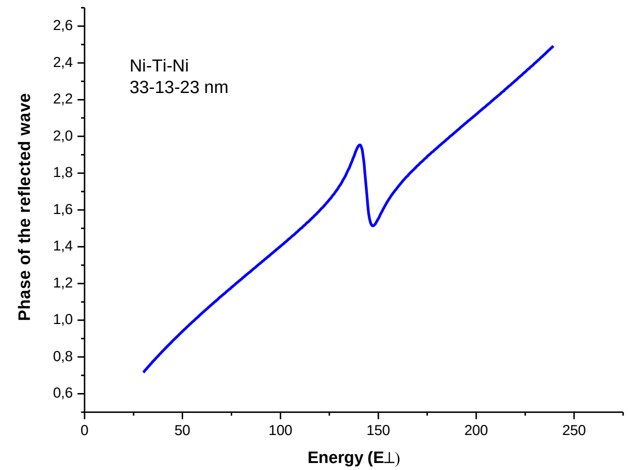
Negative group delay time

Asymmetric interference filter





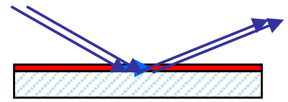


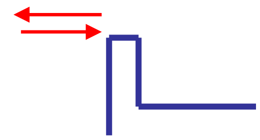


Group reflection time and reflection coefficient for the asymmetric three-layered resonant structures NiMo-Ti-NiMo

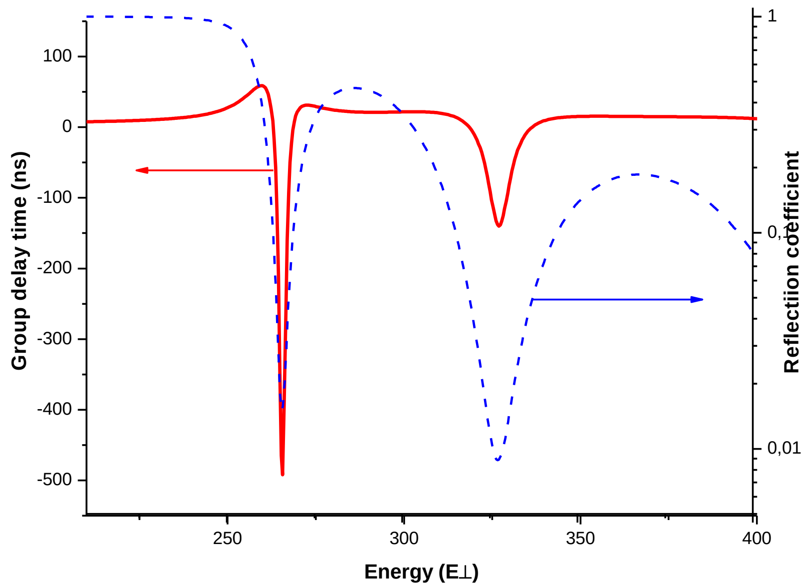
Phase of the reflected wave

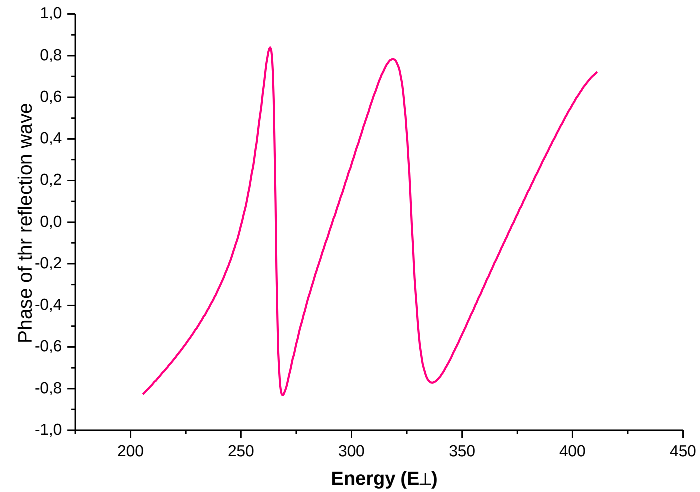
Negative group time and negative longitudinal shift





Film at the substrate (above barrier reflection)





Reflection time and coefficient of reflection for the Ni film (100nm) deposed at the quartz wafer.

