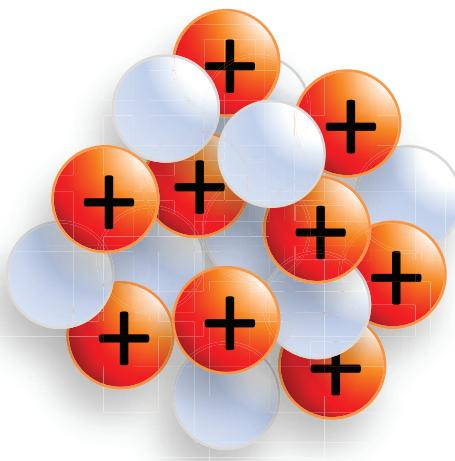




# The Potential Use of X-ray FELs in Nuclear Studies



Wen-Te Liao 賴文德

Max Planck Institute for Nuclear Physics  
Heidelberg, Germany

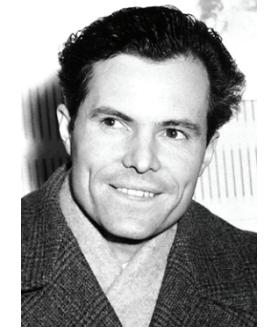
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29 August 2013 @ FEL2013

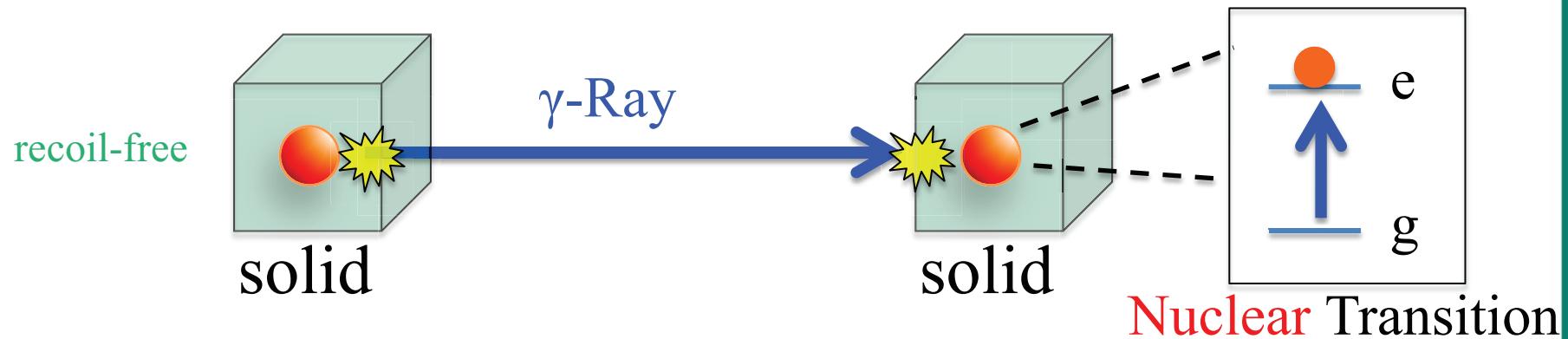




# Mössbauer effect (1958)



R. Mössbauer

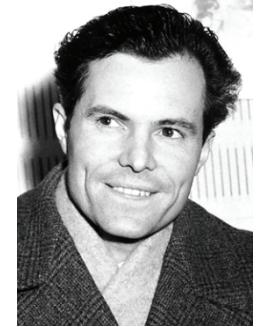


R. L. Mössbauer, Zeitschrift für Physik A 151, 124  
(1958).

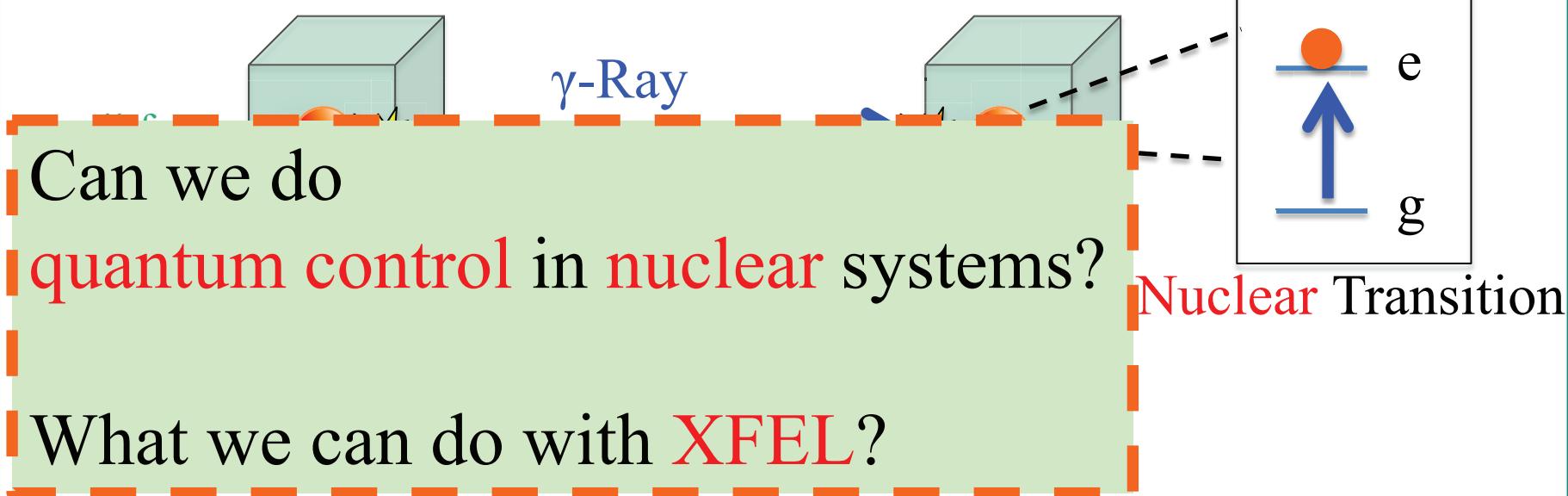




# Mössbauer effect (1958)



R. Mössbauer



R. L. Mössbauer, Zeitschrift für Physik A 151, 124  
(1958).



# Two Examples



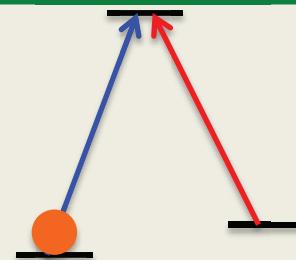
## Iron Cage for X-Ray Photon

$^{57}\text{Fe}$  nuclei and X-Rays

W.-T. Liao, A. Pálffy, C. H. Keitel, Phys. Rev. Lett. 109, 197403 (2012)

## Nuclear STIRAP

many species of nuclei and XFEL



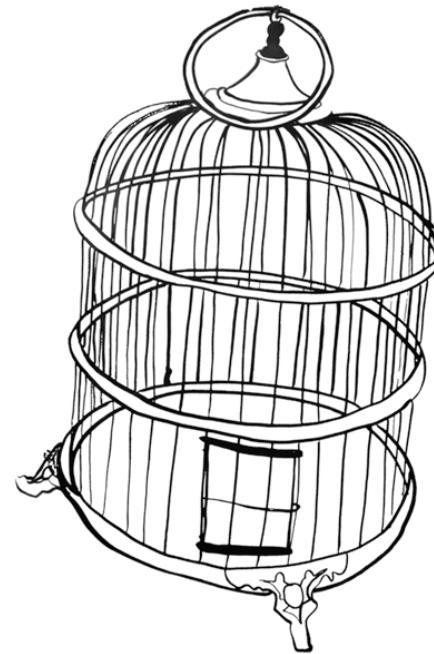
W.-T. Liao, A. Pálffy, C. H. Keitel, Phys. Lett. B 705, 134 (2011).

W.-T. Liao, A. Pálffy, C. H. Keitel, Phys. Rev. C 87, 054609 (2013).

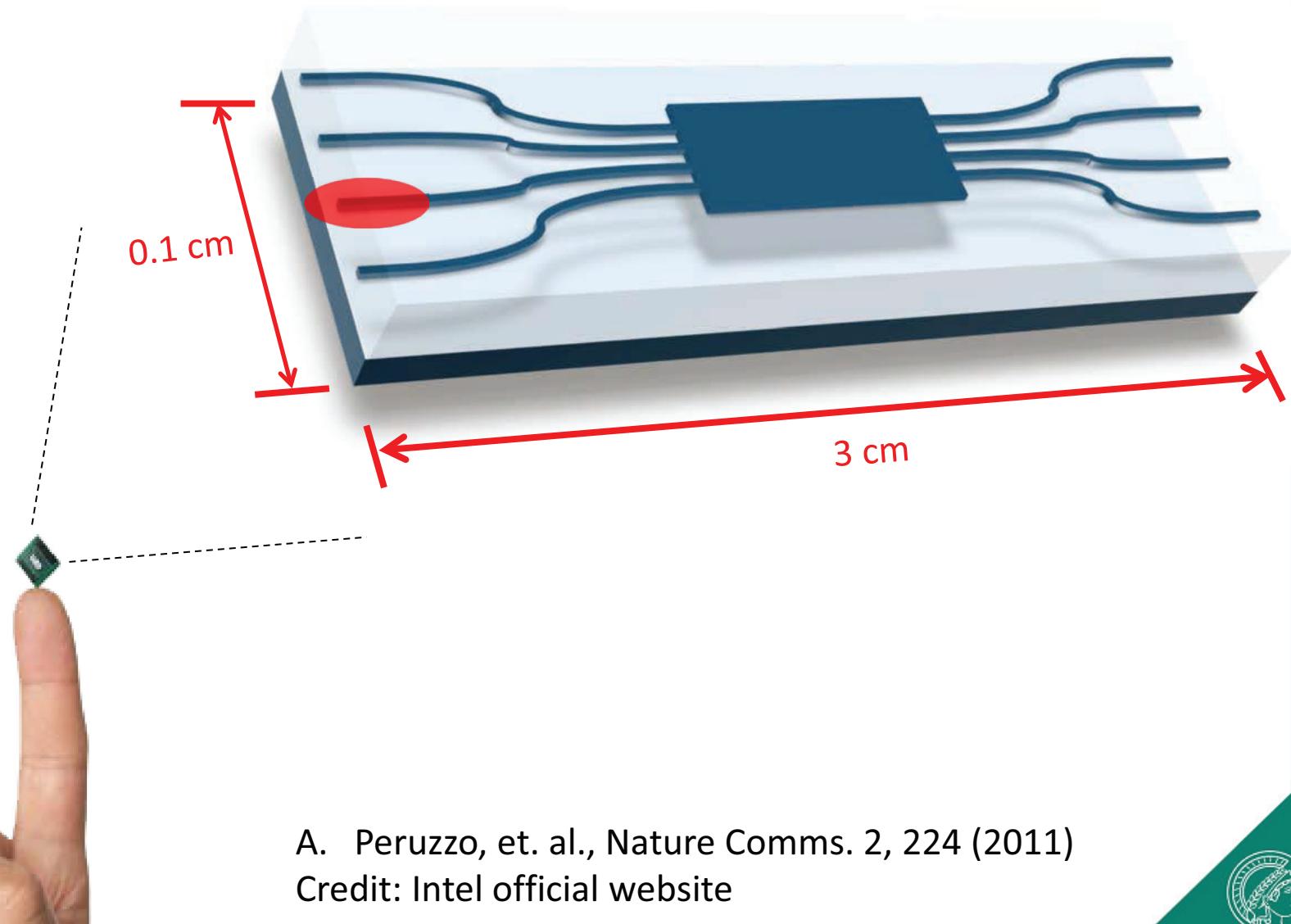


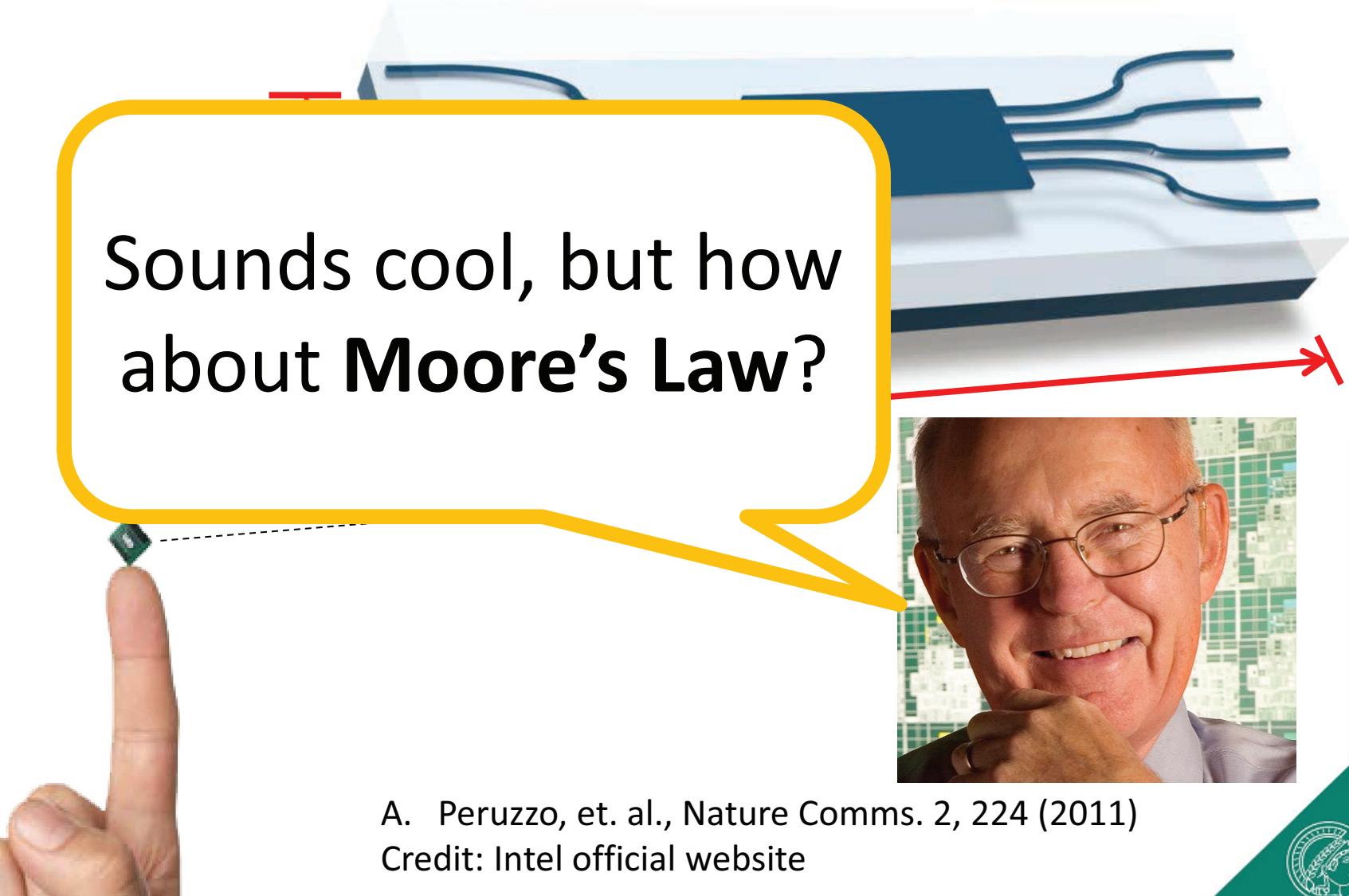
# Iron Cage for X-Ray Photons

W.-T. Liao, A. Pálffy, C. H. Keitel, Phys. Rev. Lett. 109, 197403 (2012)



# Quantum Photonic Circuit

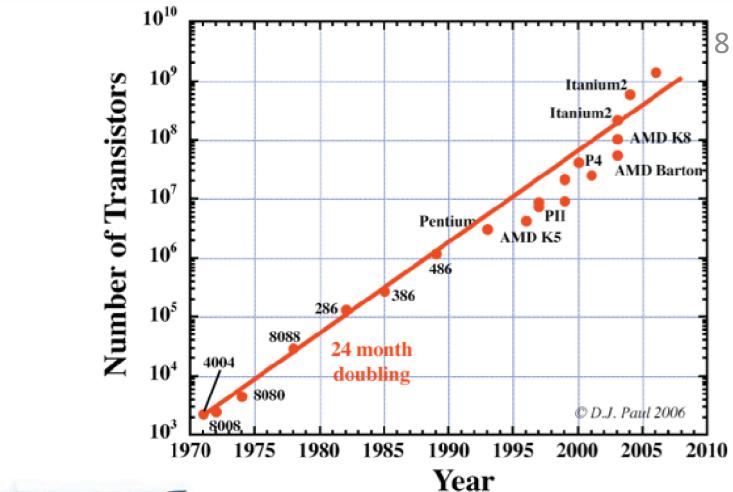
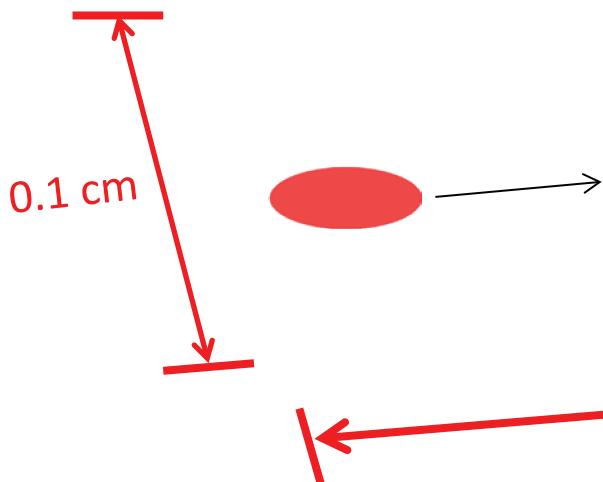




A. Peruzzo, et. al., Nature Comms. 2, 224 (2011)  
Credit: Intel official website

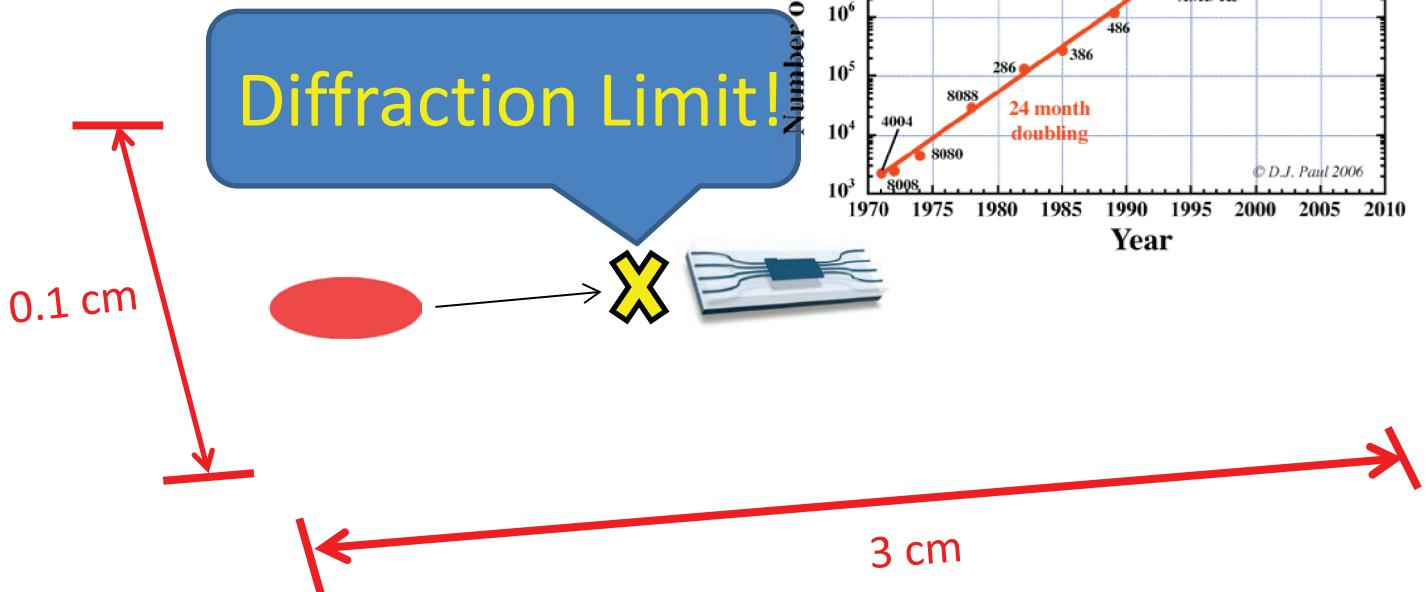


# Trouble of Shrinking



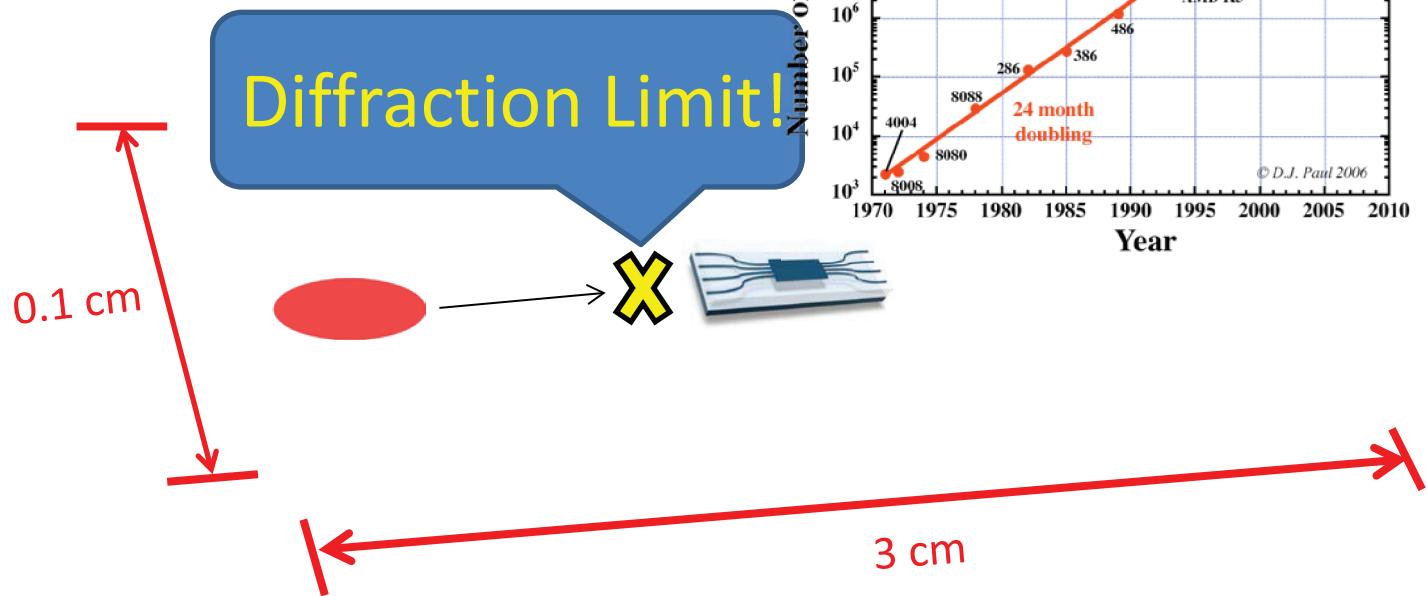


# Trouble of Shrinking



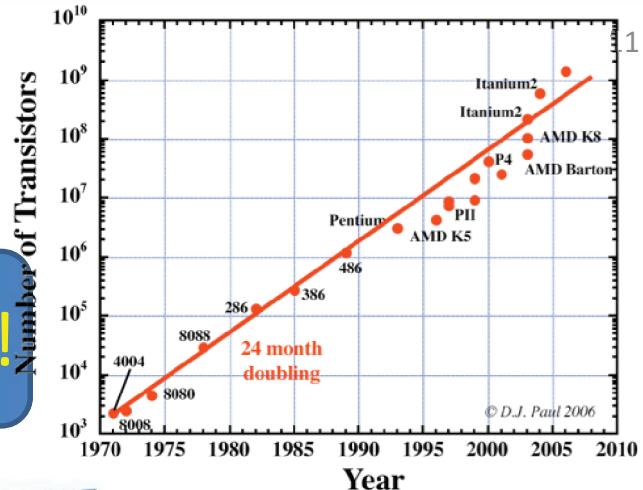
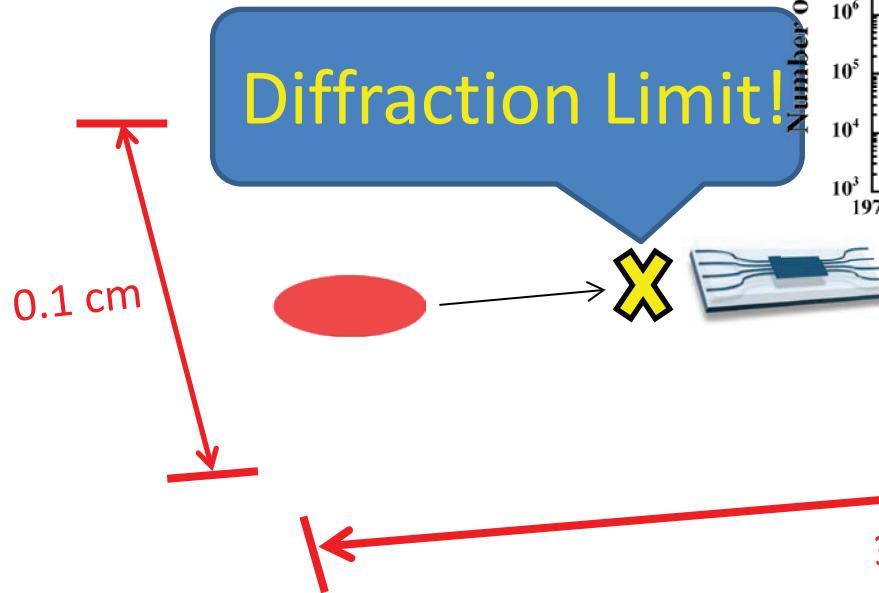