Phase of the reflected wave.

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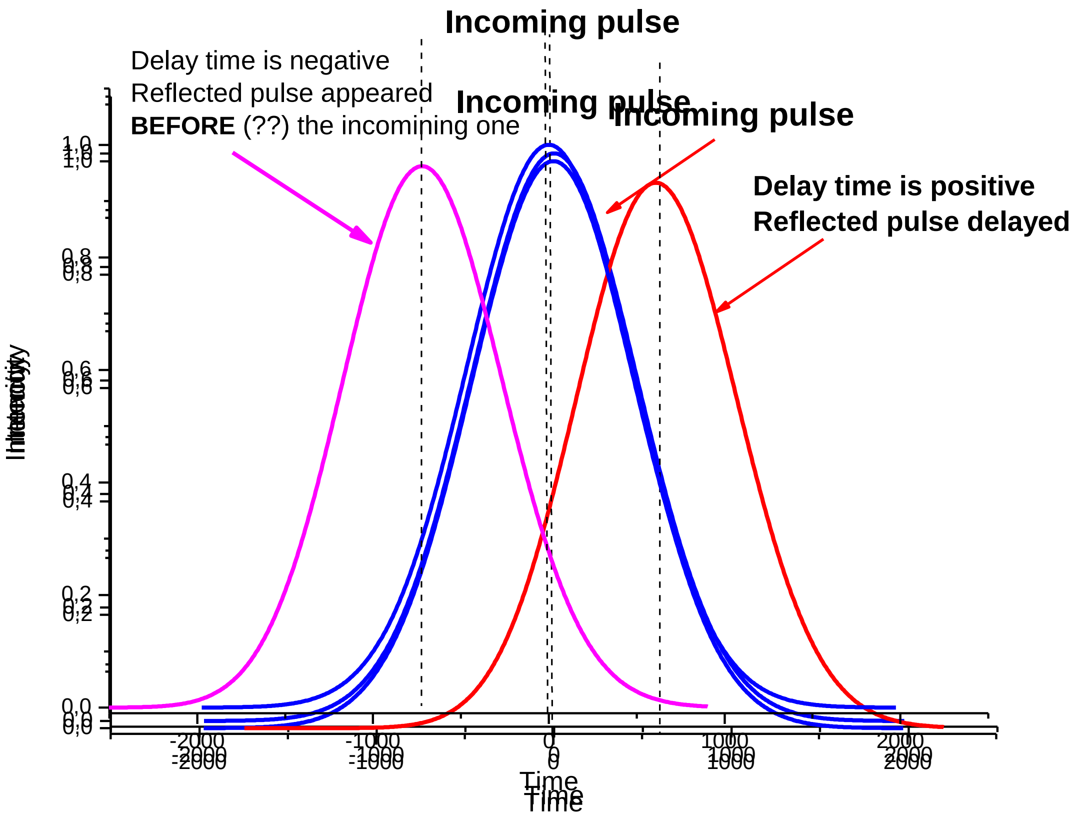
Positive and negative delay time. What is it?



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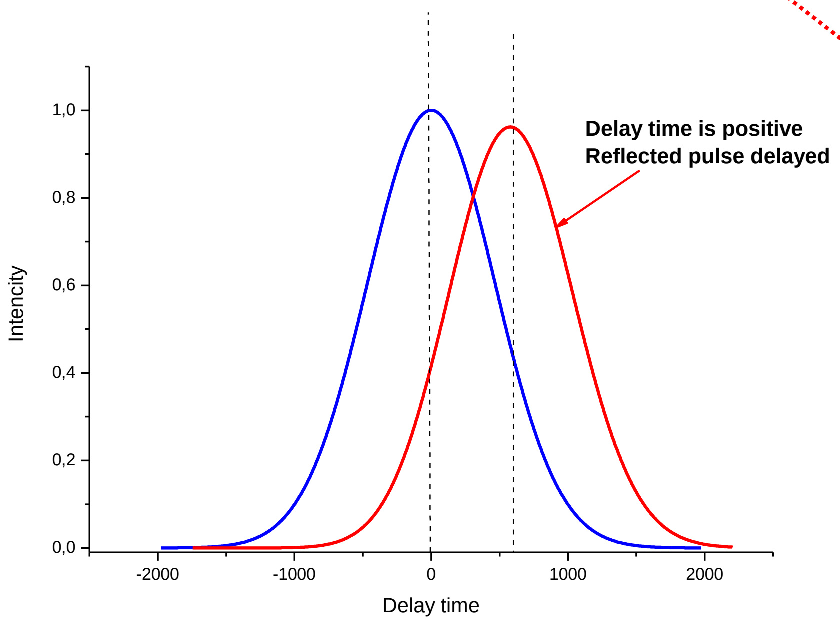

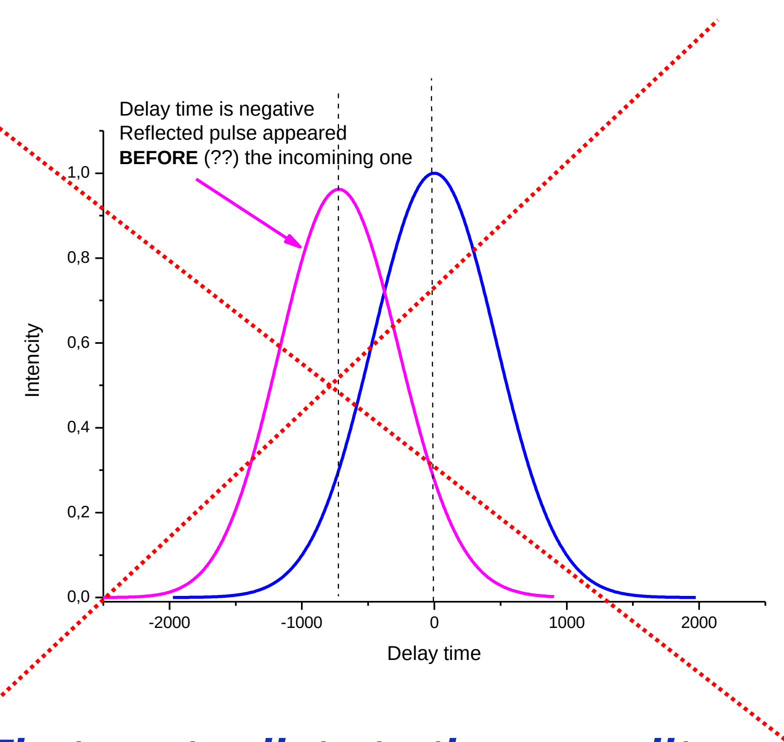

That contradicts to the causality principle

Group delay time at the reflection of wave packet

At z = 0

$$A_{in}(t) = A_0(t)\,exp(-i\omega t)$$

$$A_{in}(t) = \int_{-\infty}^{\infty} A_{in}(\omega)\,exp(-i\omega t)\,d\omega$$

$$A_R(t) = \int_{-\infty}^{\infty} A_{in}(\omega)R(\omega)\exp(-i\omega t)\,d\omega,$$

$$R(\omega) = |R(\omega)|\exp[i\varphi(\omega)]$$

$$\varphi(\omega) \cong \varphi_0(\omega_0) + \varphi'(\omega_0)(\omega - \omega_0)$$

$$A_R(t)| = |R(\omega)| \int_{-\infty}^{\infty} A_{in}(\omega)\,exp[i\omega(t-\tau)]\,d\omega.$$

$$\tau = \left(\frac{d\varphi}{d\omega}\right)_{\omega 0} = \hbar\left(\frac{d\varphi}{dE}\right)_{E0}$$