# Trouble of Shrinking



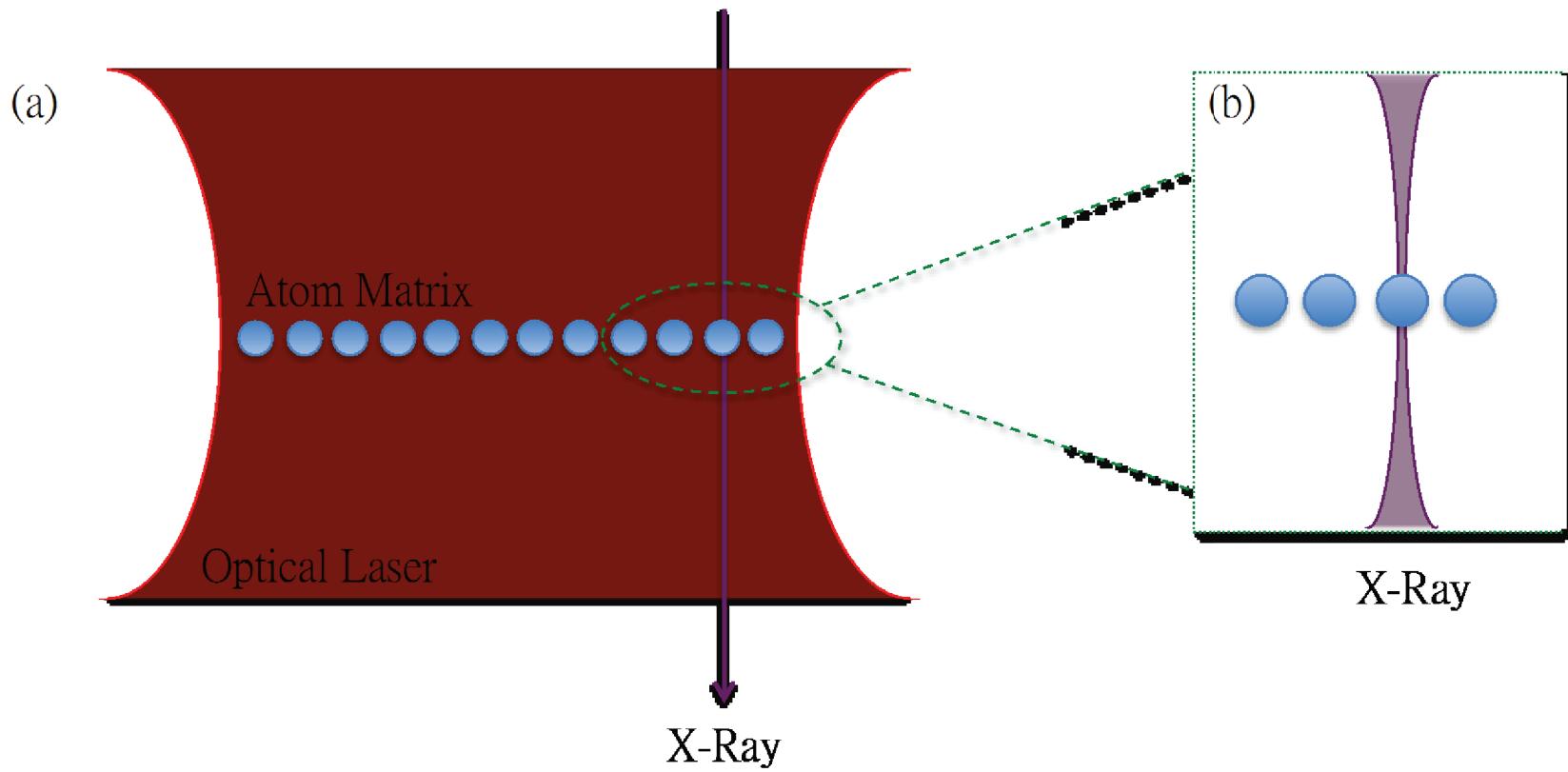


# Trouble of Shrinking





# Single Atom Memory



# Control of single x-ray photon

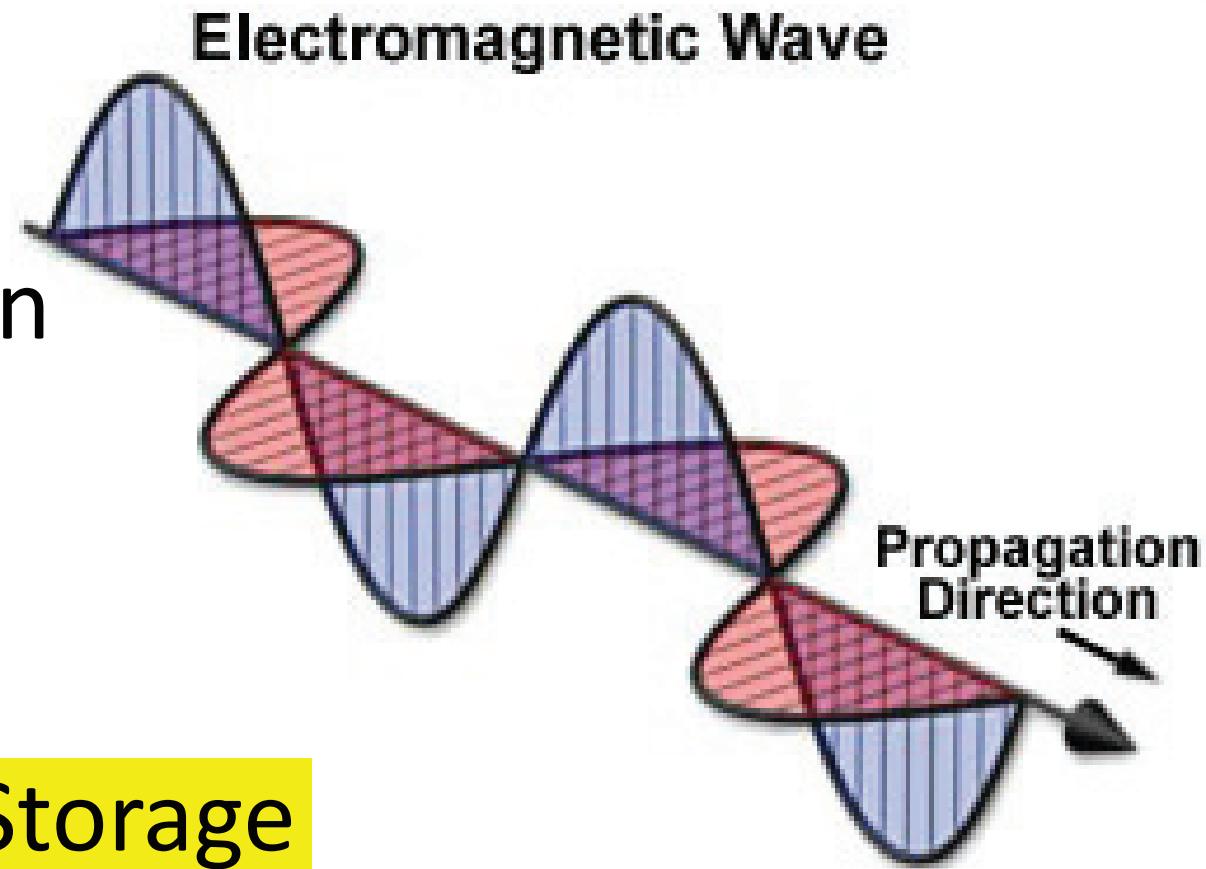
Degree of freedom:

(1) Polarization

(2) Phase

(3) Amplitude  
&

(4) Coherent Storage



Credit: Molecular Expressions website

# <sup>57</sup>Fe Nucleus

Periodic Table by Article Value

1 <b>H</b> Hydrogen	2 <b>He</b> Helium
3 <b>Li</b> Lithium	4 <b>Be</b> Beryllium
11 <b>Na</b> Sodium	12 <b>Mg</b> Magnesium
19 <b>K</b> Potassium	20 <b>Ca</b> Calcium
37 <b>Rb</b> Rubidium	38 <b>Sr</b> Strontium
55 <b>Cs</b> Caesium	56 <b>Ba</b> Barium
87 <b>Fr</b> Francium	88 <b>Ra</b> Radium
57 * <b>La</b> Lanthanum	58 <b>Ce</b> Cerium
89 ** <b>Ac</b> Actinium	59 <b>Pr</b> Praseodymium
104 <b>Rf</b> Rutherfordium	60 <b>Nd</b> Neodymium
105 <b>Db</b> Dubnium	61 <b>Pm</b> Promethium
106 <b>Sg</b> Seaborgium	62 <b>Sm</b> Samarium
107 <b>Bh</b> Bohrium	63 <b>Eu</b> Europium
108 <b>Hs</b> Hassium	64 <b>Gd</b> Gadolinium
109 <b>Mt</b> Meitnerium	65 <b>Tb</b> Terbium
110 <b>Ds</b> Darmstadtium	66 <b>Dy</b> Dysprosium
111 <b>Rg</b> Roentgenium	67 <b>Ho</b> Holmium
112 <b>Cn</b> Copernicium	68 <b>Er</b> Erbium
113 <b>Uut</b> Uuntrium	69 <b>Tm</b> Thulium
114 <b>Fl</b> Flerovium	70 <b>Yb</b> Ytterbium
115 <b>Uup</b> Uunpentium	71 <b>Lu</b> Lutetium
116 <b>Lv</b> Livermorium	
117 <b>Uus</b> Uunseptium	
118 <b>Uuo</b> Ununoctium	

Views      Quality     
 

High	Showcase	Mid
High		
Mid		
Low	Treasure	Under the Rug

 Low



# <sup>57</sup>Fe Nucleus

Periodic Table by Article Value

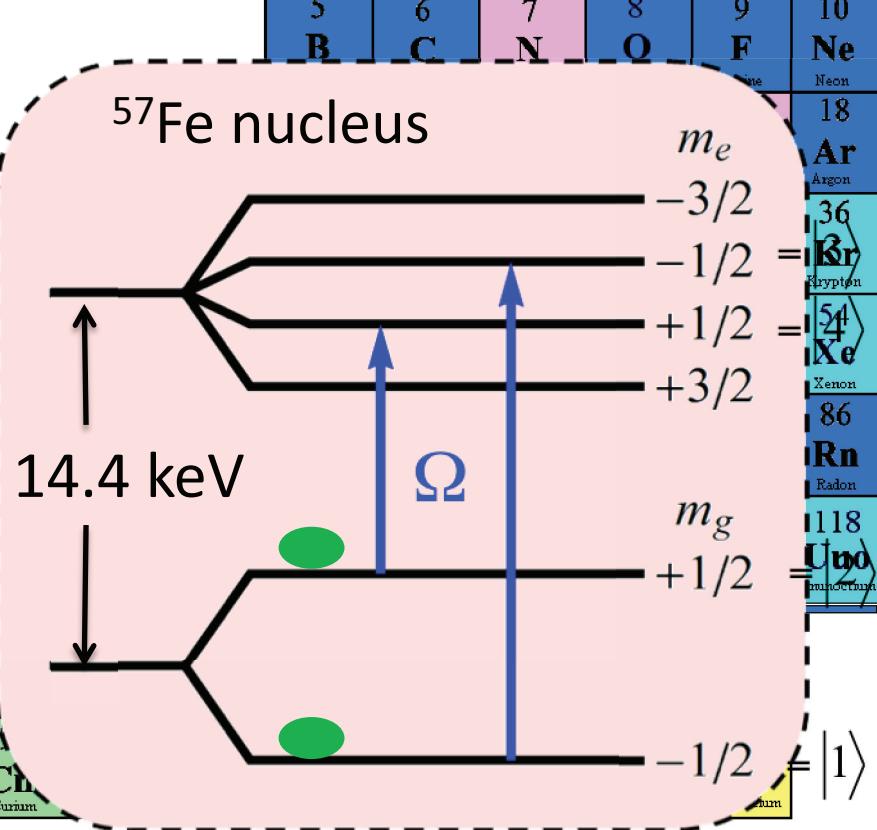
	1 H Hydrogen	2 He Helium															
3 Li Lithium	4 Be Beryllium																
11 Na Sodium	12 Mg Magnesium																
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Telurium	53 I Iodine	54 Xe Xenon	
55 Cs Caesium	56 Ba Barium	57 * La Lanthanum	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89 ** Ac Actinium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Uut Uranium	114 Fl Flerovium	115 Uup Ununpentium	116 Lv Livermorium	117 Uus Ununseptium	118 Uuo Ununoctium
*	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium			
**	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium			



# $^{57}\text{Fe}$ Nucleus

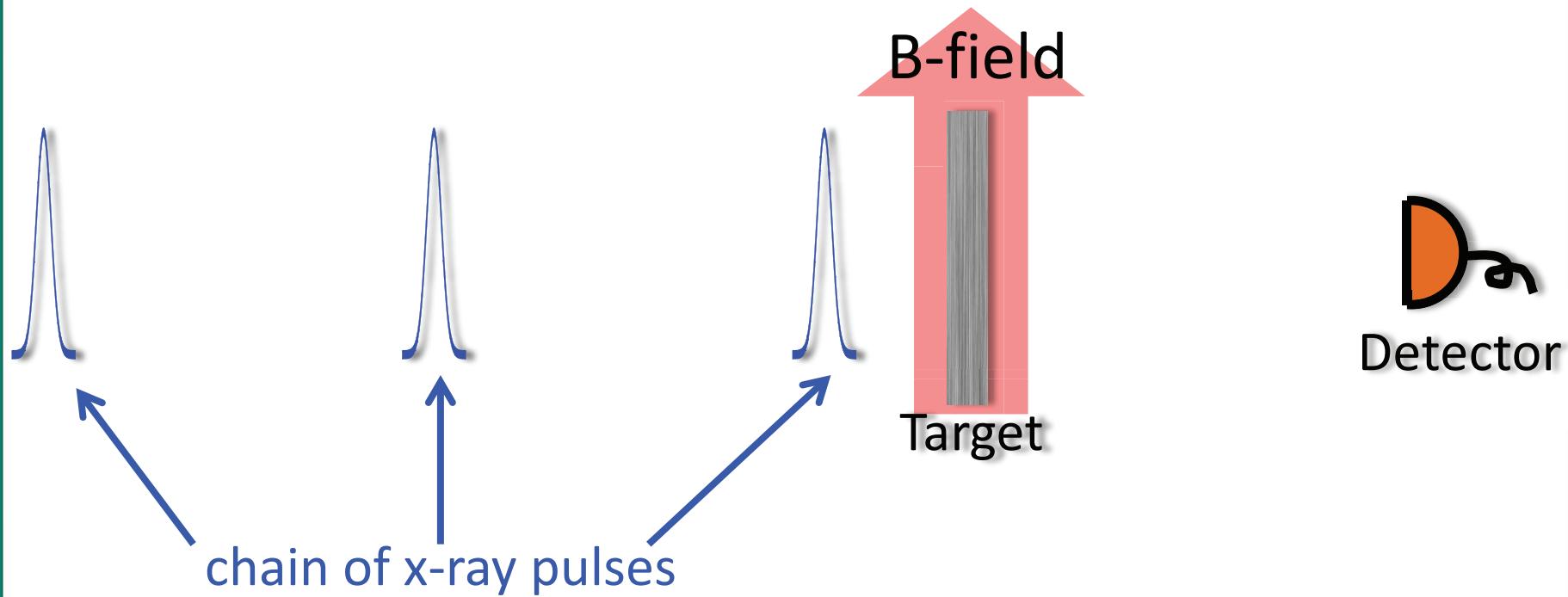
Periodic Table by Article Value

		Views												
		High			Mid			Low						
		Showcase				Blemish								
		High	Mid	Low	High	Mid	Low	High	Mid	Low	High	Mid	Low	
1	H	Hydrogen												
3	Li	Lithium												
11	Na	Sodium												
12	Mg	Magnesium												
19	K	Potassium												
20	Ca	Calcium												
21	Sc	Scandium												
22	Ti	Titanium												
23	V	Vanadium												
24	Cr	Chromium												
25	Mn	Manganese												
26	Fe	Iron												
27	Co	Cobalt												
37	Rb	Rubidium												
38	Sr	Strontium												
39	Y	Yttrium												
40	Zr	Zirconium												
41	Nb	Niobium												
42	Mo	Molybdenum												
43	Tc	Technetium												
45	Rh	Ruthenium												
55	Cs	Caesium												
56	Ba	Barium												
57 *	La	Lanthanum												
72	Hf	Hafnium												
73	Ta	Tantalum												
74	W	Tungsten												
75	Re	Rhenium												
77	Ir	Iridium												
87	Fr	Francium												
88	Ra	Radium												
89 **	Ac	Actinium												
104	Rf	Rutherfordium												
105	Db	Dubnium												
106	Sg	Seaborgium												
107	Bh	Bohrium												
108	Hs	Hassium												
109	Mt	Meitnerium												
*	58	Ce	Cerium											
*	59	Pr	Praseodymium											
*	60	Nd	Neodymium											
*	61	Pm	Promethium											
*	62	Sm	Samarium											
*	63	Eu	Europium											
**	90	Th	Thorium											
**	91	Pa	Protactinium											
**	92	U	Uranium											
**	93	Np	Neptunium											
**	94	Pu	Plutonium											
**	95	Am	Americium											
**	96	Cm	Curium											