Group delay time at the reflection of wave packet

$$\tau = \left(\frac{d\varphi}{d\omega}\right)_{\omega 0} = \hbar\left(\frac{d\varphi}{dE}\right)_{E0}$$

That is very rough approximation

$$A_R(t) = \int_{-\infty}^{\infty} A_{in}(\omega)R(\omega)\exp(-i\omega t)\,d\omega,$$

where $$A_{in}(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} A_{in}(t)\exp(i\omega t)\,dt$$

Must be calculated

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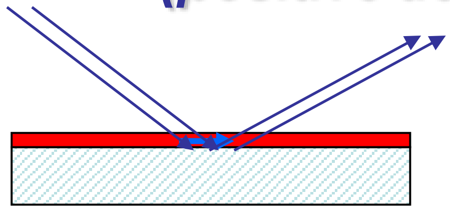
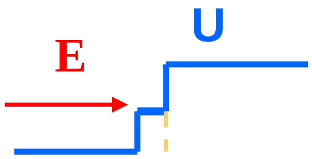
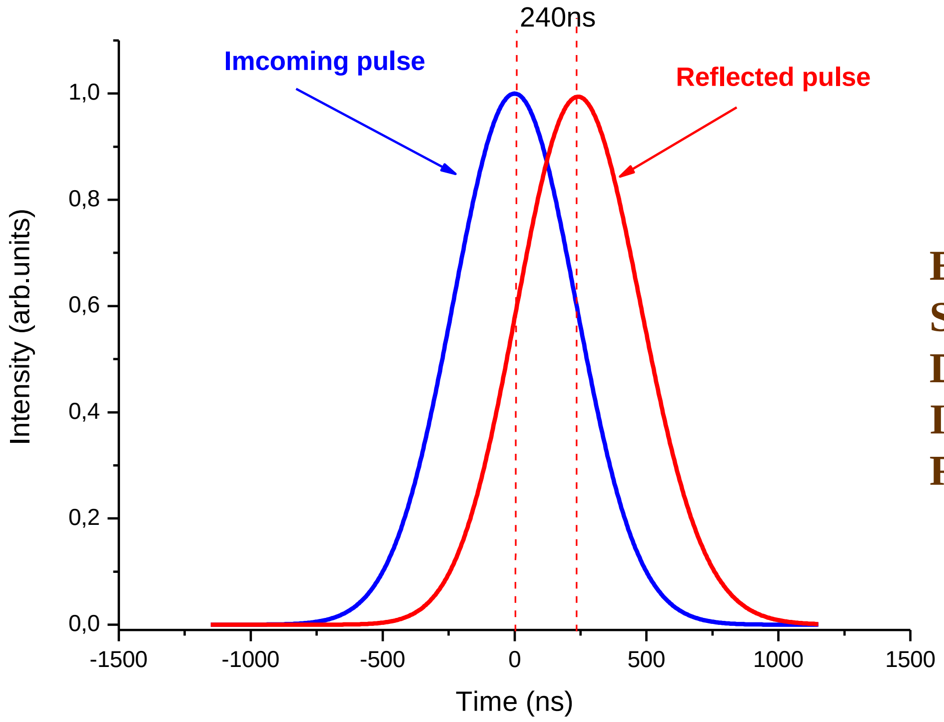
Reflection of the short time pulse (positive delay time)