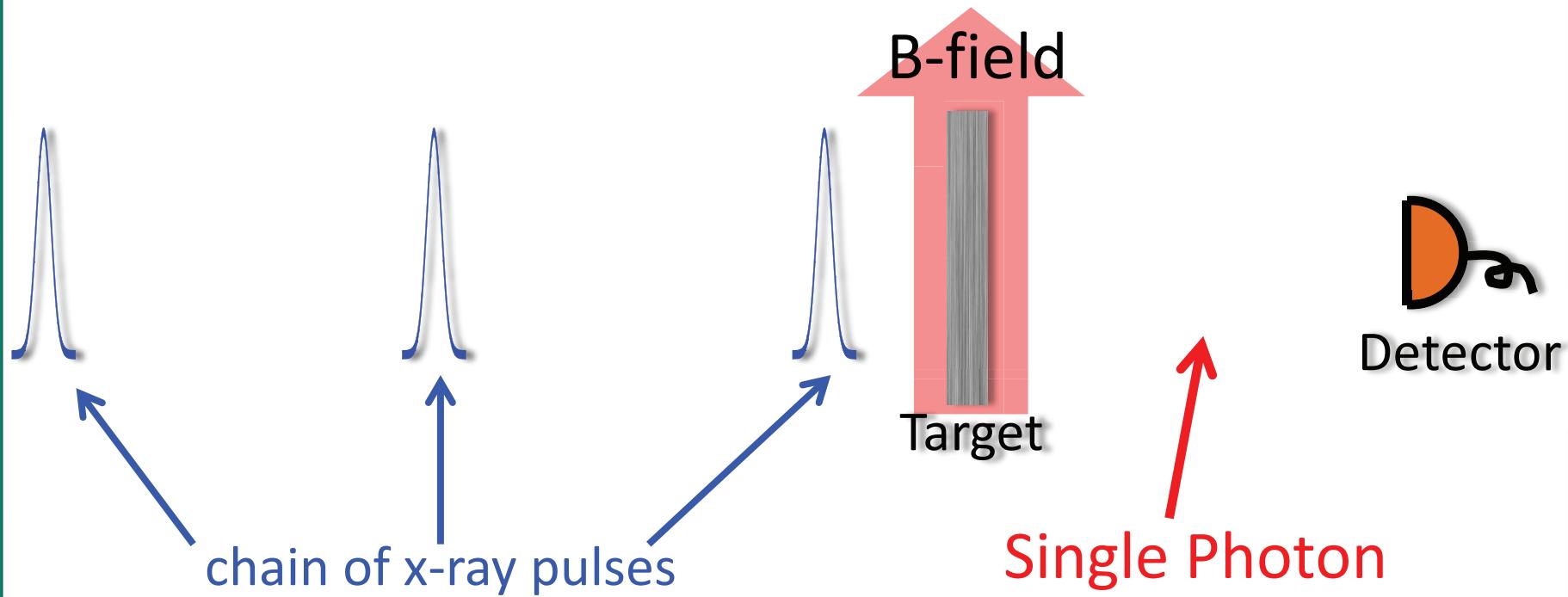


# Nuclear Forward Scattering Time Spectrum



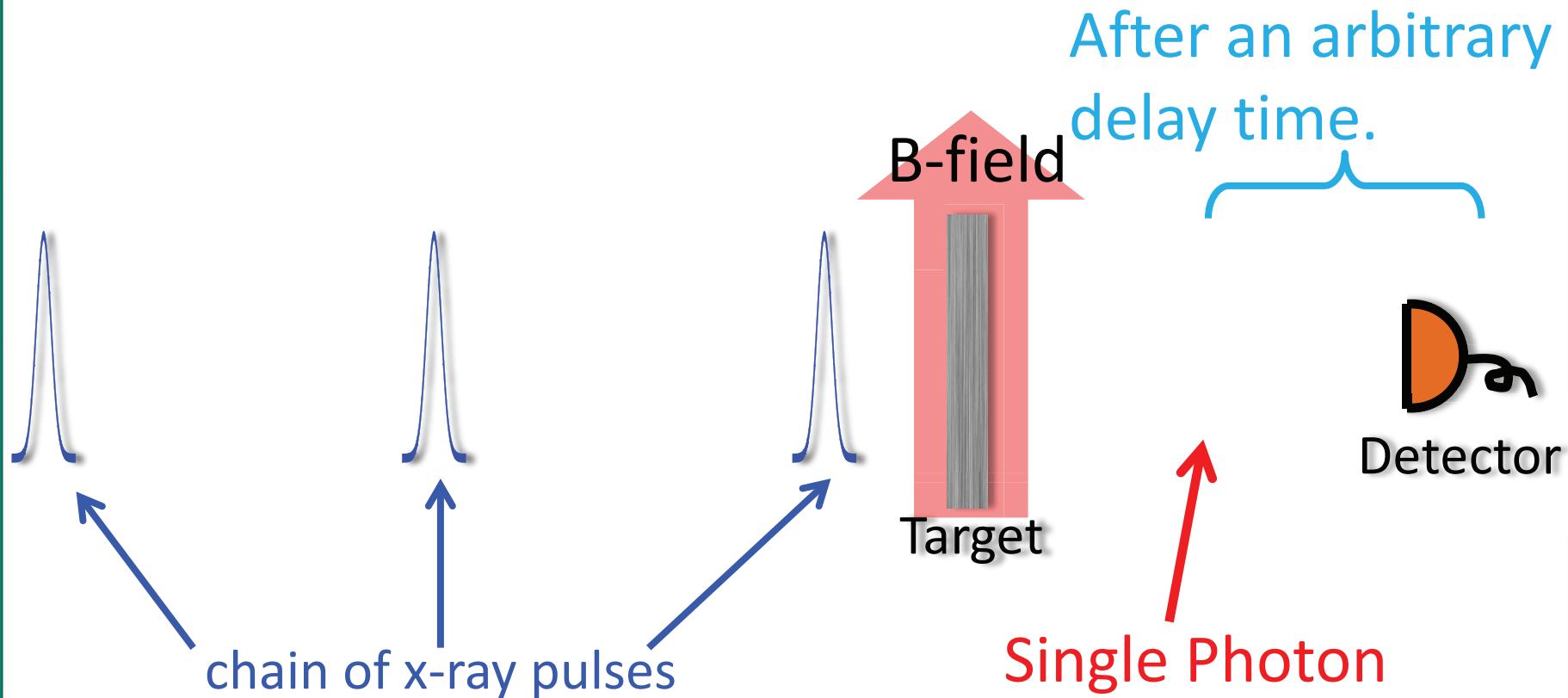


# Nuclear Forward Scattering Time Spectrum



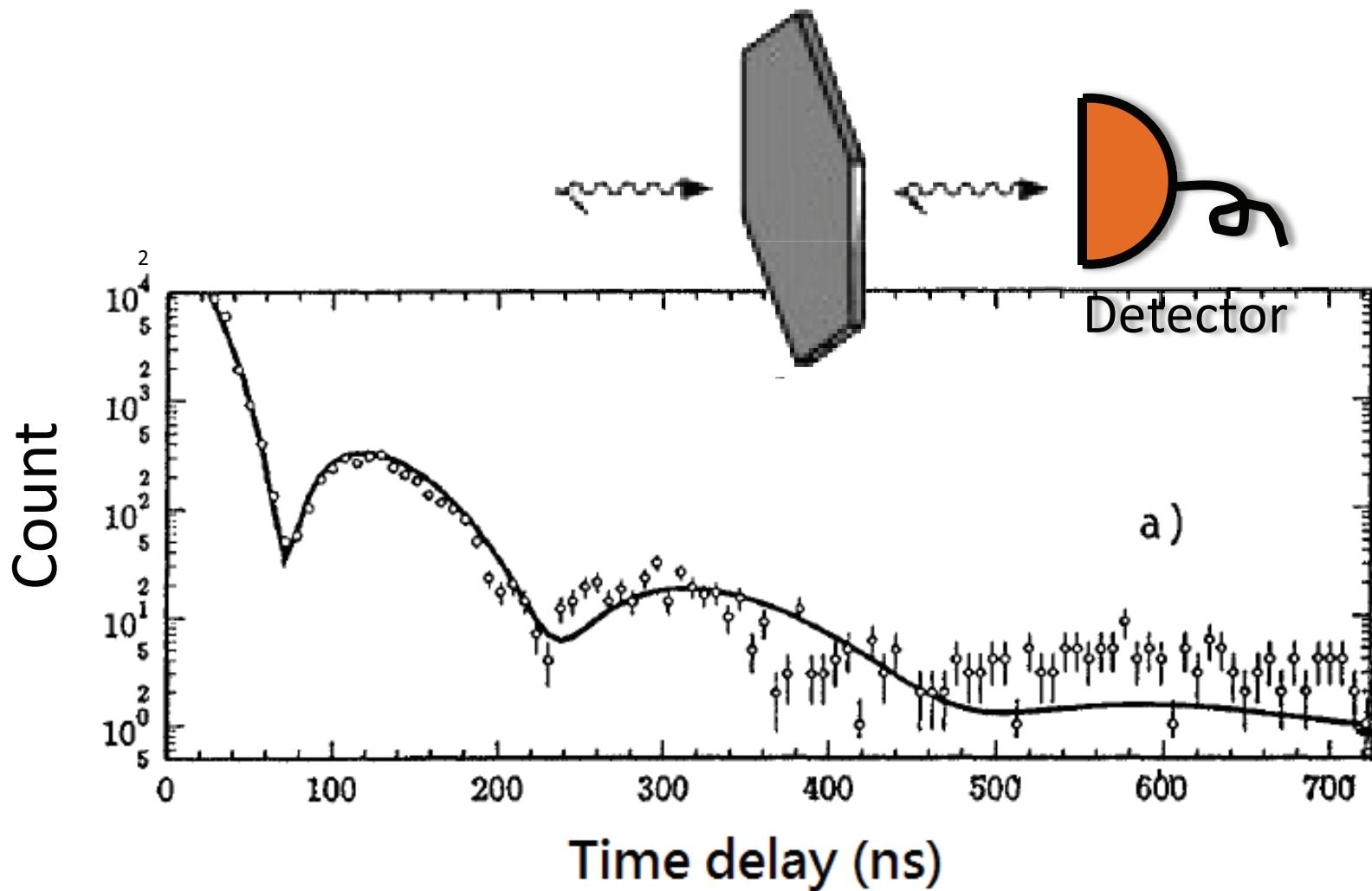


# Nuclear Forward Scattering Time Spectrum



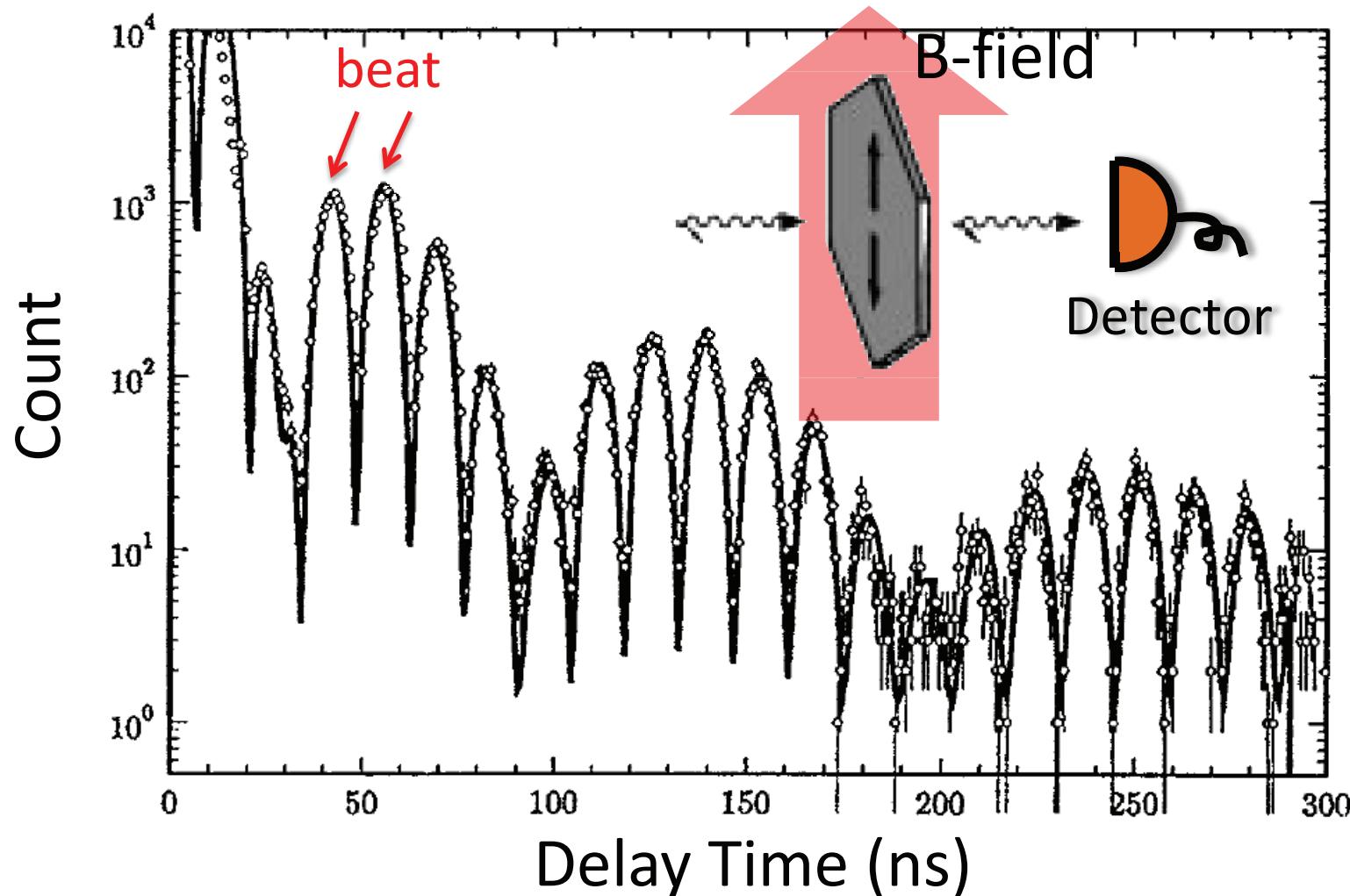


# Time Spectrum without Hyperfine field



U. van Brück, Hyperfine Interact. 123, 483 (1999)

# Time Spectrum with Hyperfine field



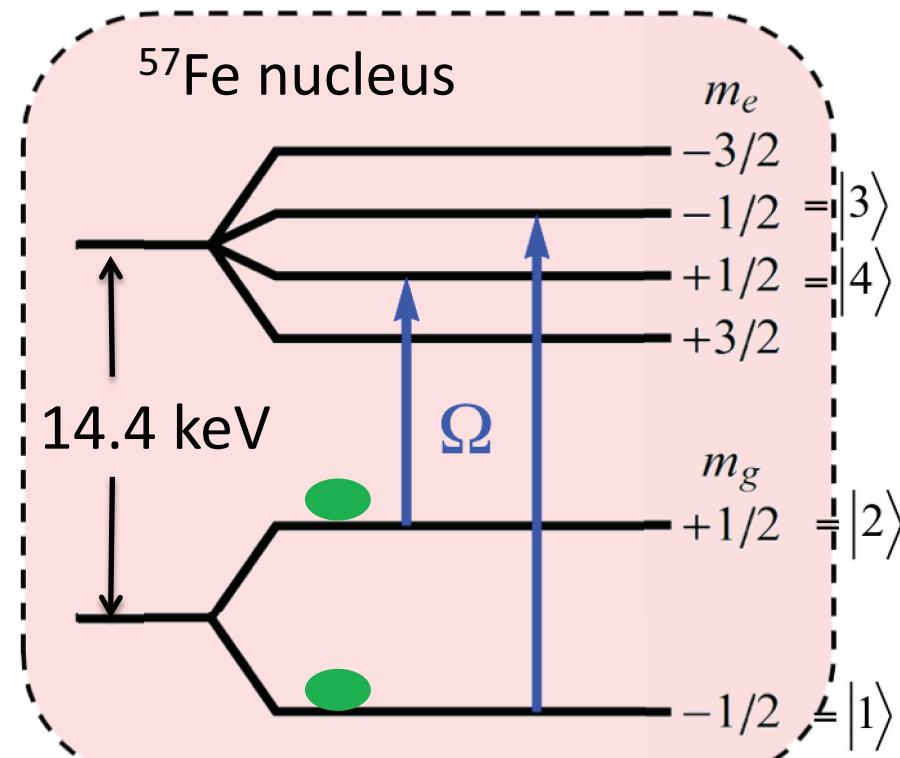


# Maxwell-Bloch equations

$$\partial_t \hat{\rho} = \frac{1}{i\hbar} [\hat{H}, \hat{\rho}] + \hat{\rho}_s,$$

$$\frac{1}{c} \partial_t \Omega + \partial_y \Omega = i\eta (\rho_{31} + \rho_{42})$$

Transition Currents



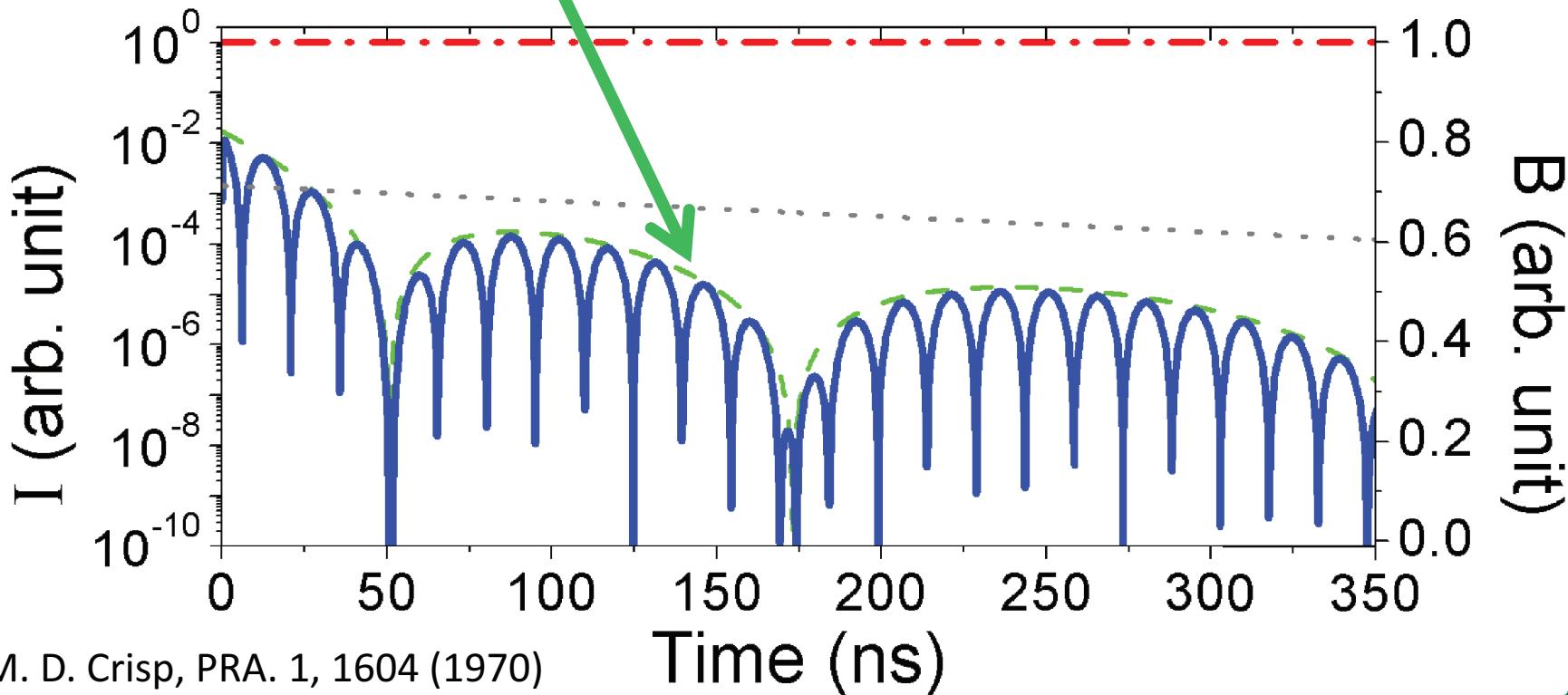
W.-T. Liao, A. Pálffy, C. H. Keitel, PRL 109, 197403 (2012)



# Solution

$$\left( \frac{\alpha}{\sqrt{\alpha \Gamma t}} J_1 \left[ 2\sqrt{\alpha \Gamma t} \right] \right)^2 e^{-\Gamma t}$$

J<sub>1</sub>: Bessel function of 1<sup>st</sup> kind  
Γ: Spontaneous Decay Rate  
α: Resonant Thickness

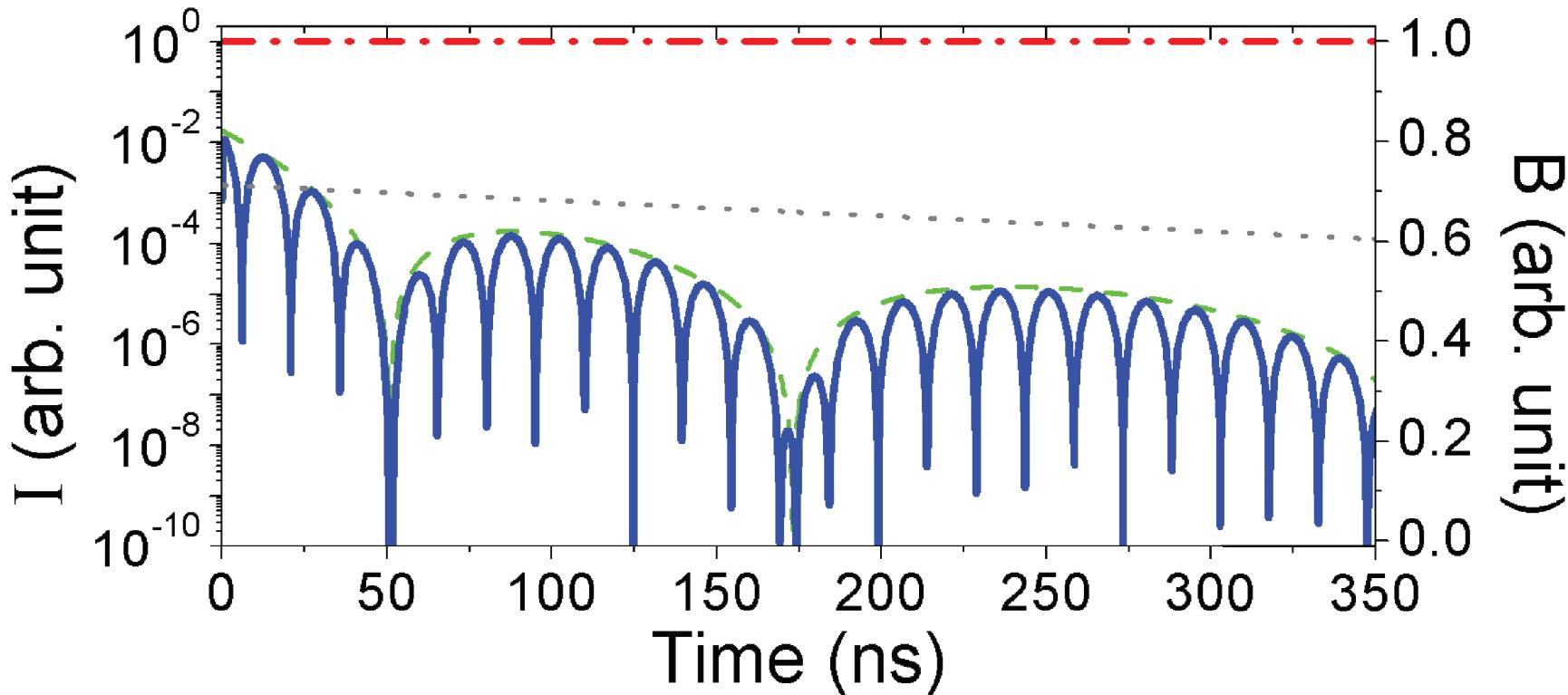


M. D. Crisp, PRA. 1, 1604 (1970)

Yu. Shvyd'ko, et. al, PRB. 59, 9132 (1999)

W.-T. Liao, A. Pálffy, C. H. Keitel, PRL 109, 197403 (2012)

# Why Beating?

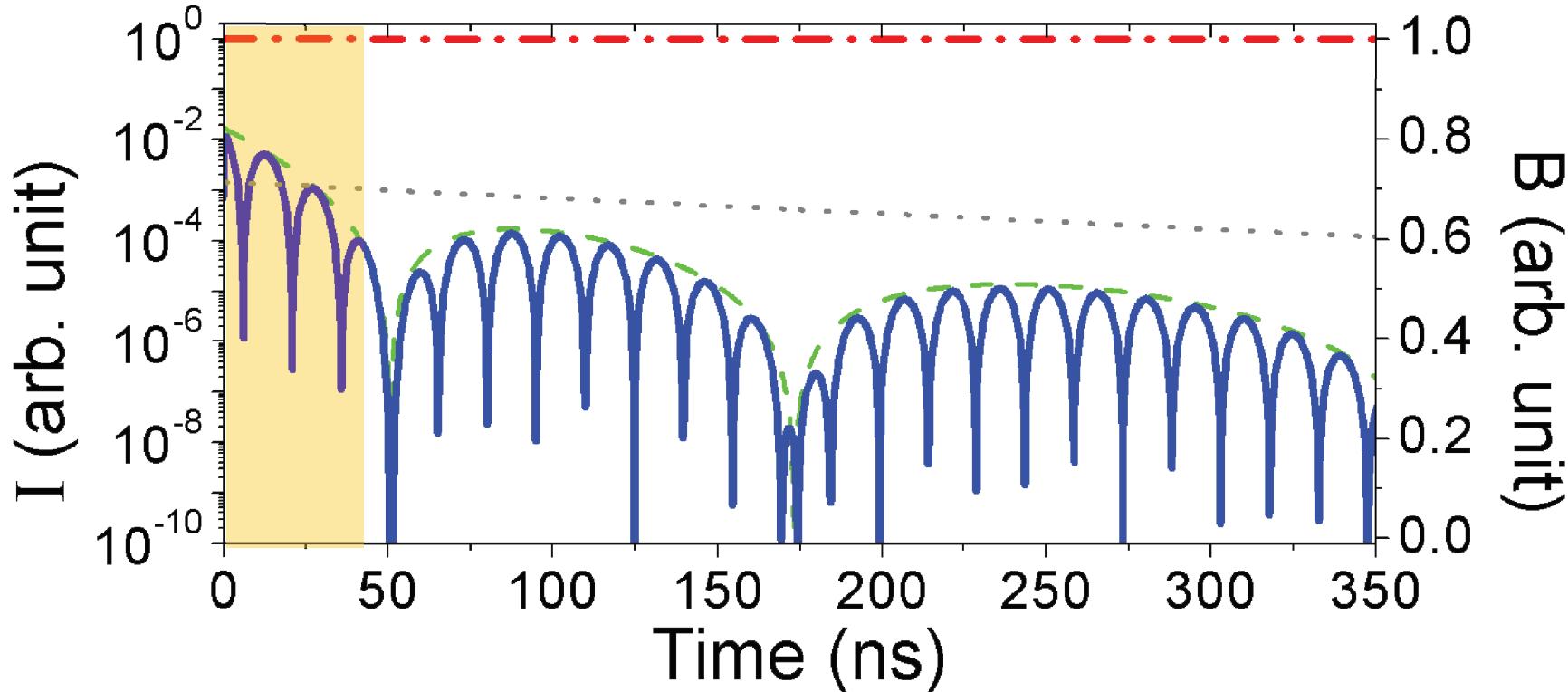


M. D. Crisp, PRA. 1, 1604 (1970)

Yu. Shvyd'ko, et. al, PRB. 59, 9132 (1999)



# Why Beating?

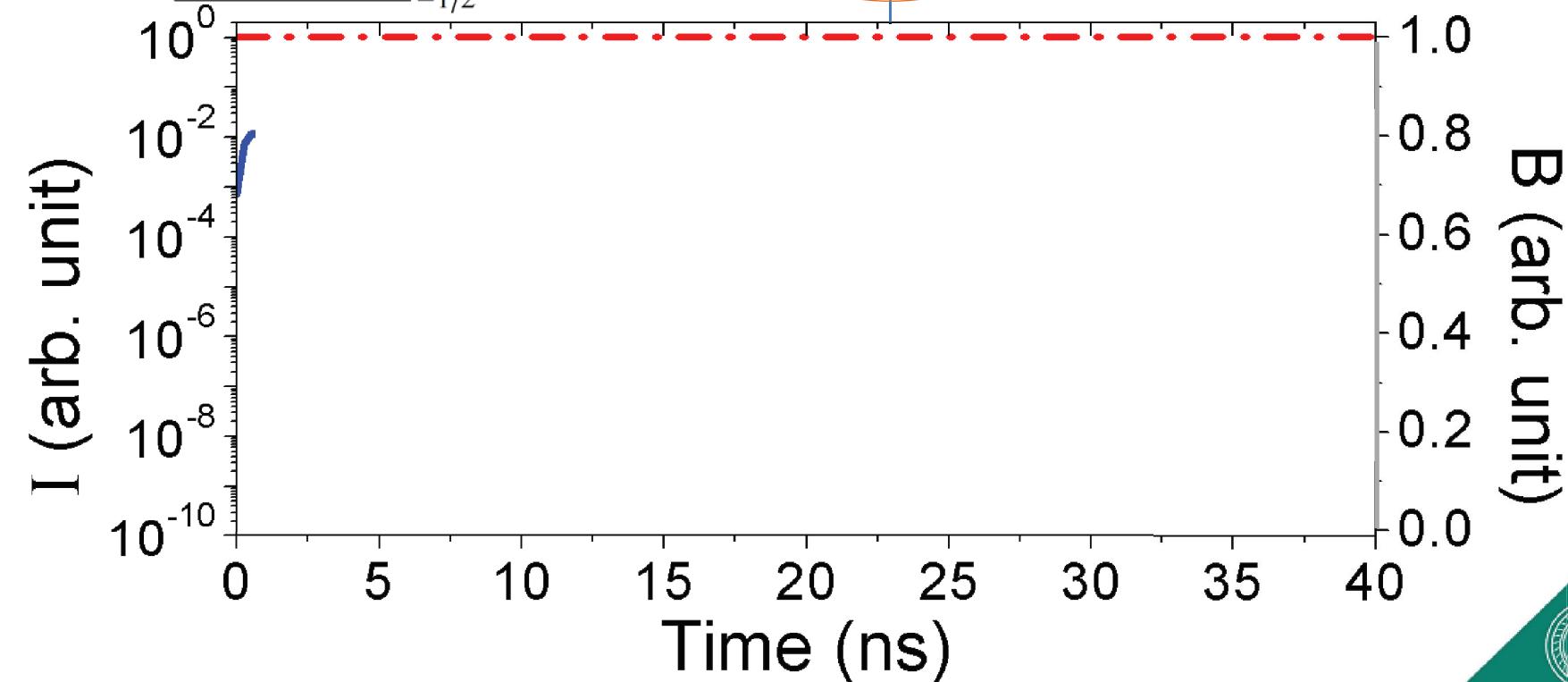
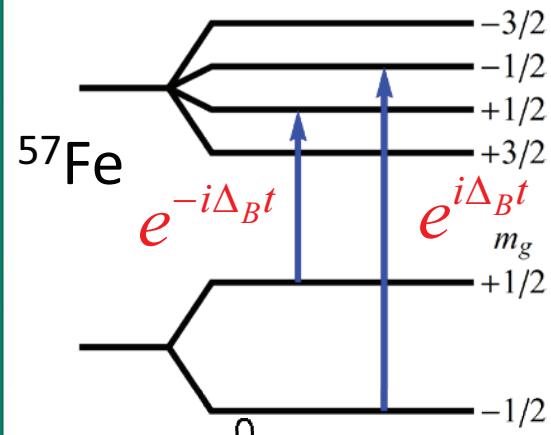


M. D. Crisp, PRA. 1, 1604 (1970)

Yu. Shvyd'ko, et. al, PRB. 59, 9132 (1999)

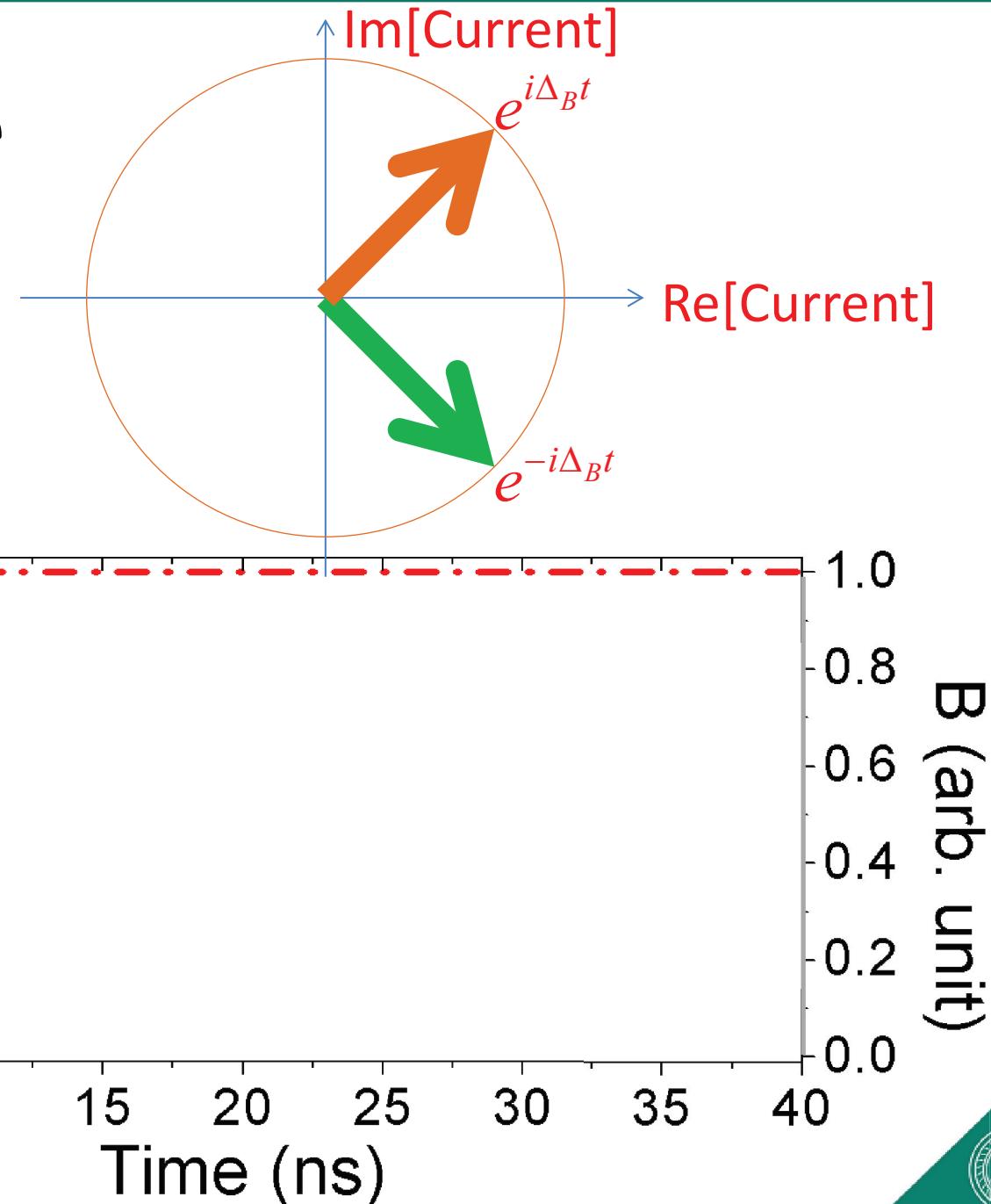
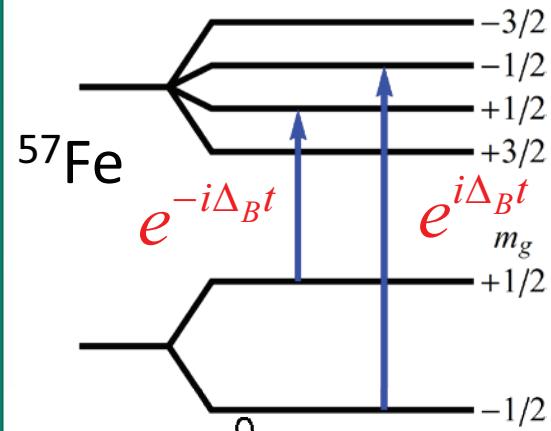


# Interference



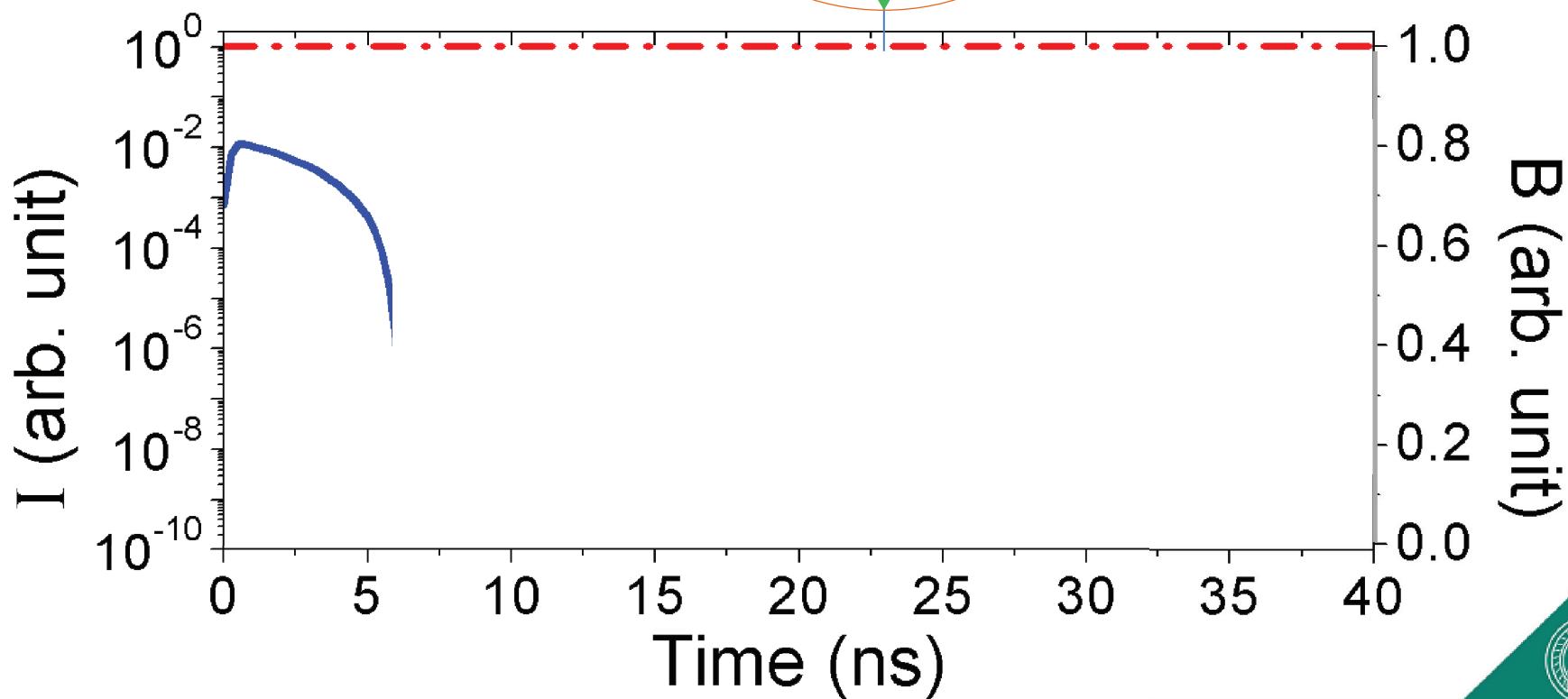


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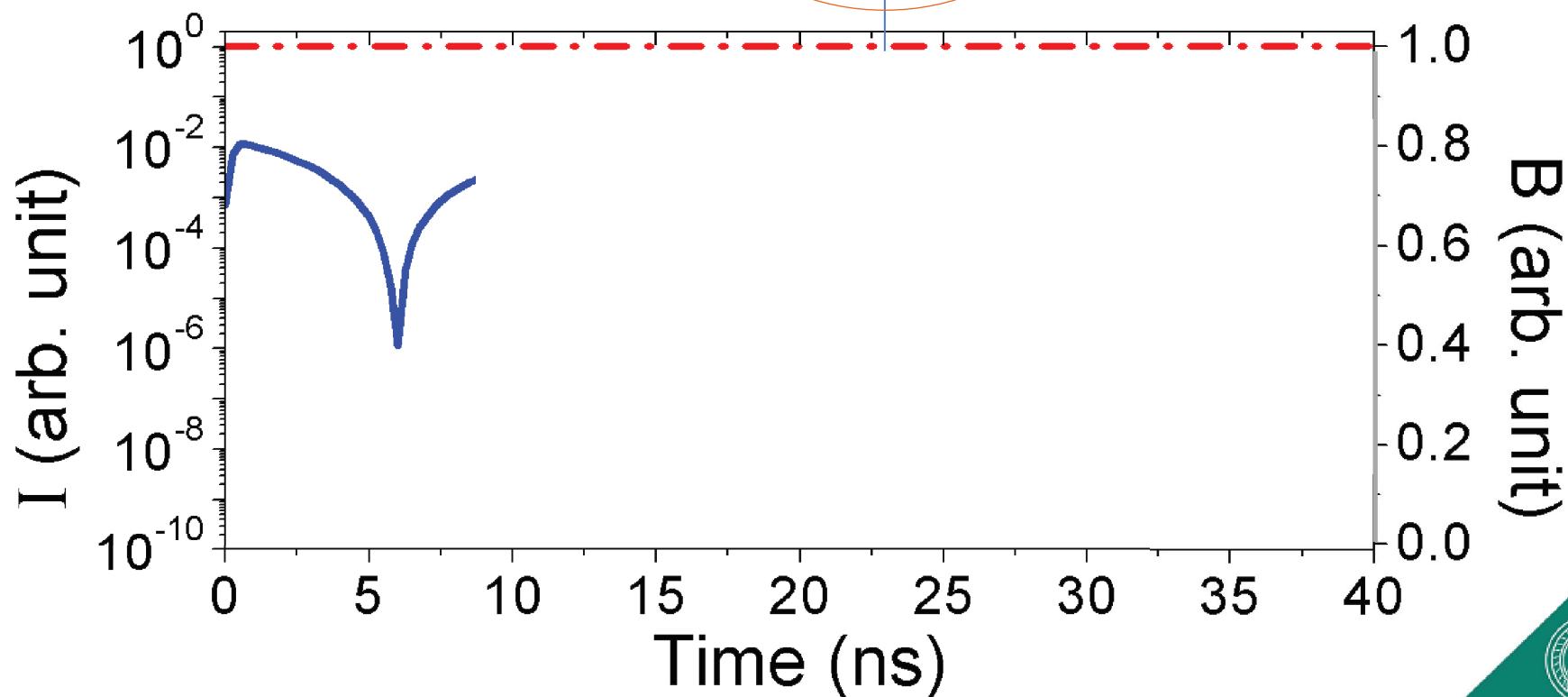
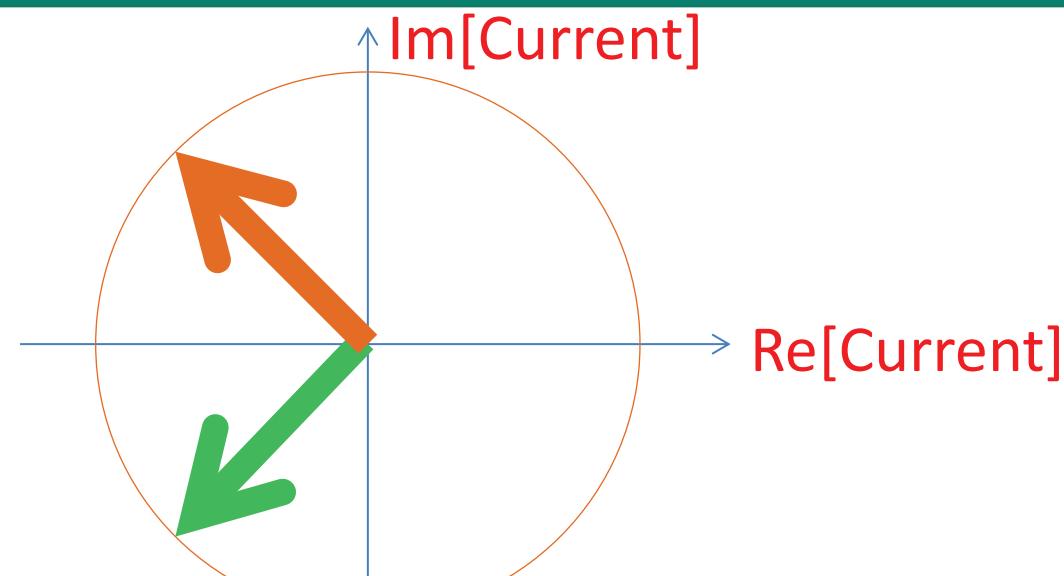


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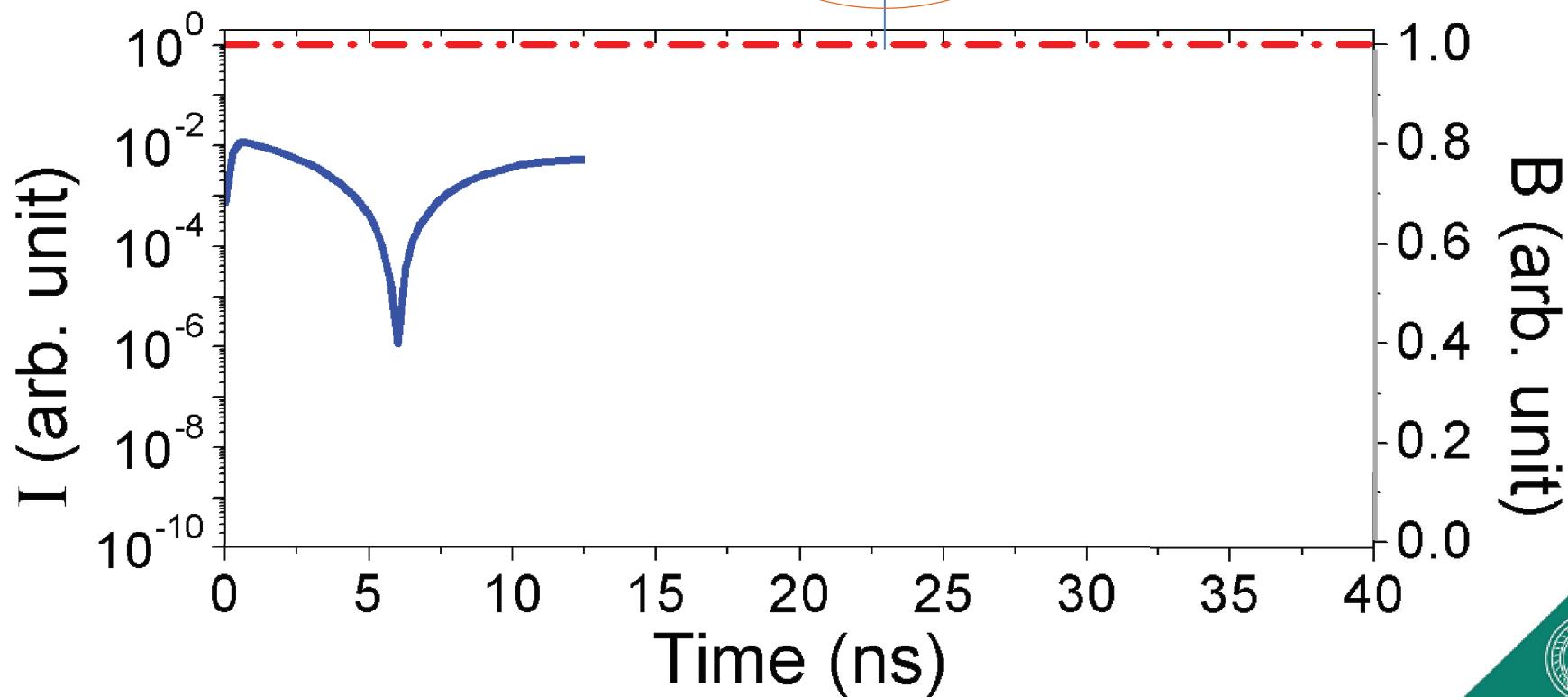
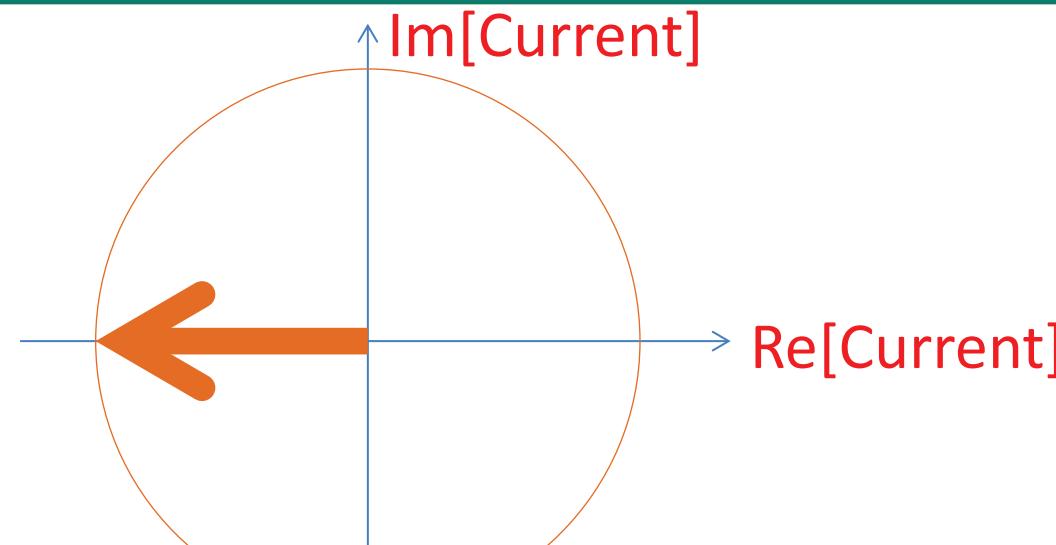


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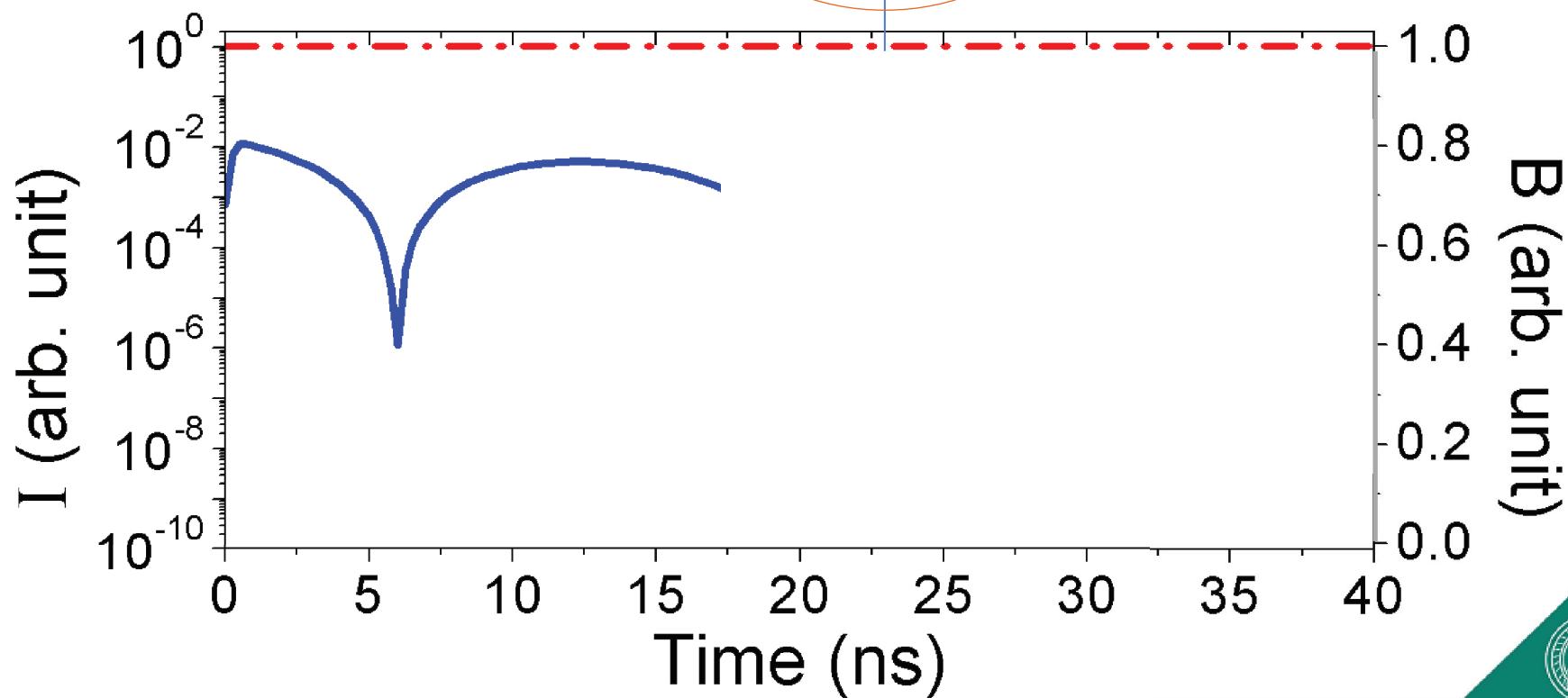
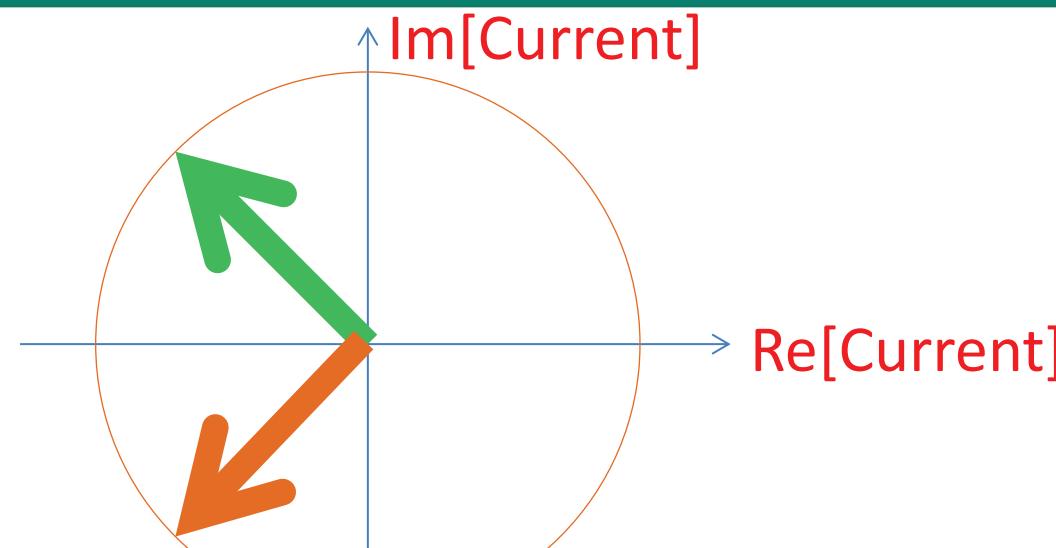