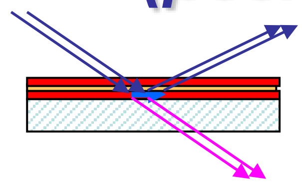


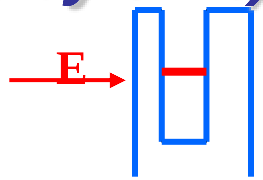


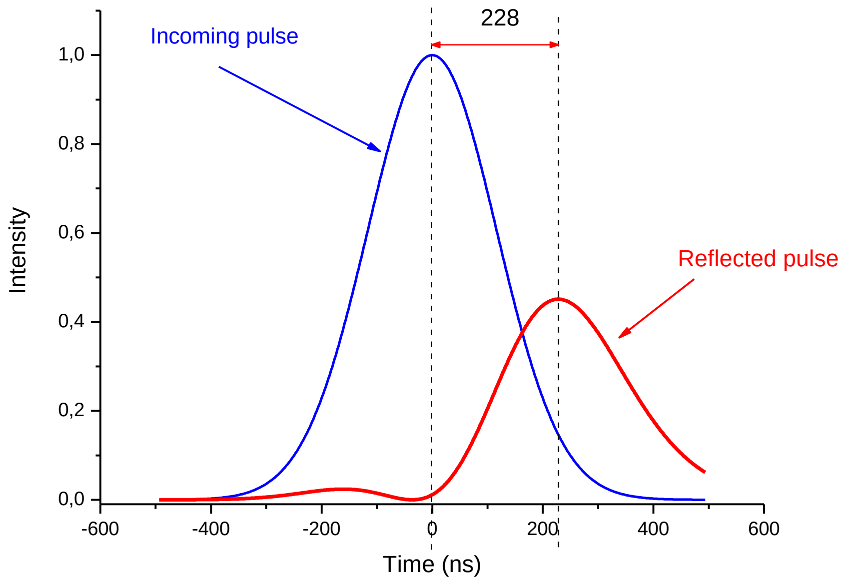


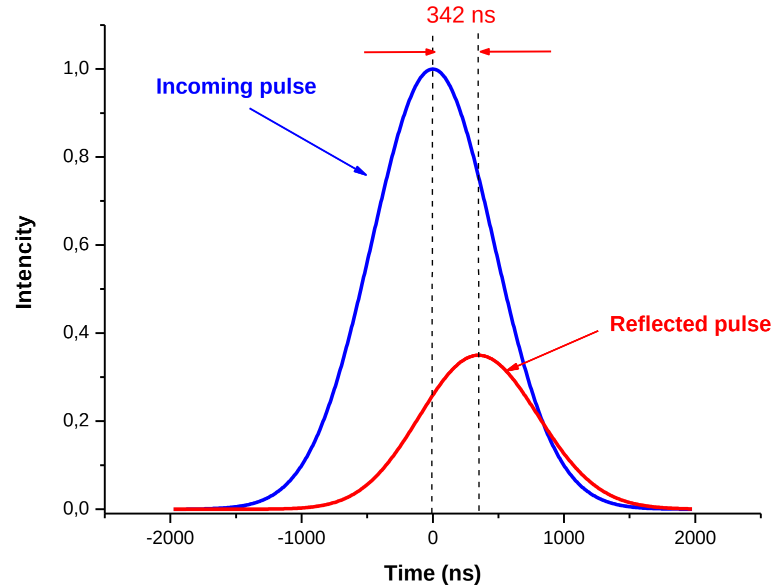
Energy 121 nev
Spectrum width (FWHM) 2 nev
Duration of the time pulse 330 ns
Ideal time shift (GDT) 277ns
Real time shift 240 ns

Reflection of the short time pulse (positive delay time)