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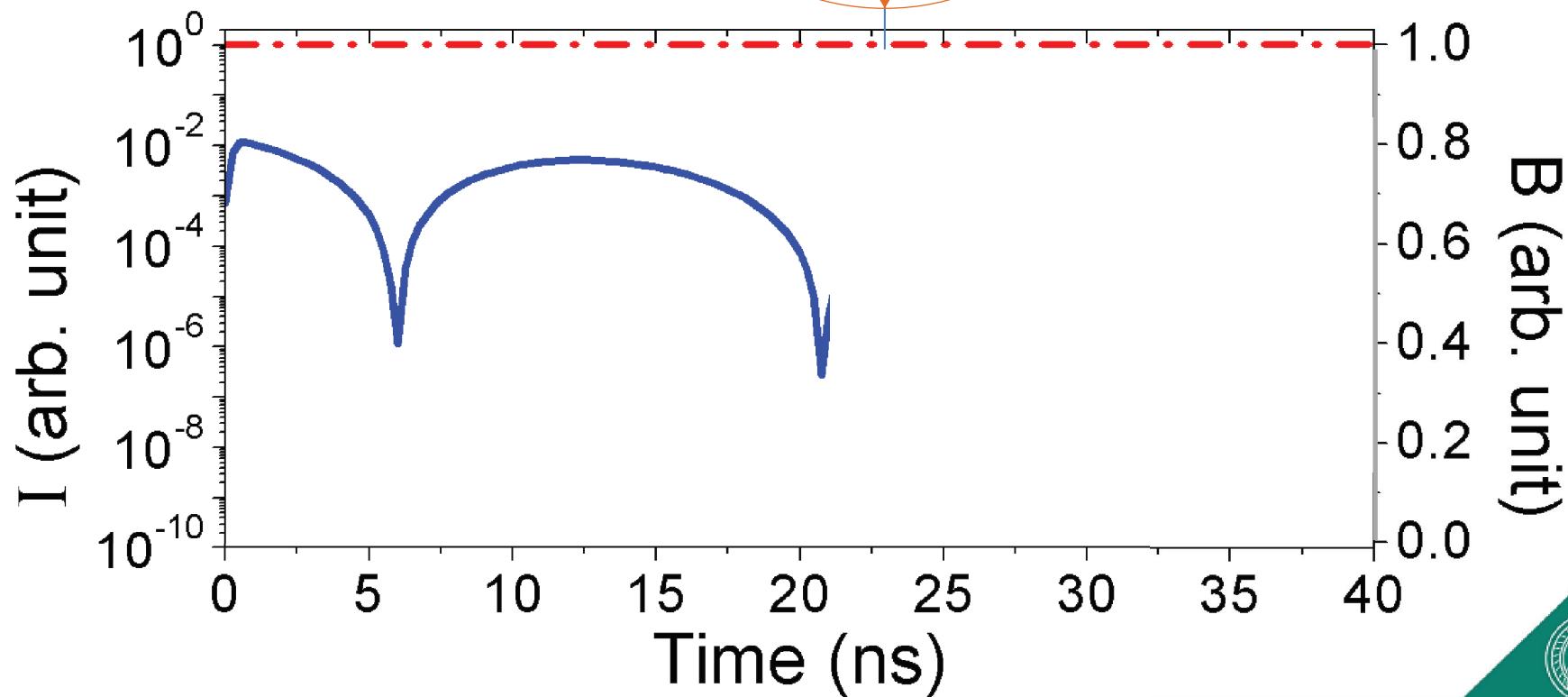
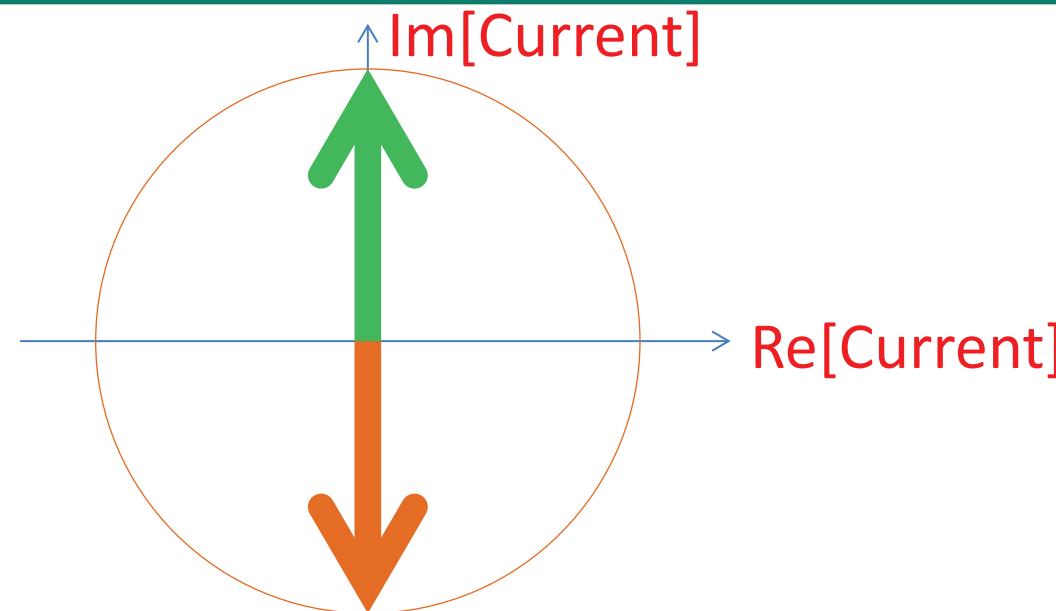


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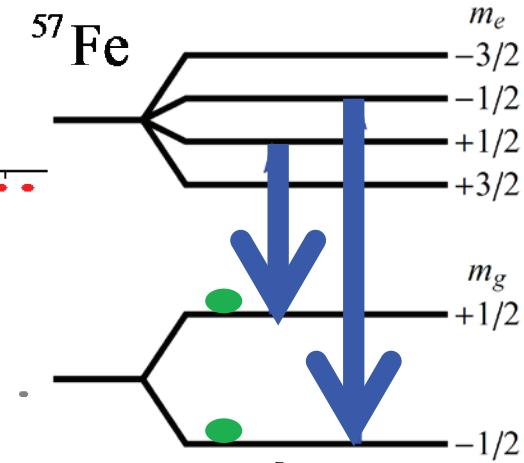
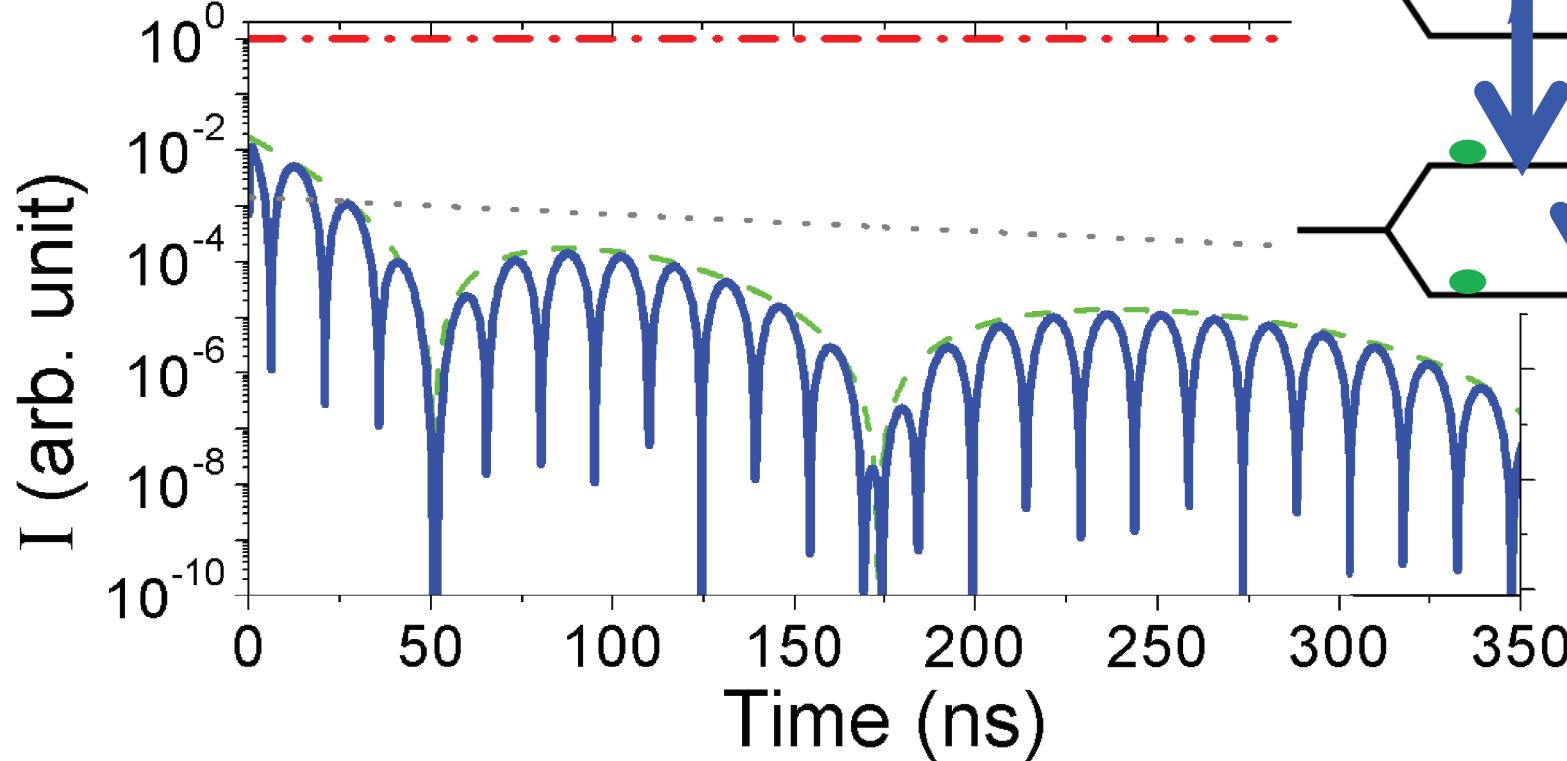


# Interference





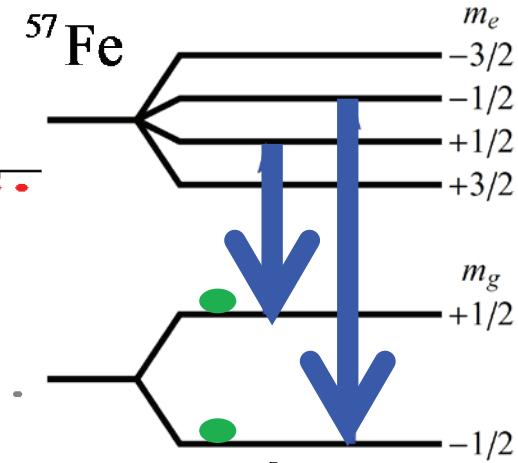
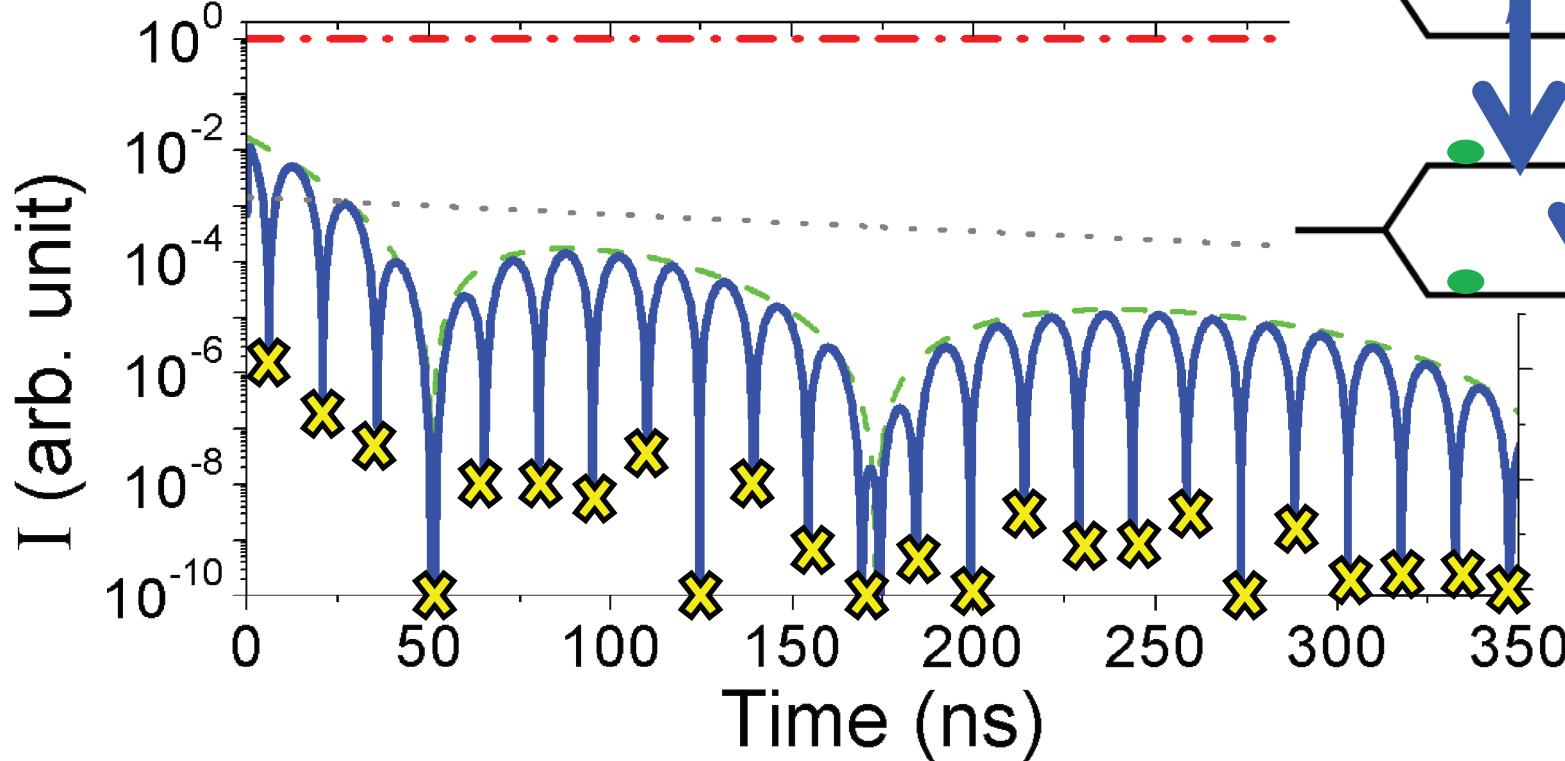
# Coherent Storage-How?



$$\frac{1}{c} \partial_t \Omega + \partial_y \Omega = i\eta (\rho_{31} + \rho_{42})$$



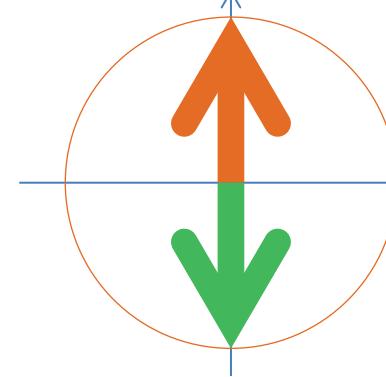
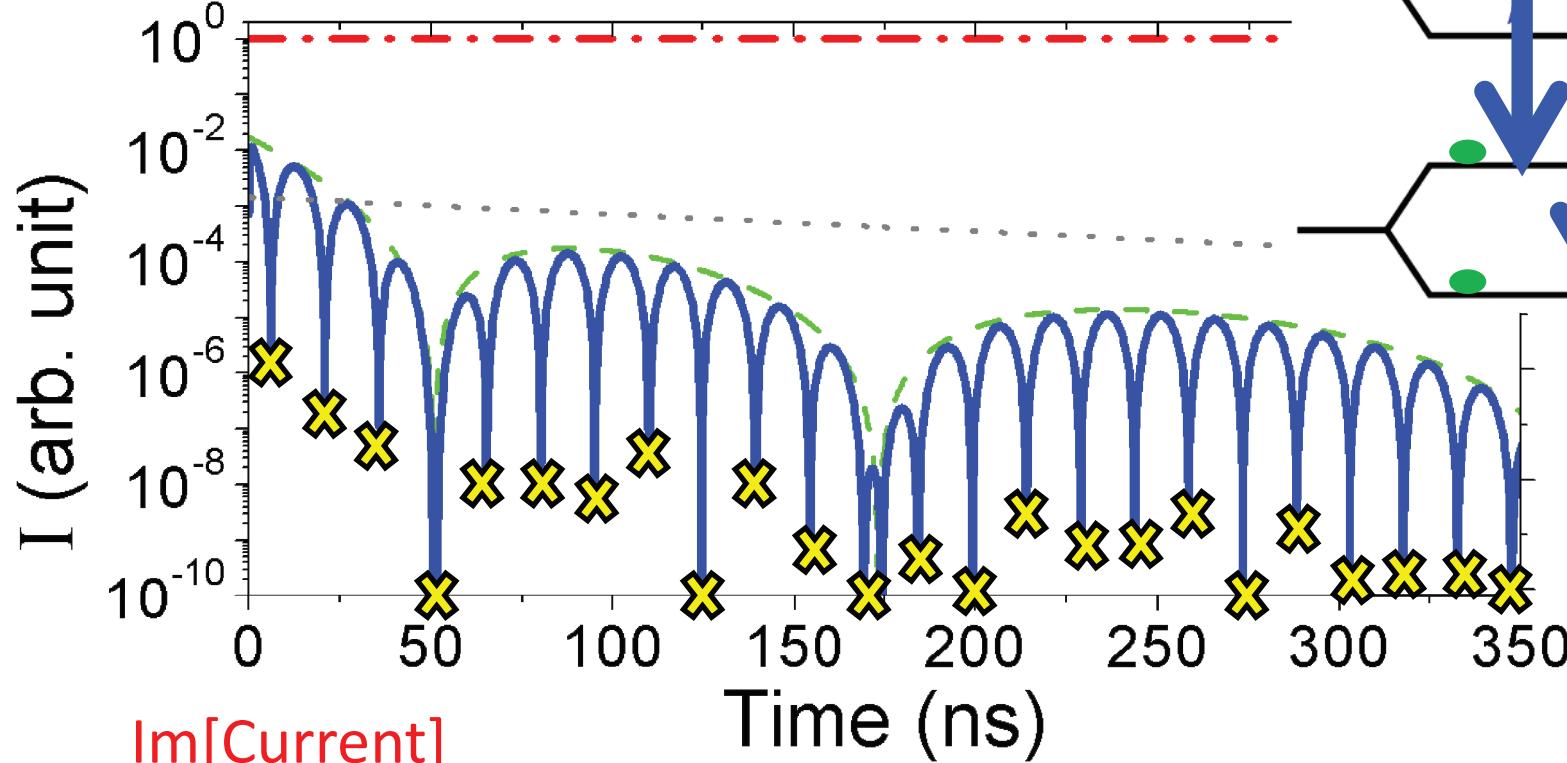
# Coherent Storage-How?



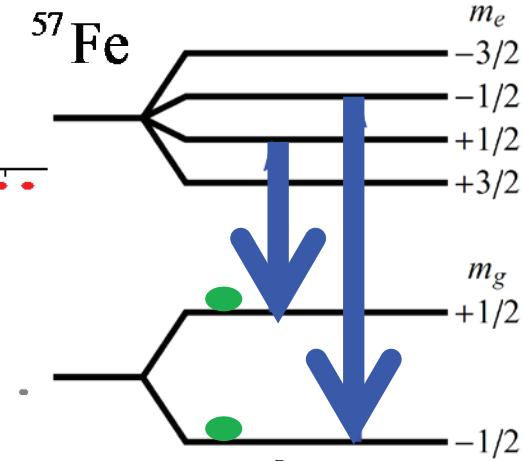
$$\frac{1}{c} \partial_t \Omega + \partial_y \Omega = i\eta (\rho_{31} + \rho_{42})$$



# Coherent Storage-How?

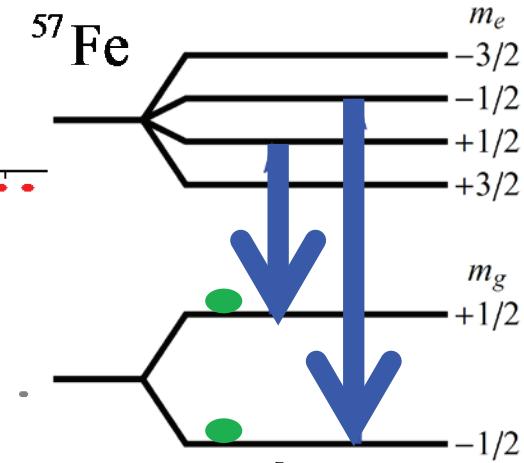
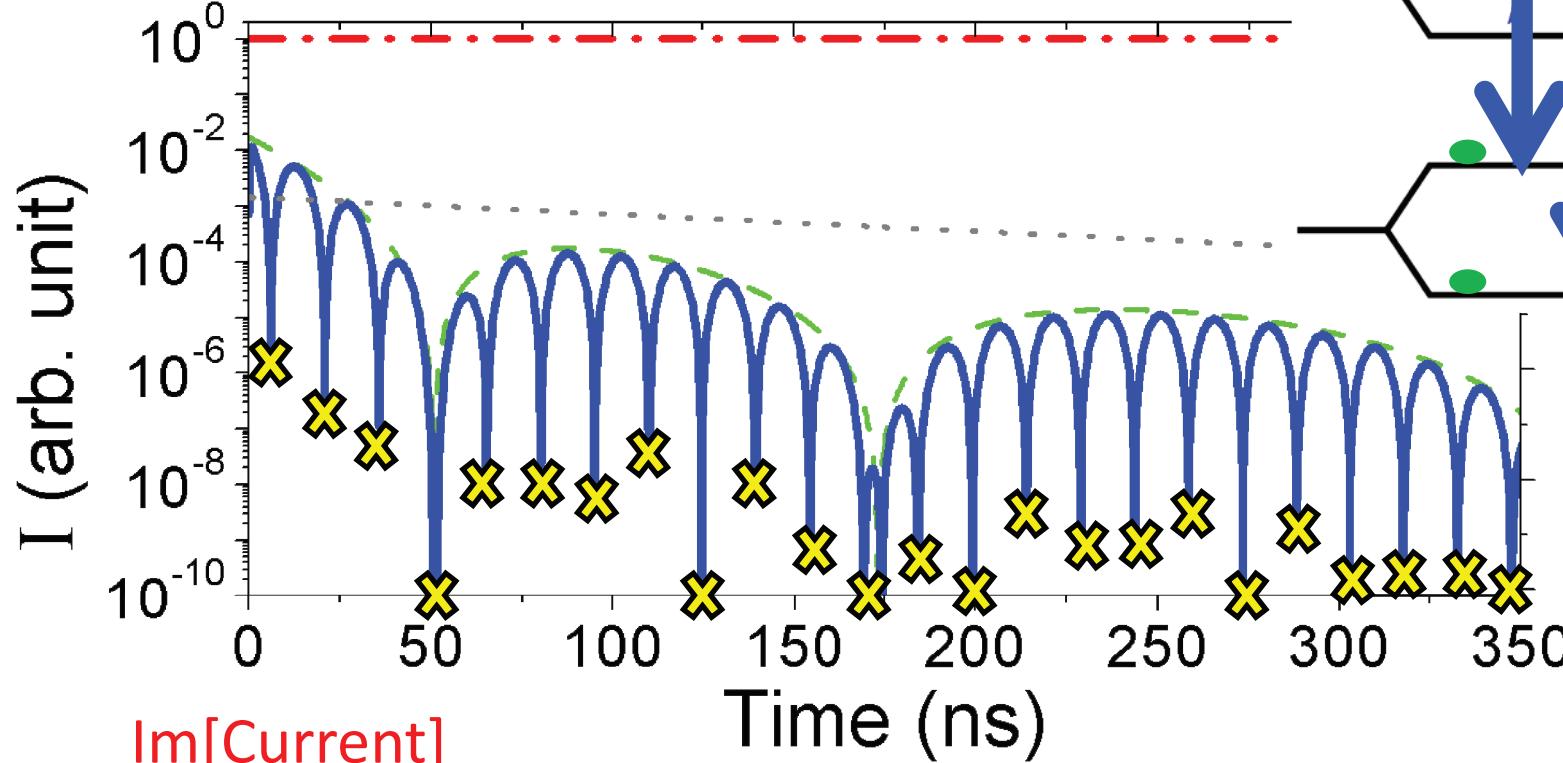


$$\frac{1}{c} \partial_t \Omega + \partial_y \Omega = i\eta (\rho_{31} + \rho_{42})$$

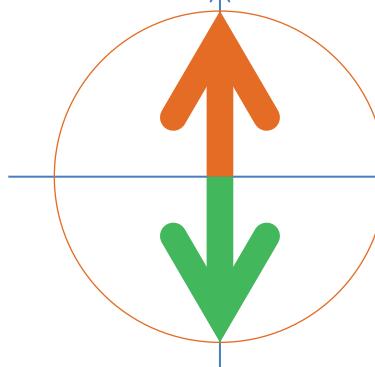




# Coherent Storage-How?



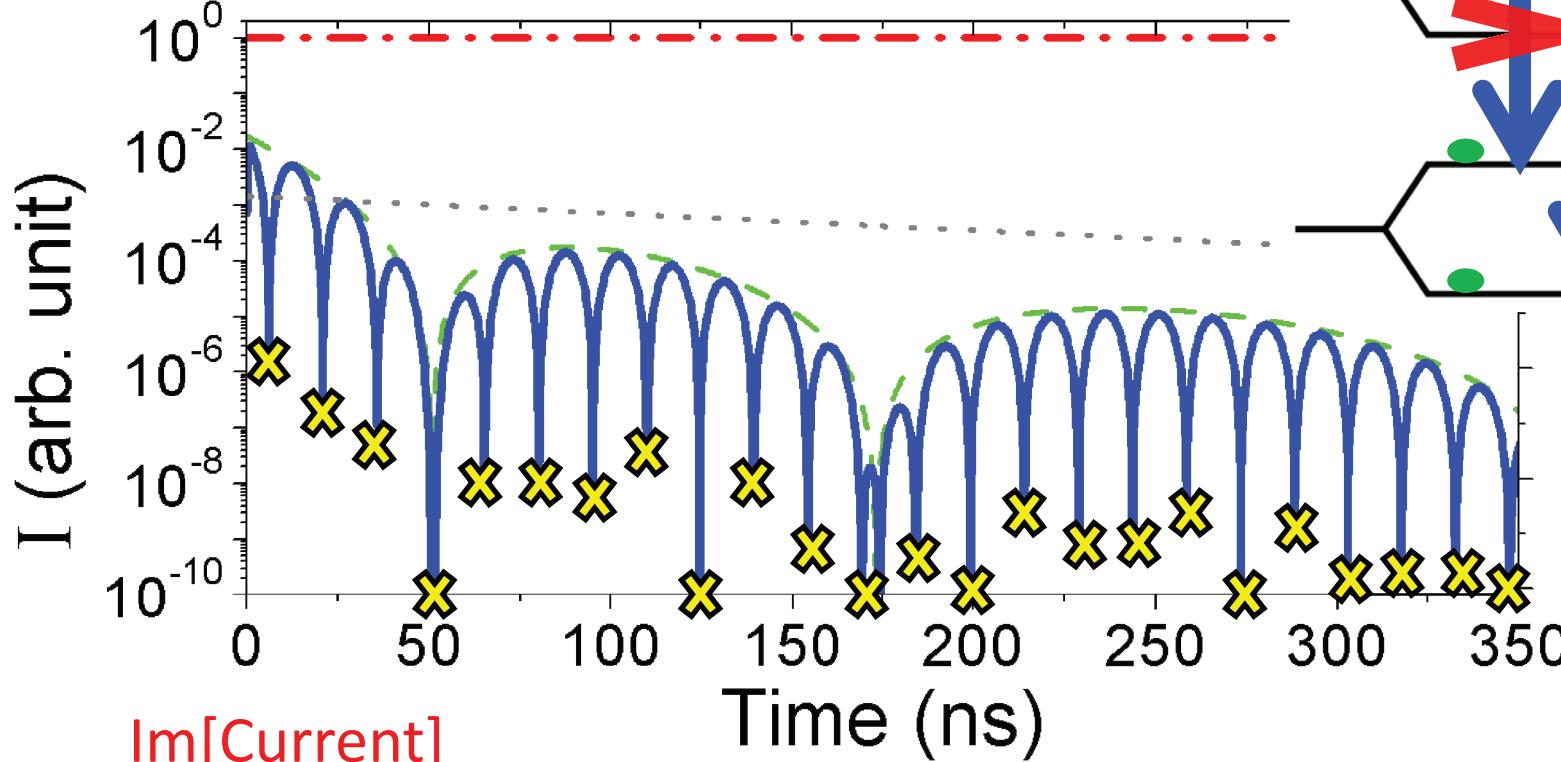
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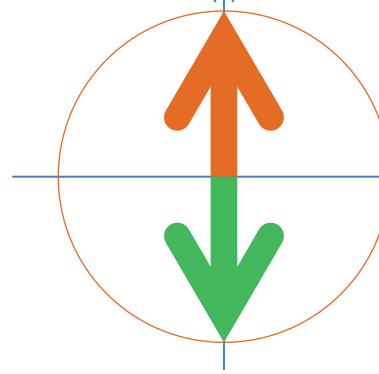
Re[Current]

$$\frac{1}{c} \partial_t \Omega + \partial_y \Omega = i\eta (\rho_{31} + \rho_{42})$$

# Coherent Storage-How?

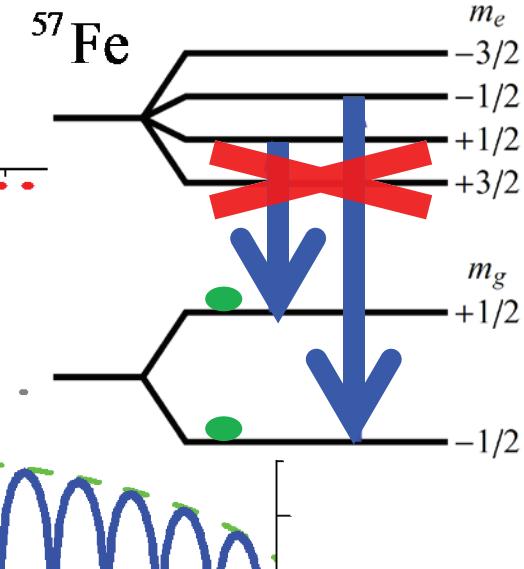


Im[Current]



Re[Current]

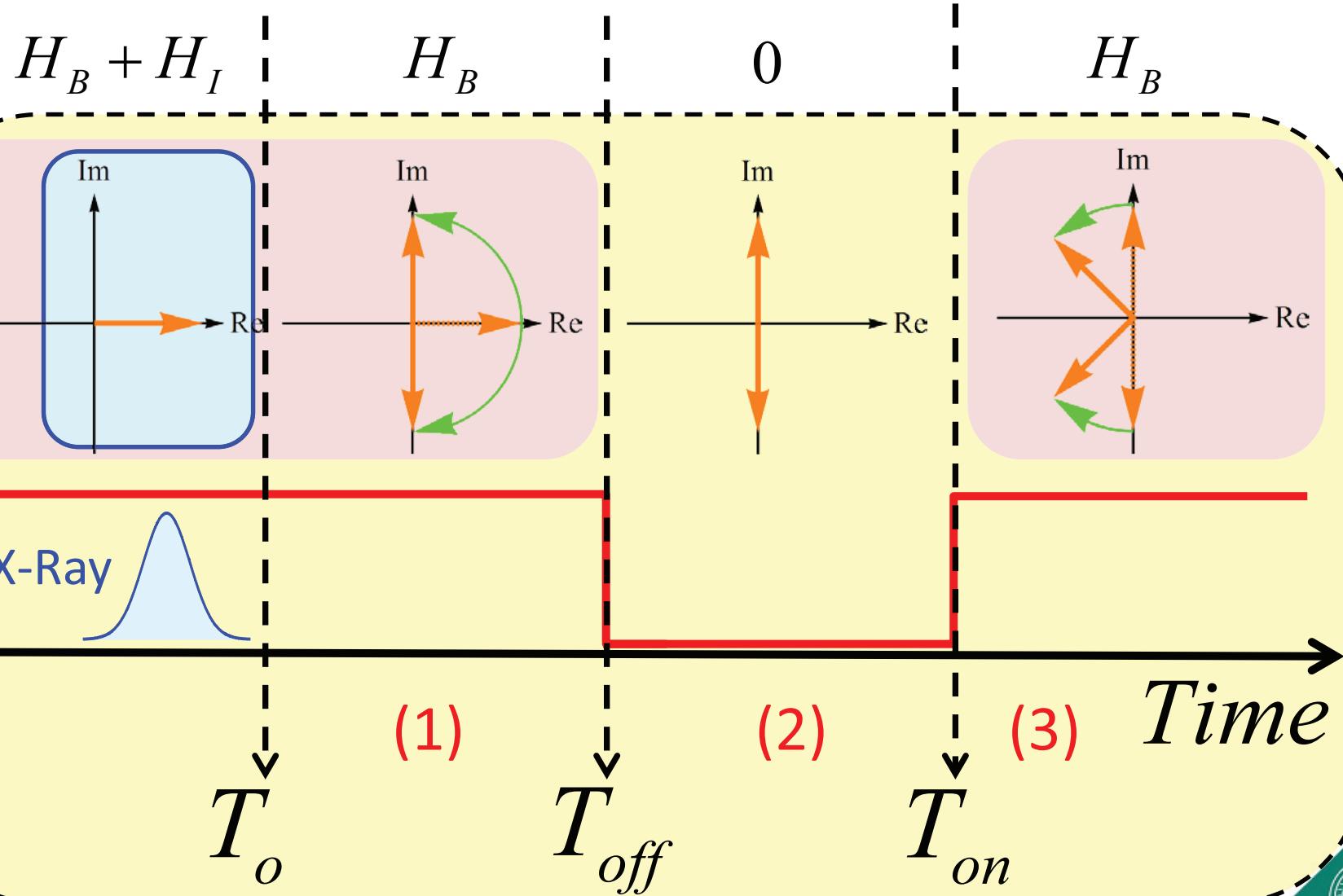
$$\frac{1}{c} \partial_t \Omega + \partial_y \Omega = i\eta (\rho_{31} + \rho_{42})$$





# Coherent Storage-How?

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

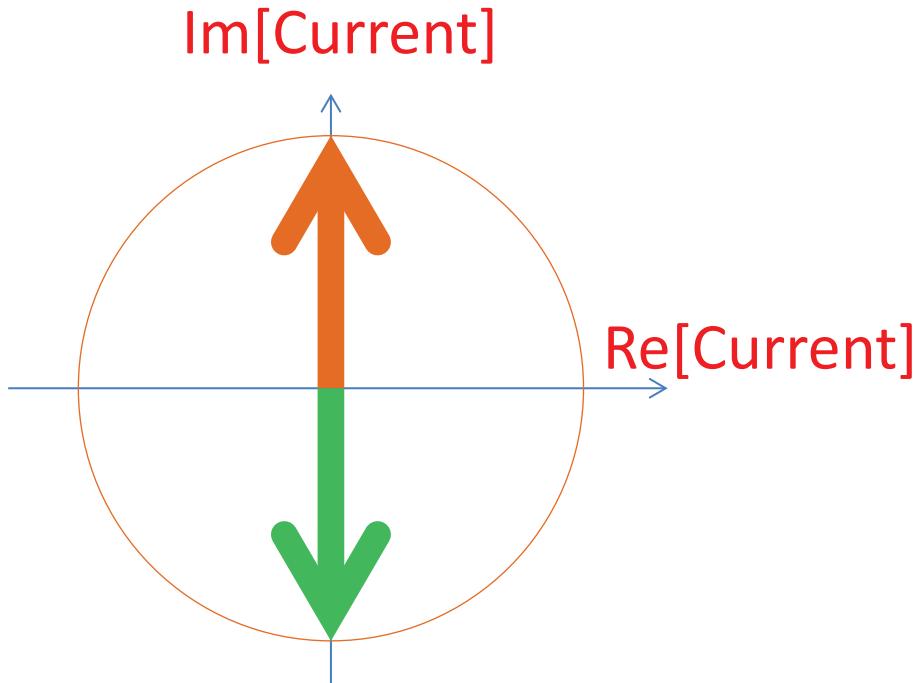


MAX-PLANCK-GESSELLSCHAFT

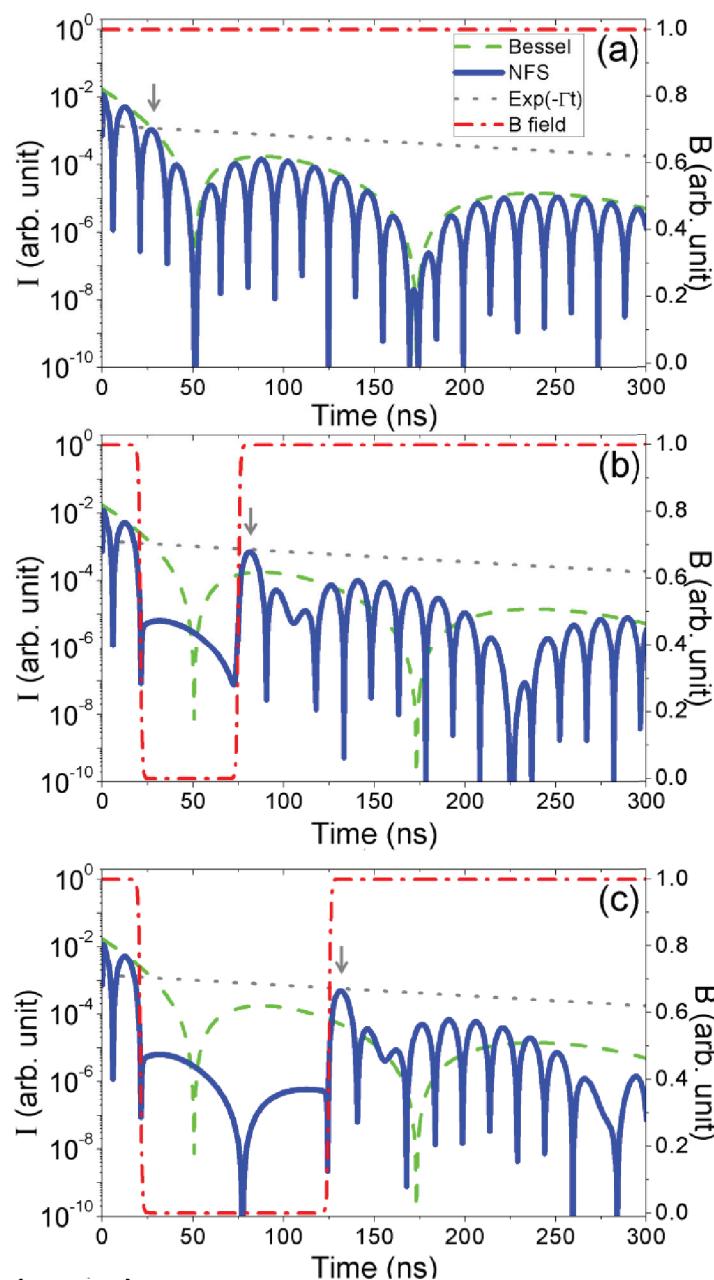


# Coherent Storage

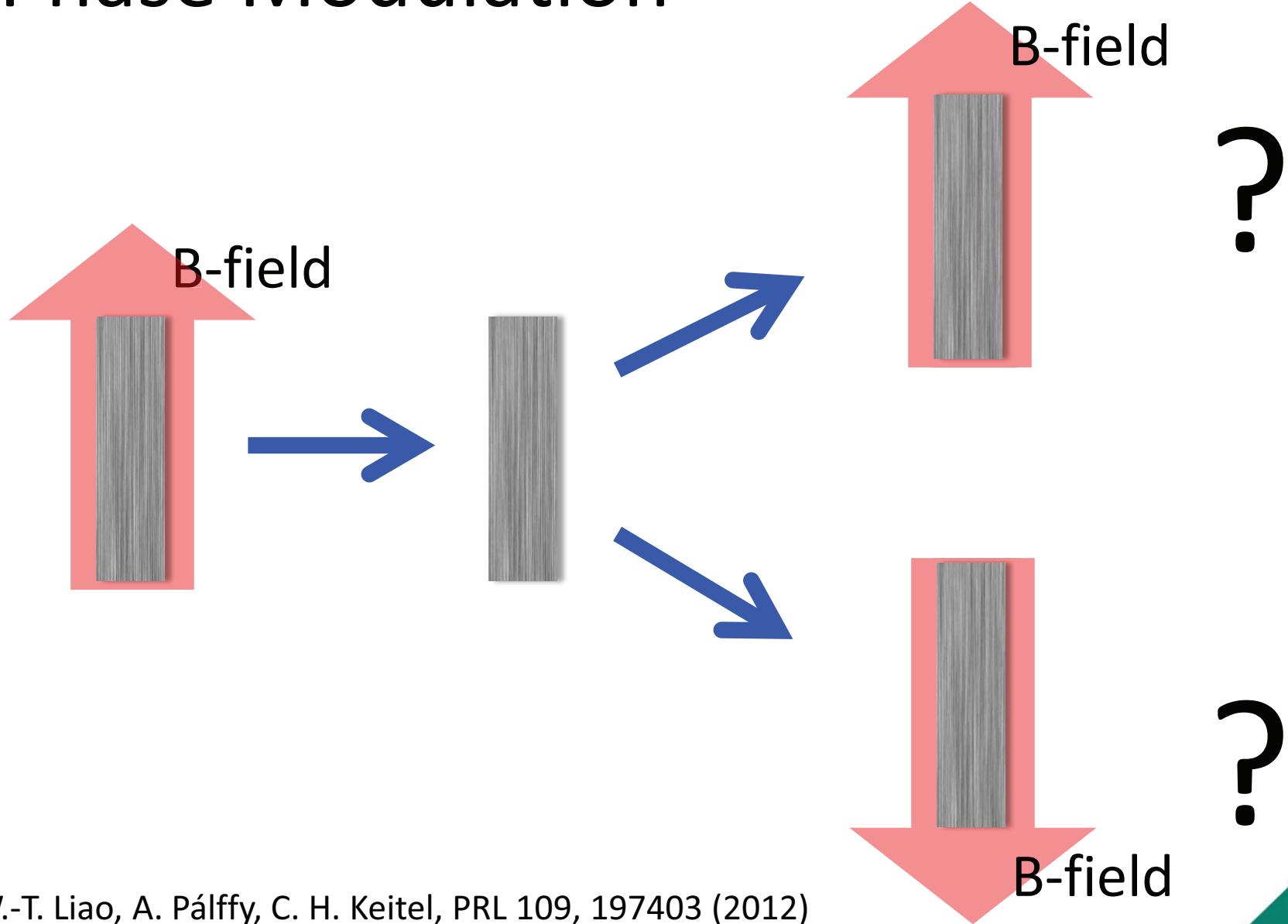
Phase and Polarization  
are Conserved!



W.-T. Liao, A. Pálffy, C. H. Keitel, PRL 109, 197403 (2012)



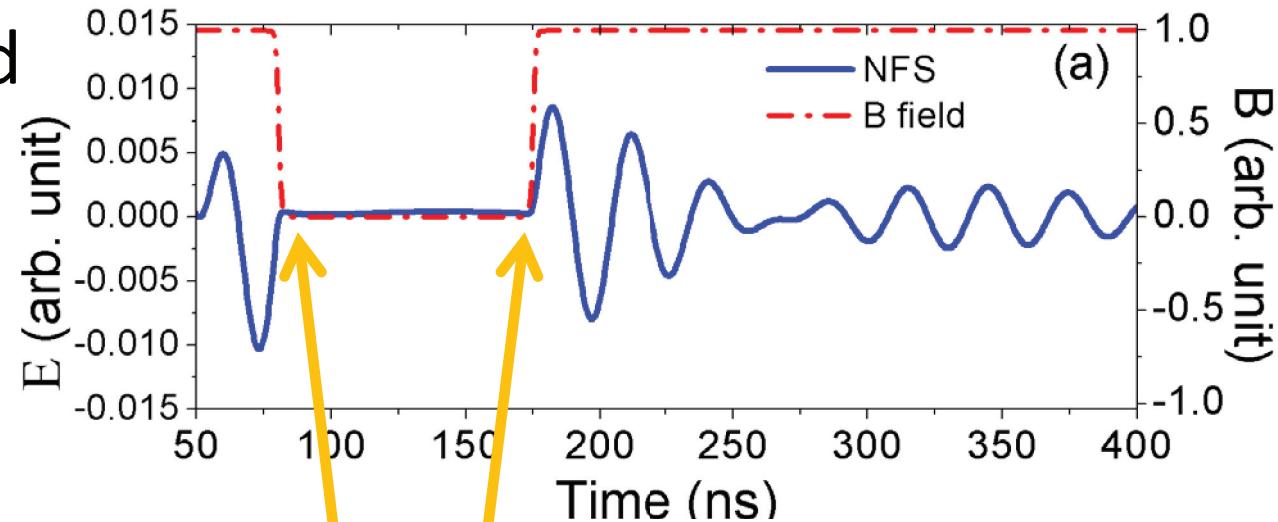
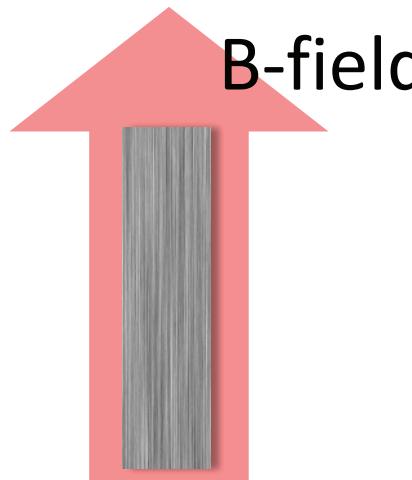
# Phase Modulation



W.-T. Liao, A. Pálffy, C. H. Keitel, PRL 109, 197403 (2012)



# Phase Modulation

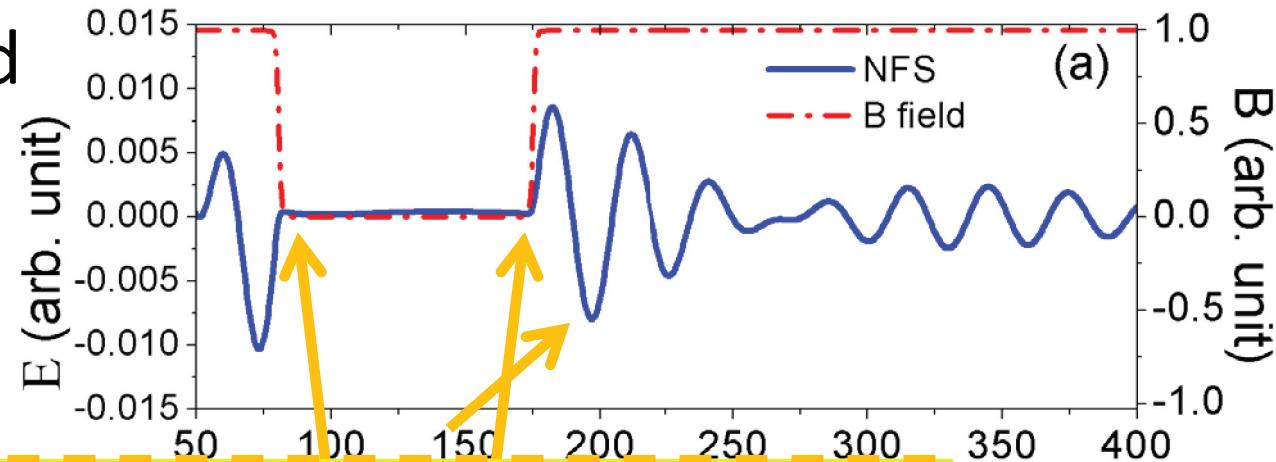
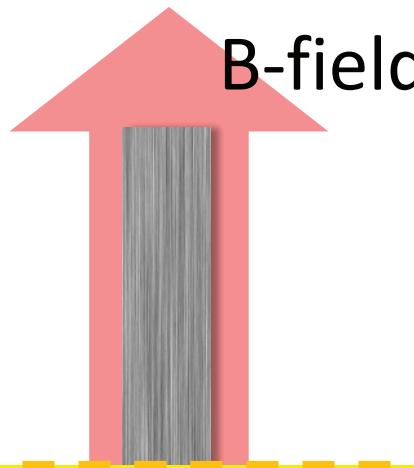


Phase is Conserved!

W.-T. Liao, A. Pálffy, C. H. Keitel, PRL 109, 197403 (2012)  
Yu. Shvyd'ko, et. al, PRB. 52, R711 (1995)



# Phase Modulation



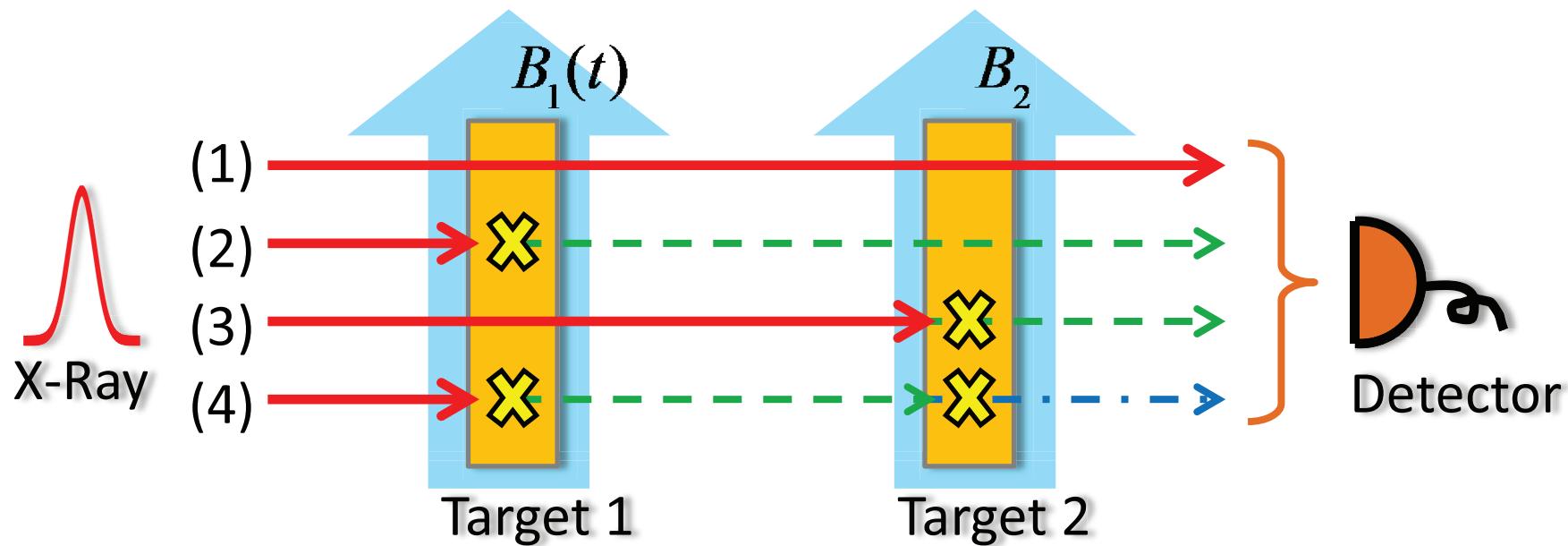
Phase is  $\pi$  modulated by *time reversal*!