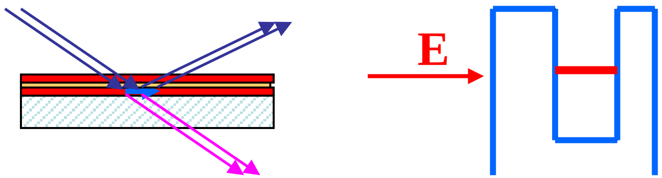


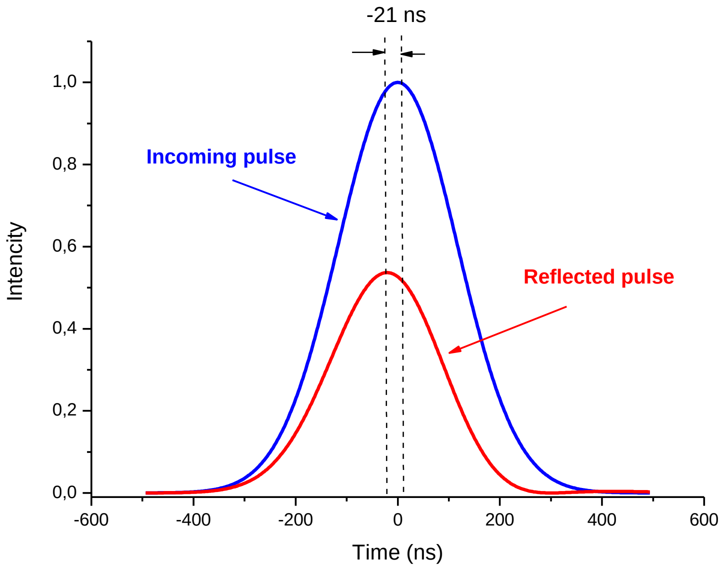


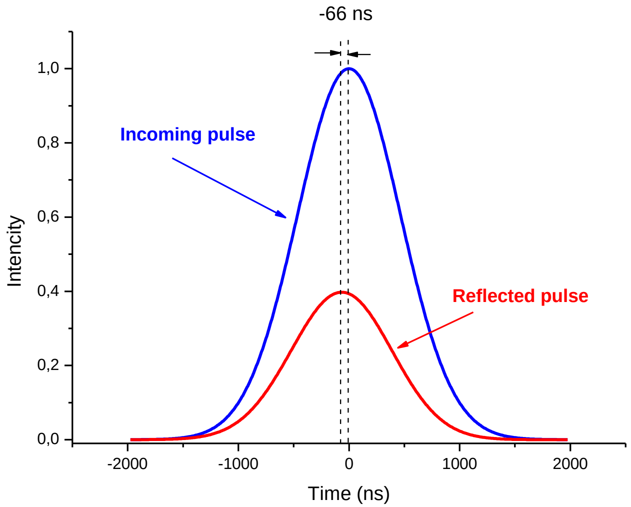
Energy 144nev
Spectrum width (FWHM) 4 nev
Duration of the time pulse 165 ns
Ideal time shift (GDT) 337ns
Real time shift 228 ns

Energy 144nev
Spectrum width (FWHM) 1 nev
Duration of the time pulse 660 ns
Ideal time shift (GDT) 337ns
Real time shift 349ns

Reflection of the short time pulse (negative delay time)