Phase is Conserved!

W.-T. Liao, A. Pálffy, C. H. Keitel, PRL 109, 197403 (2012)  
Yu. Shvyd'ko, et. al, PRB. 52, R711 (1995)

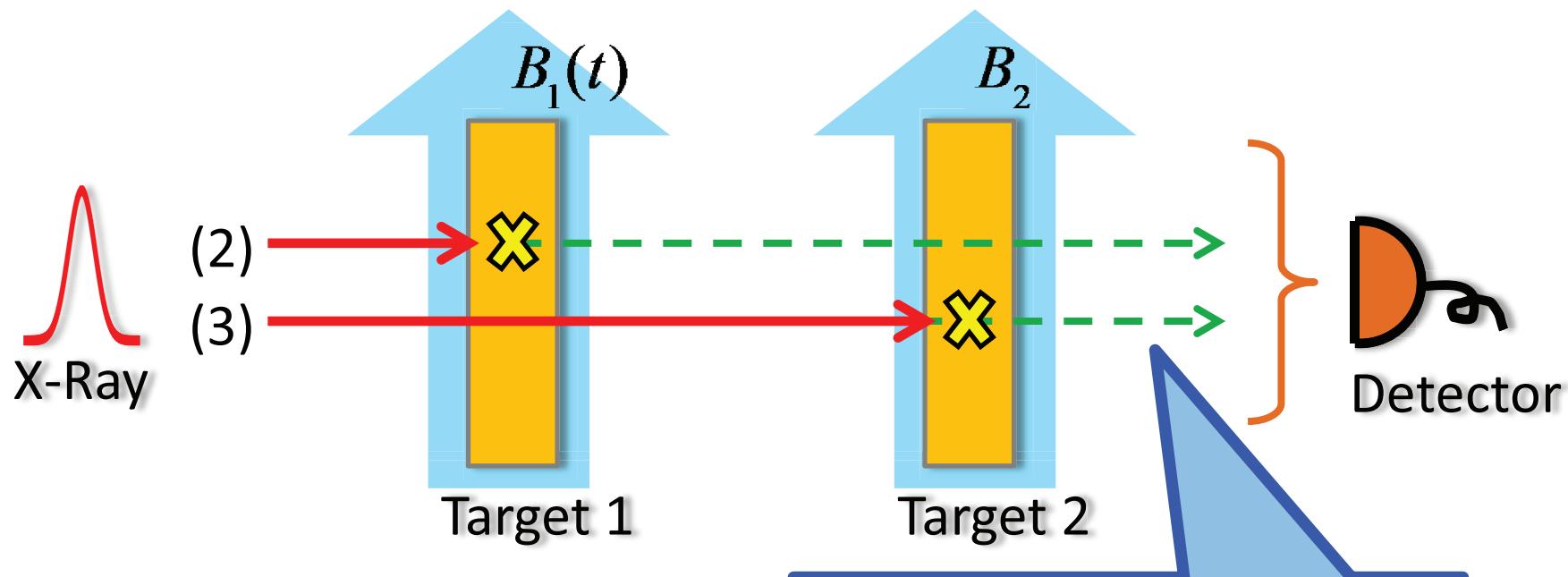


# How to Measure the Phase?



- W.-T. Liao, A. Pálffy, C. H. Keitel, PRL 109, 197403 (2012)  
G. V. Smirnov, et. al., PRA. 71, 023804 (2005)  
G. V. Smirnov, et. al., PRL. 77, 183 (1996)  
R. Röhlsberger, Book, Springer-Verlag (2004)

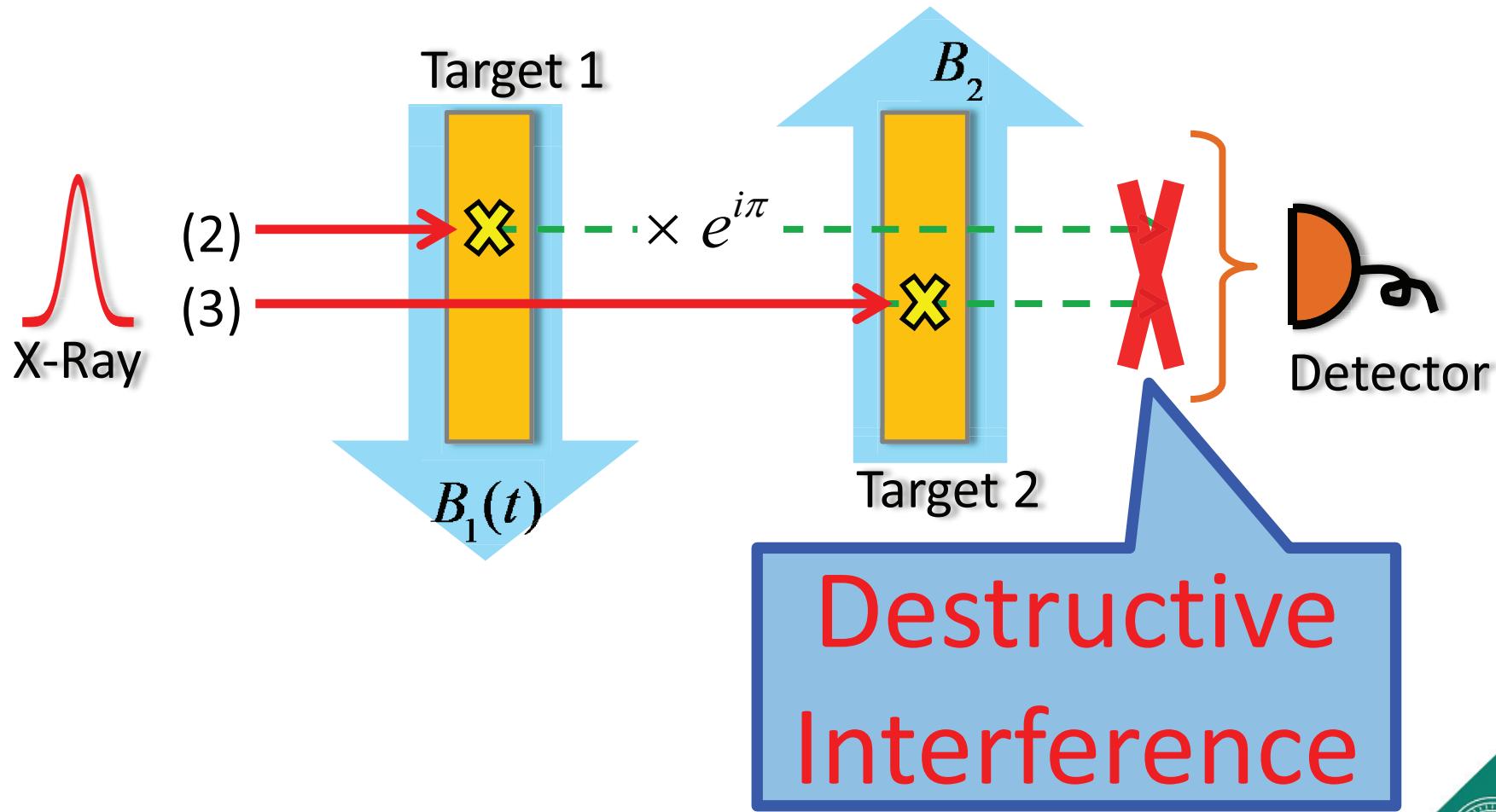
# How to Measure the Phase?



Constructive  
Interference



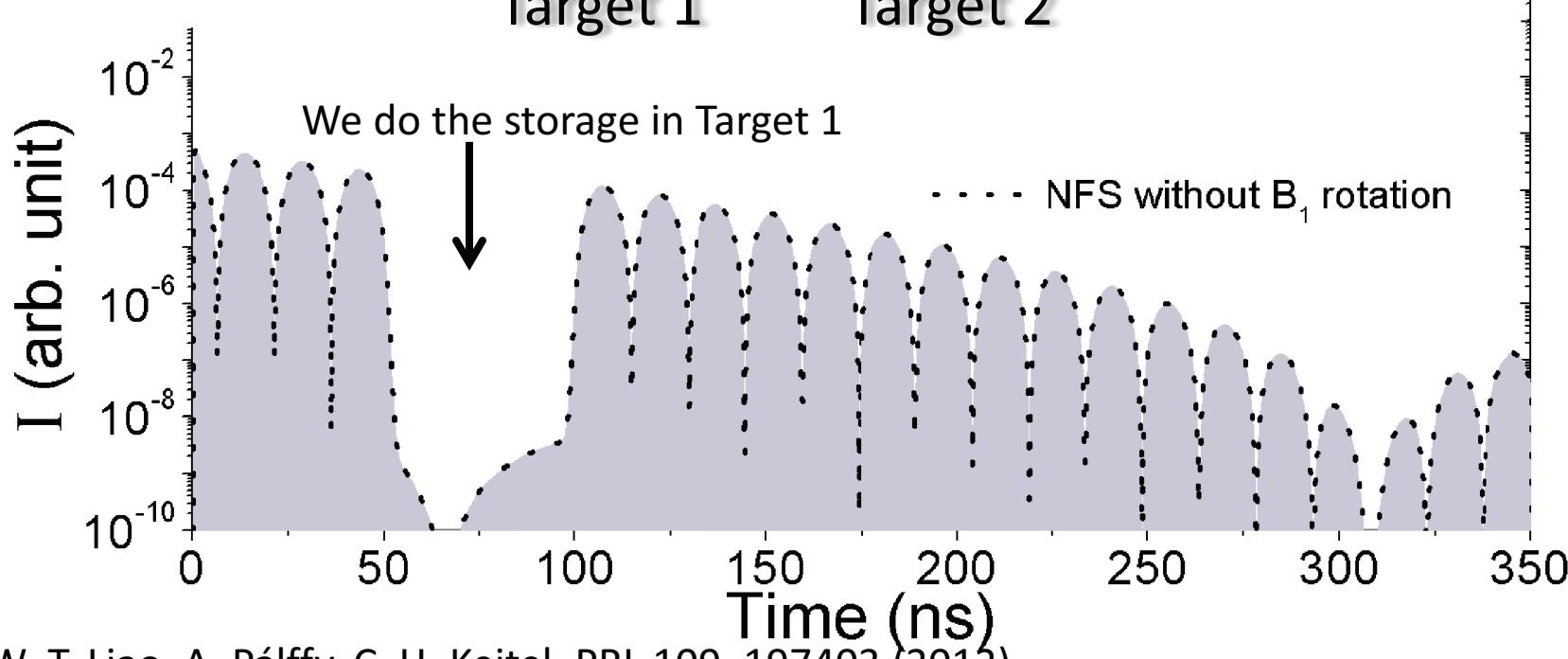
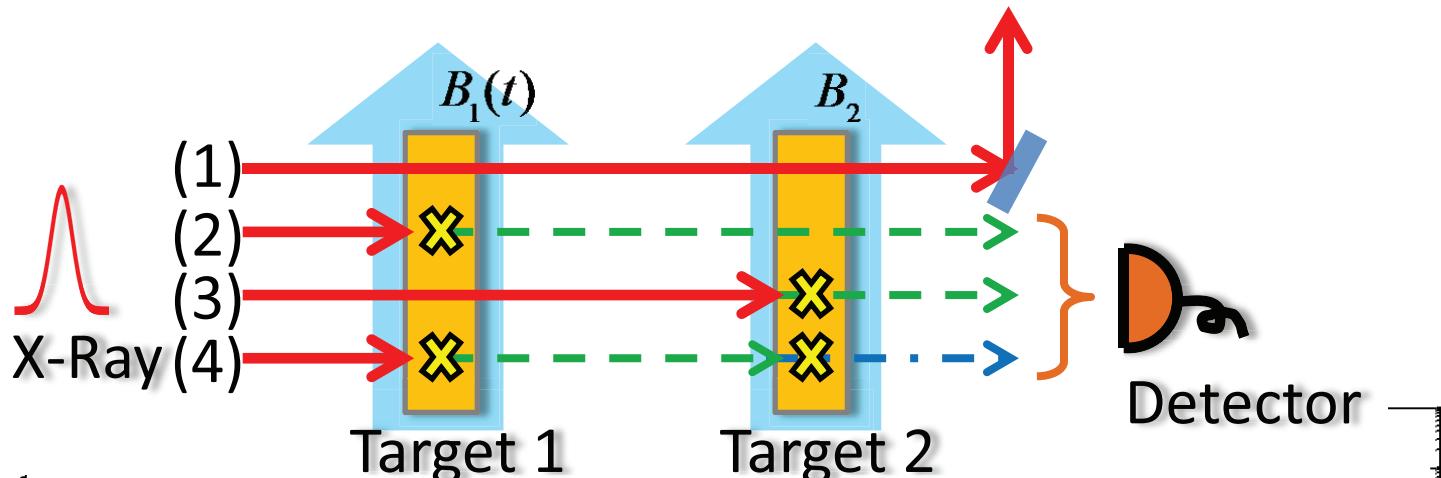
# How to Measure the Phase?



W.-T. Liao, A. Pálffy, C. H. Keitel, PRL 109, 197403 (2012)

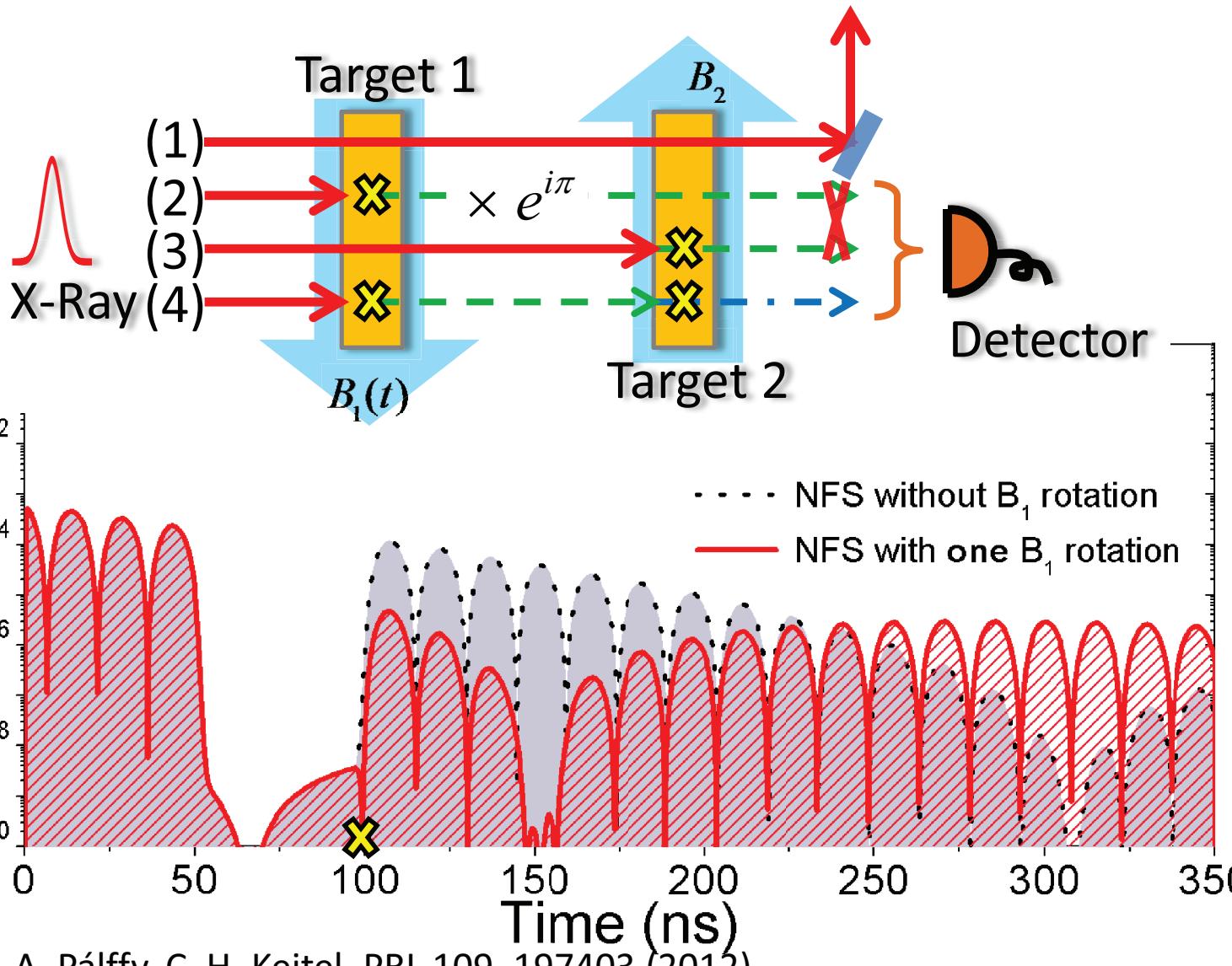


# How to Measure the Phase?

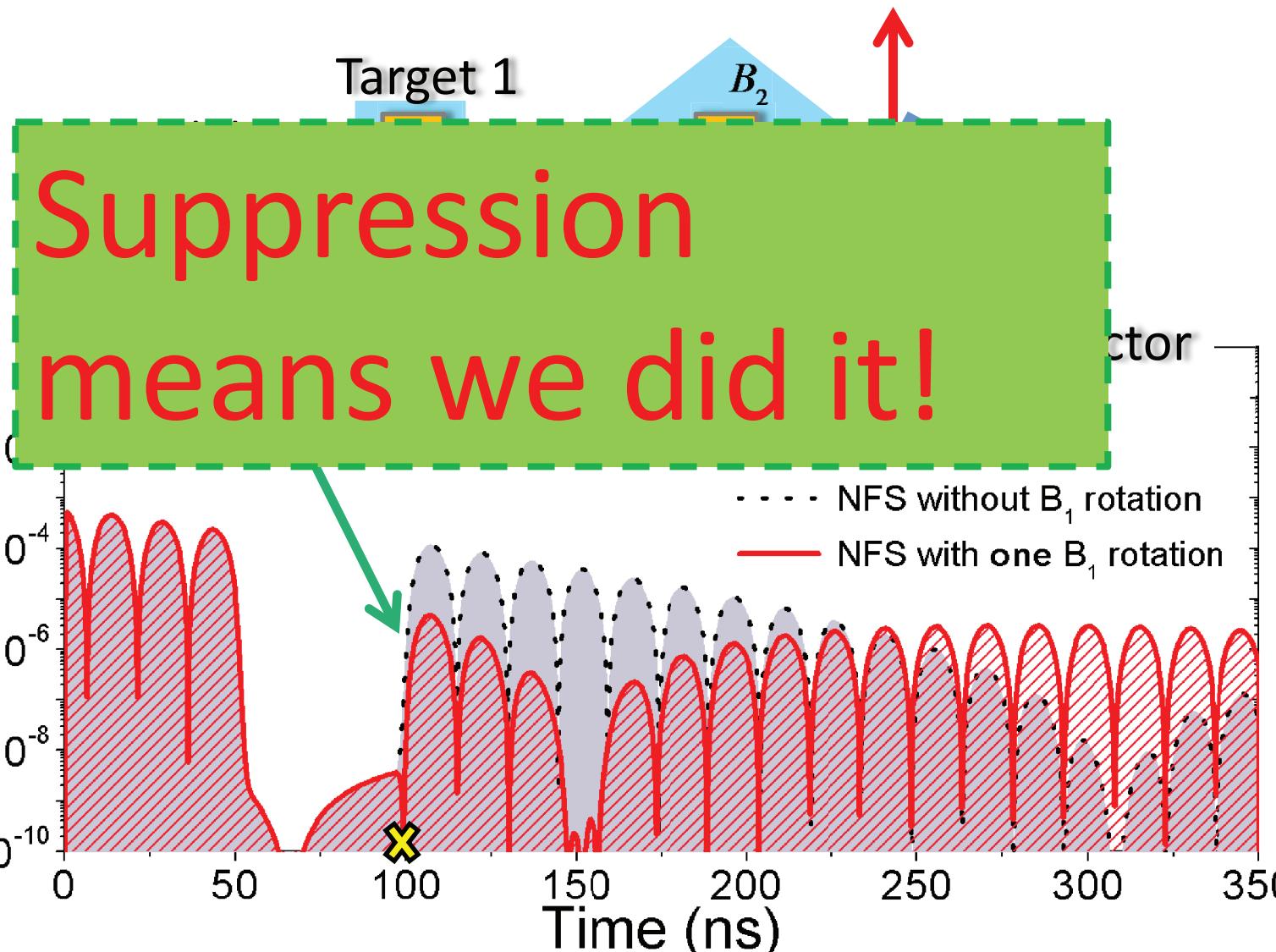




# How to Measure the Phase?

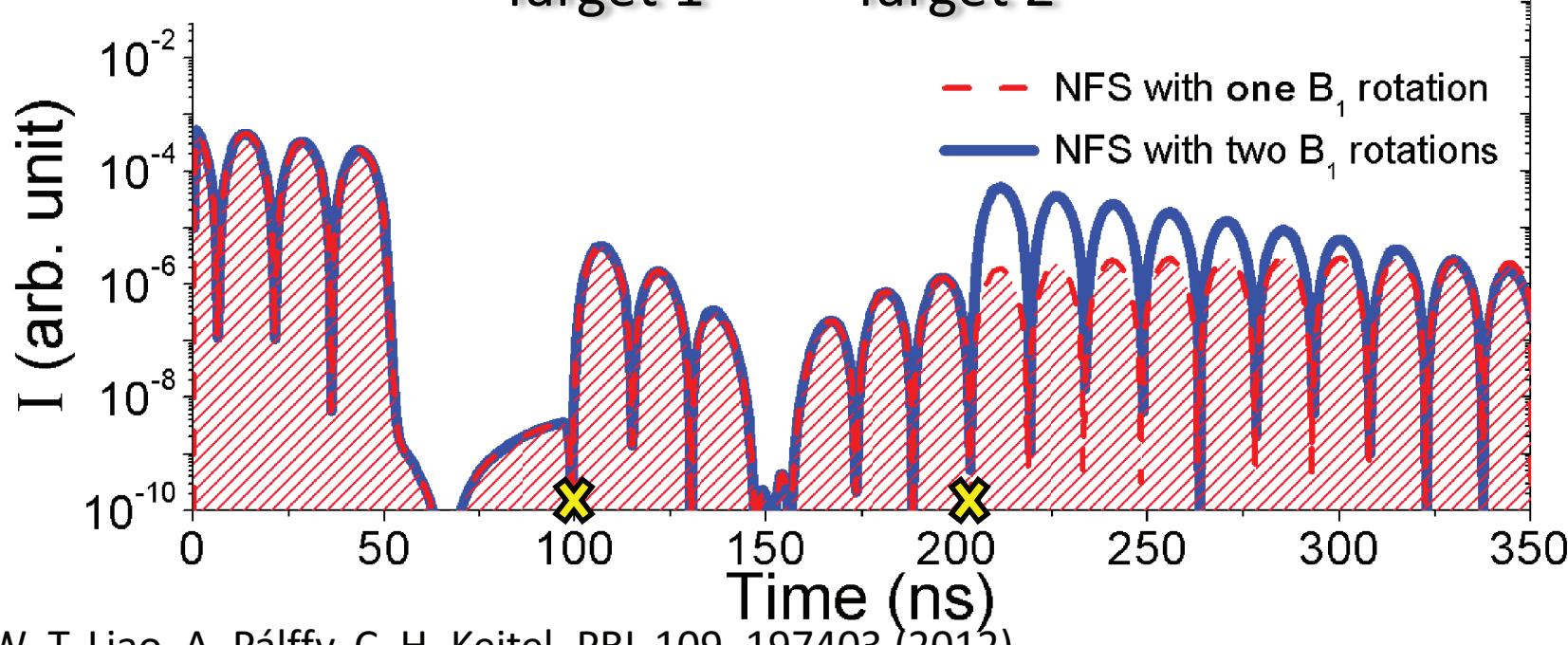
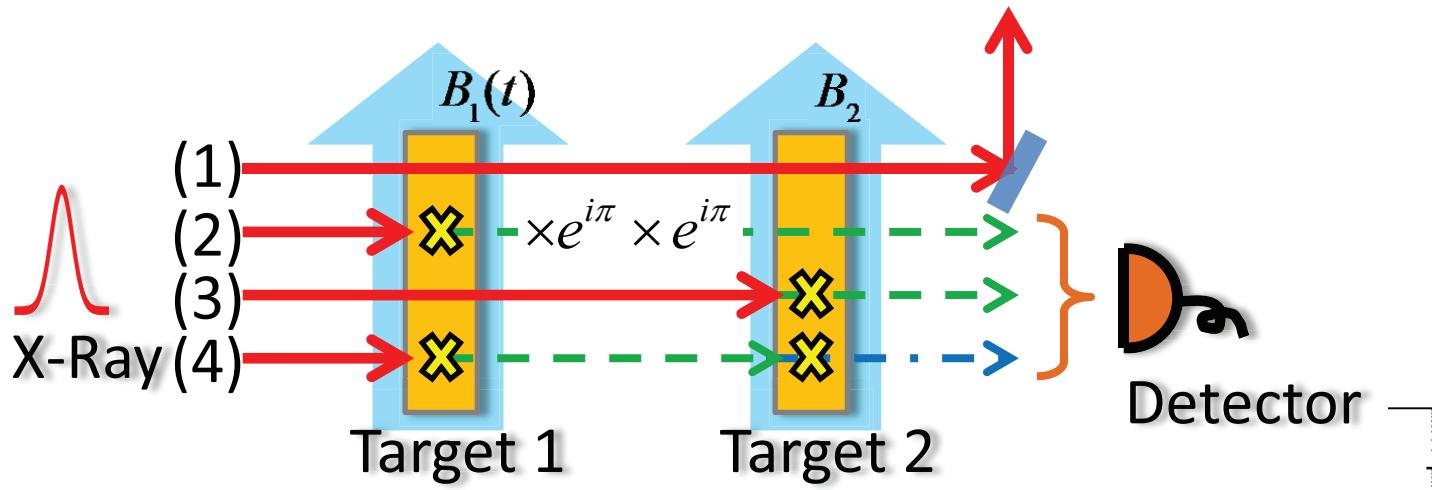