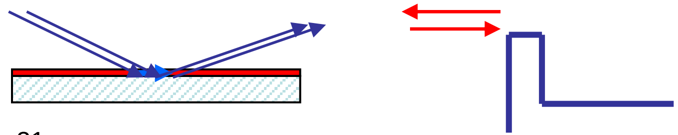


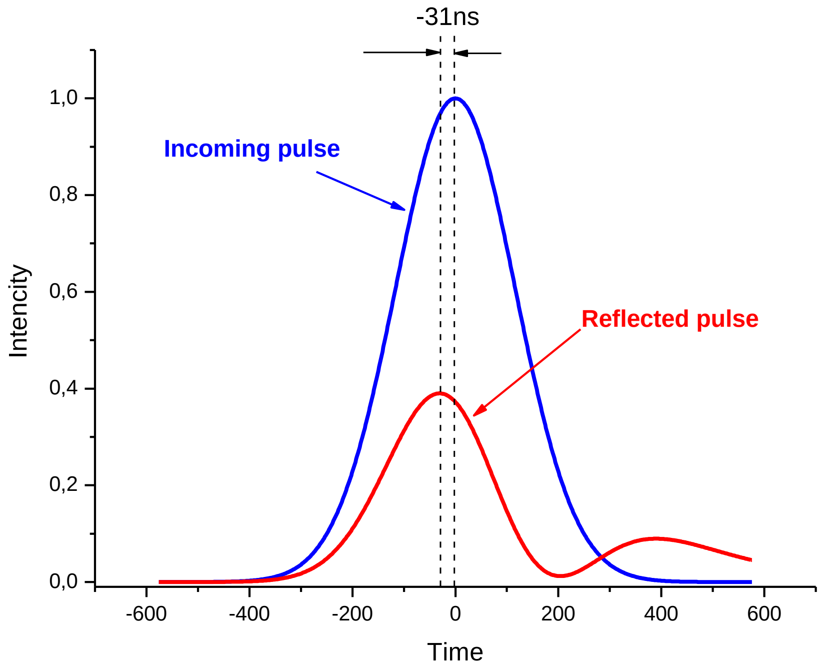


Energy 144nev
Spectrum width (FWHM) 4 nev
Duration of the time pulse 164 ns
Ideal time shift (GDT) -80ns
Real time shift -21 ns

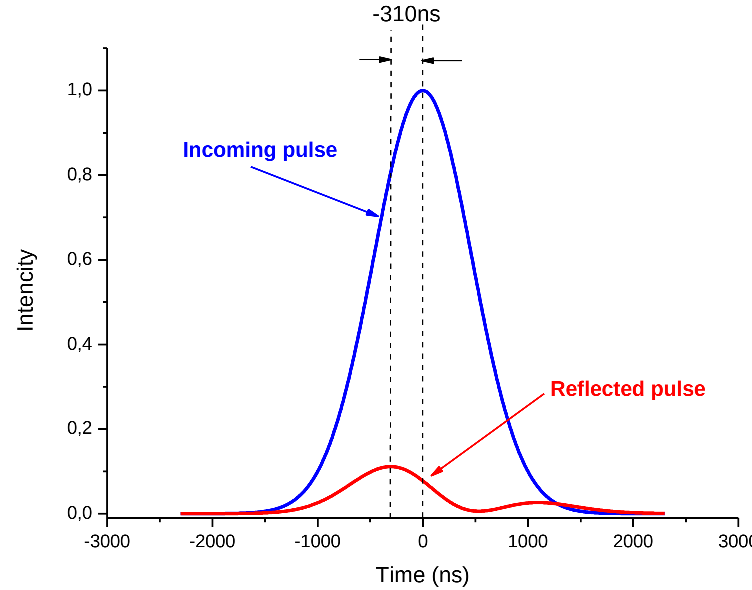
Energy 144nev
Spectrum width (FWHM) 1 nev
Duration of the time pulse 660 ns
Ideal time shift (GDT) -80ns
Real time shift -66 ns

Reflection of the short time pulse (negative delay time)





Duration of the time pulse 164
Energy 256 nev
Energy width 4 nev
Ideal time shift - 500 ns
Real time shift - 31ns



Duration of the time pulse 660
Energy 256 nev
Energy width 1 nev
Ideal time shift - 500 ns
Real time shift - 310 ns

Conclusion

1. Group delay time (GDT) at neutron reflection from multilayered structures really may reach very large positive and negative value.

2. GDT is only very rough measure of the time distribution of the reflected pulse.

3. Peak of the reflected pulse may be really appeared before the incoming pulse would reach its maximum.

4. Negative shift of the time pulse at neutron reflection from layered structures is not due to early appearing of reflected wave but due to the leakage of waves into other channels like transmission and absorption.

5. Existing of the negative pulse shift is not contradict to the causality principle

Thank you for your attention