# How to Measure the Phase?



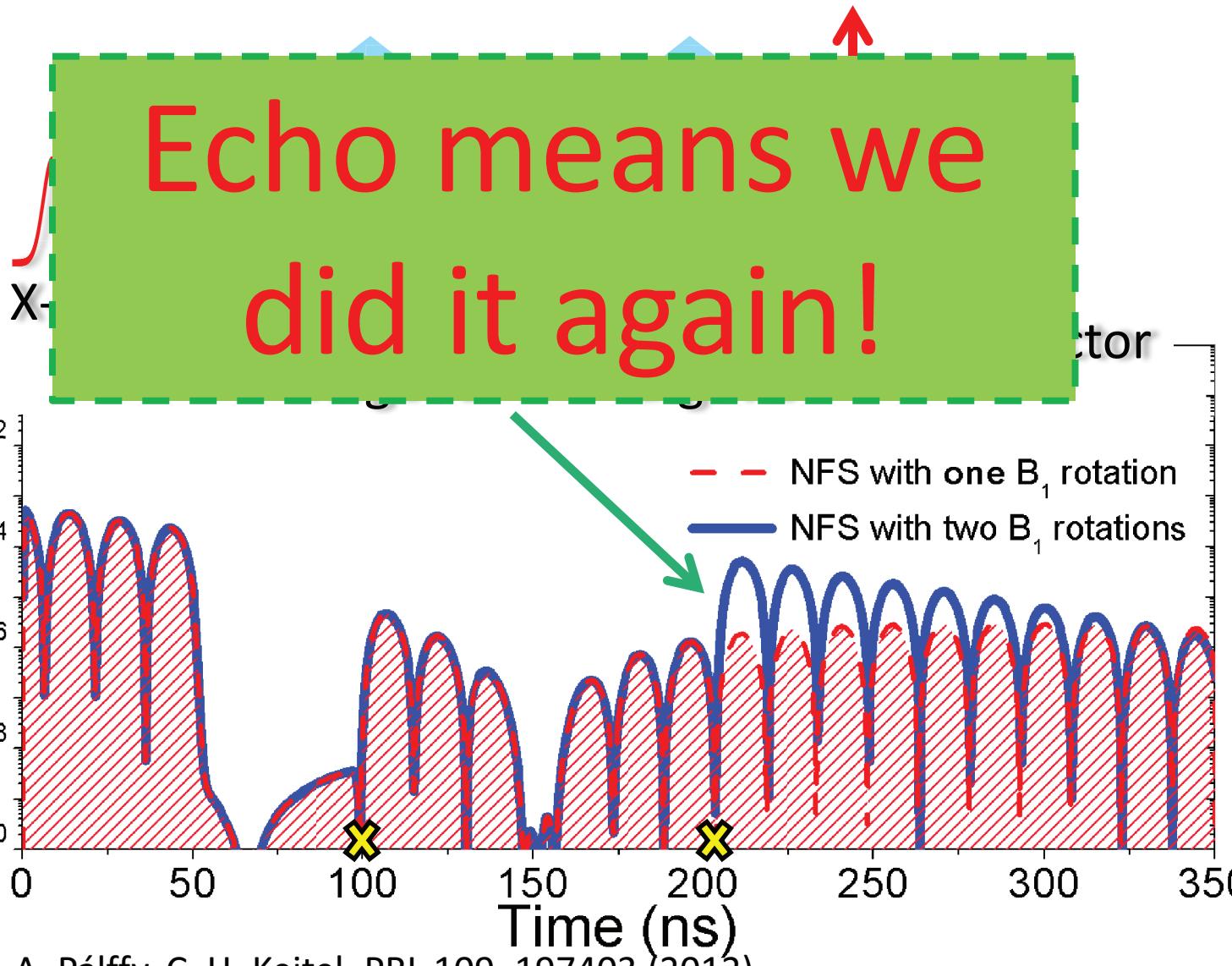


# How to Measure the Phase?





# How to Measure the Phase?

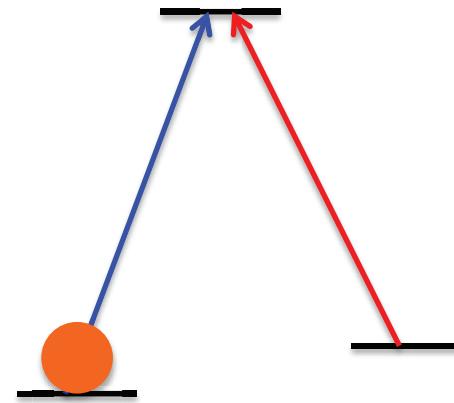




# Nuclear STIRAP

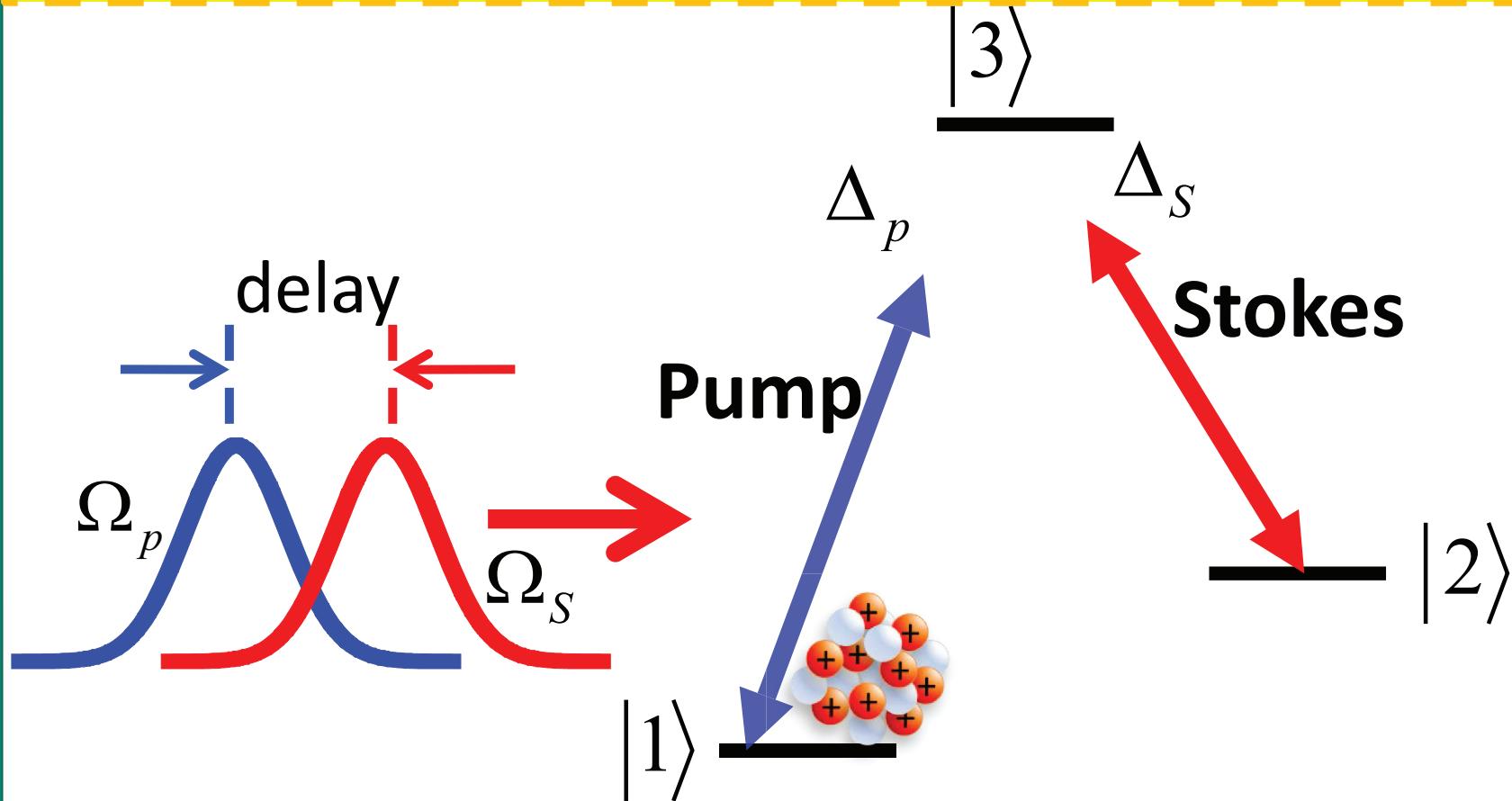
W.-T. Liao, A. Pálffy, C. H. Keitel, Phys. Lett. B 705, 134 (2011).

W.-T. Liao, A. Pálffy, C. H. Keitel, Phys. Rev. C 87, 054609 (2013).



# STIRAP

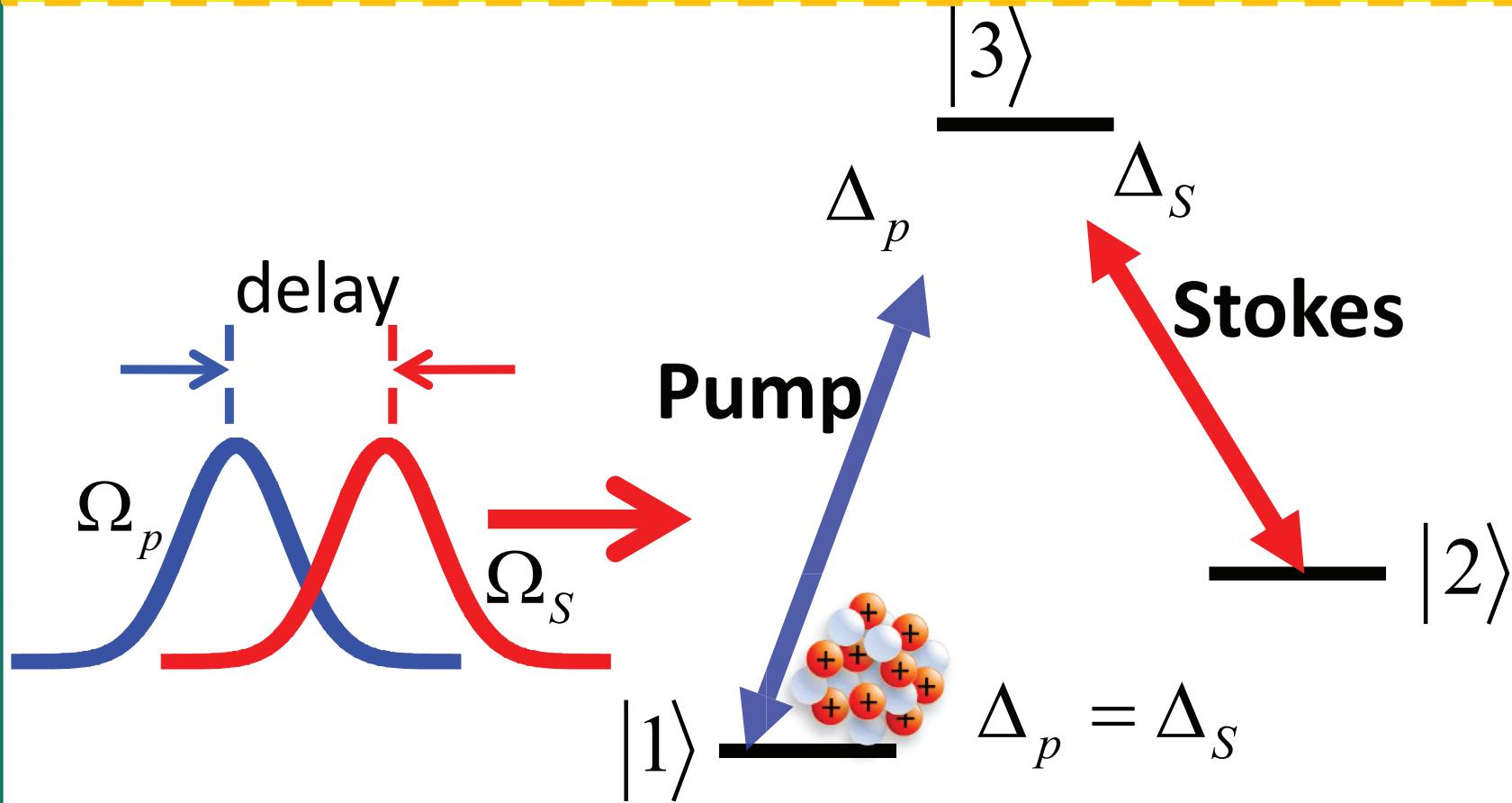
stimulated Raman adiabatic passage (STIRAP)



K. Bergmann, H. Theuer and B. W. Shore, RMP. 70, 1003 (1998).

# STIRAP

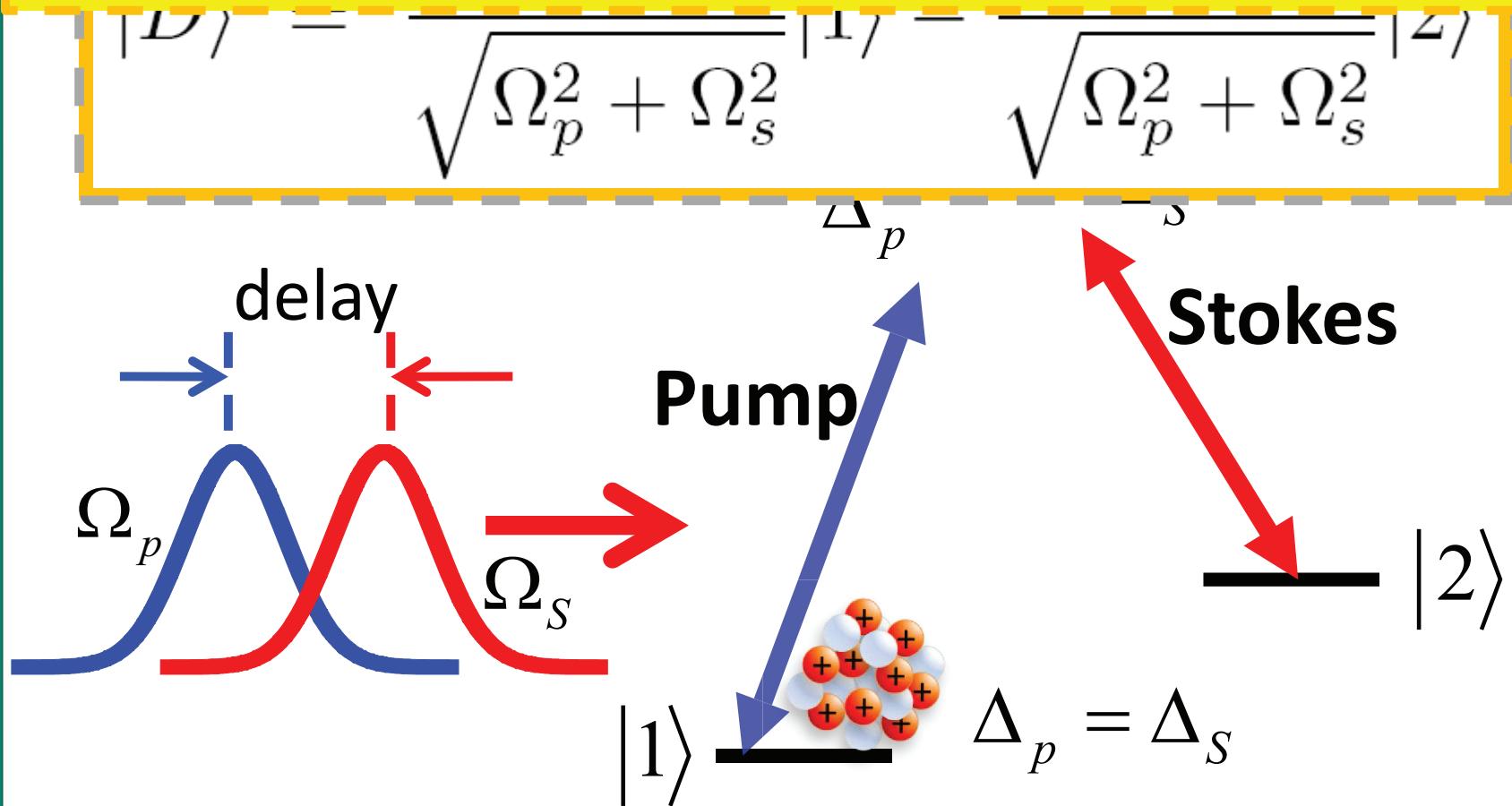
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# STIRAP

stimulated Raman adiabatic passage (STIRAP)

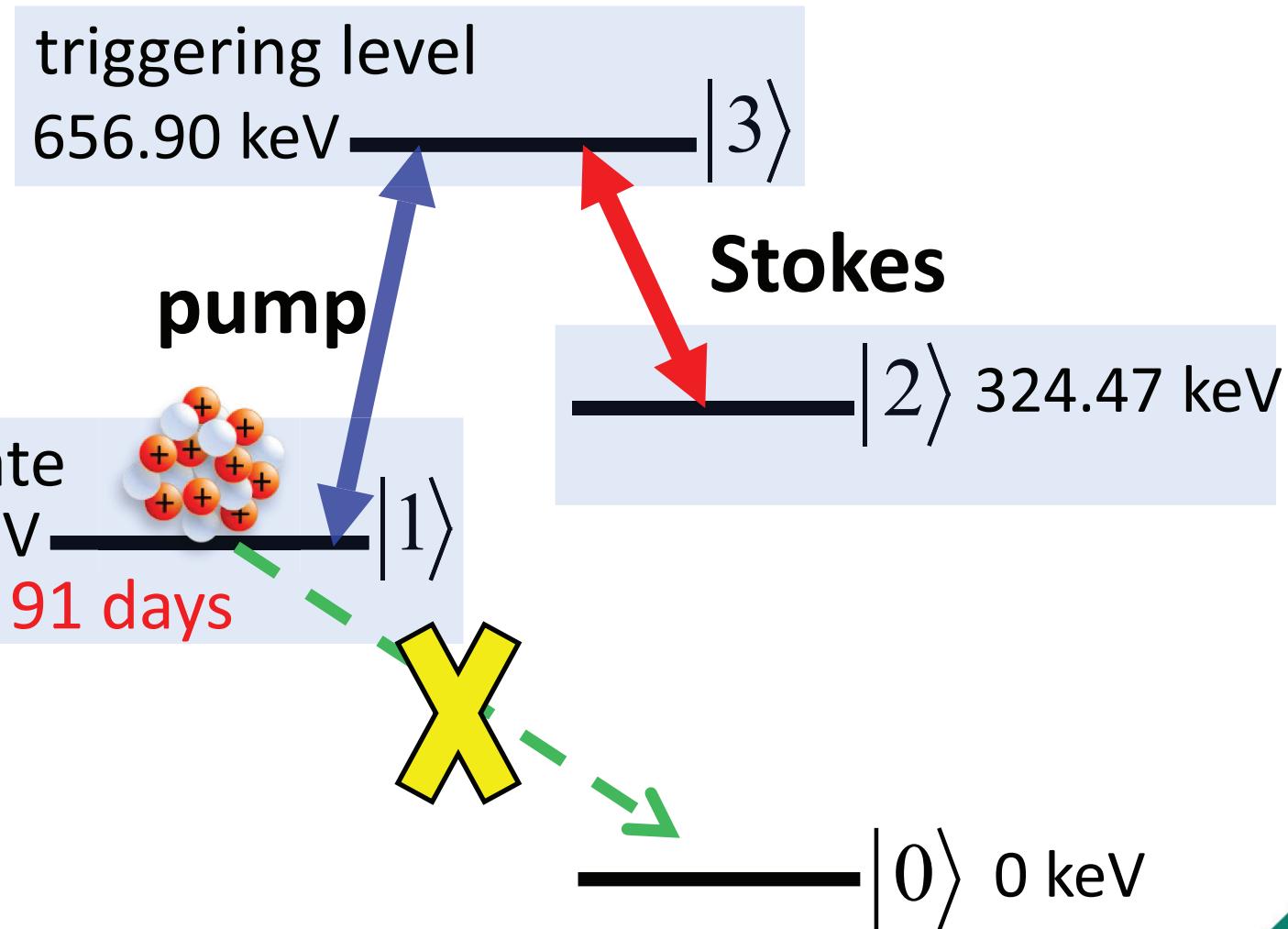


K. Bergmann, H. Theuer and B. W. Shore, RMP. 70, 1003 (1998).



# Motivation-Isomer Triggering

$^{97}\text{Tc}$

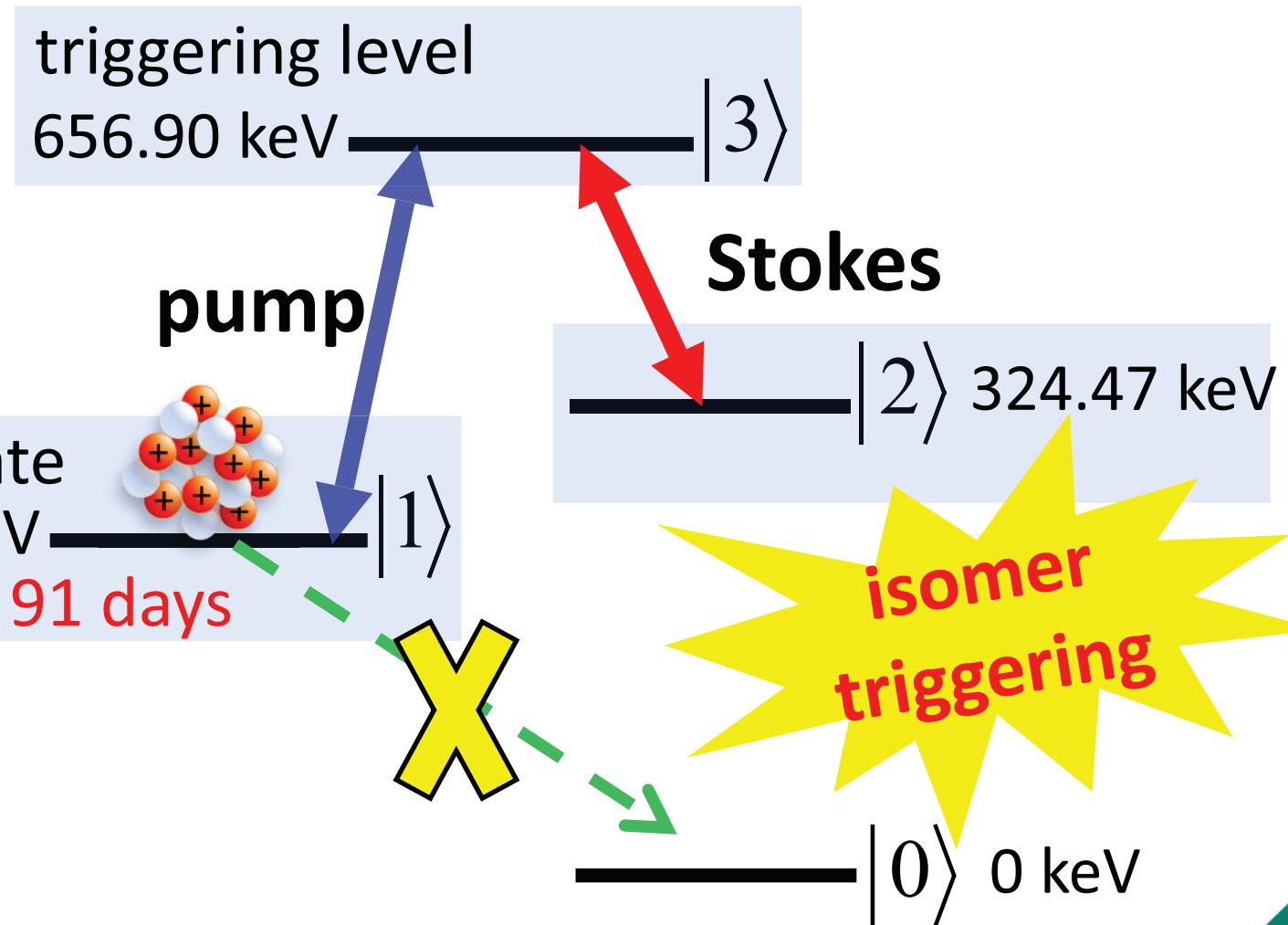


Nuclear Coherent Population Transfer (NCPT)



# Motivation-Isomer Triggering

$^{97}\text{Tc}$

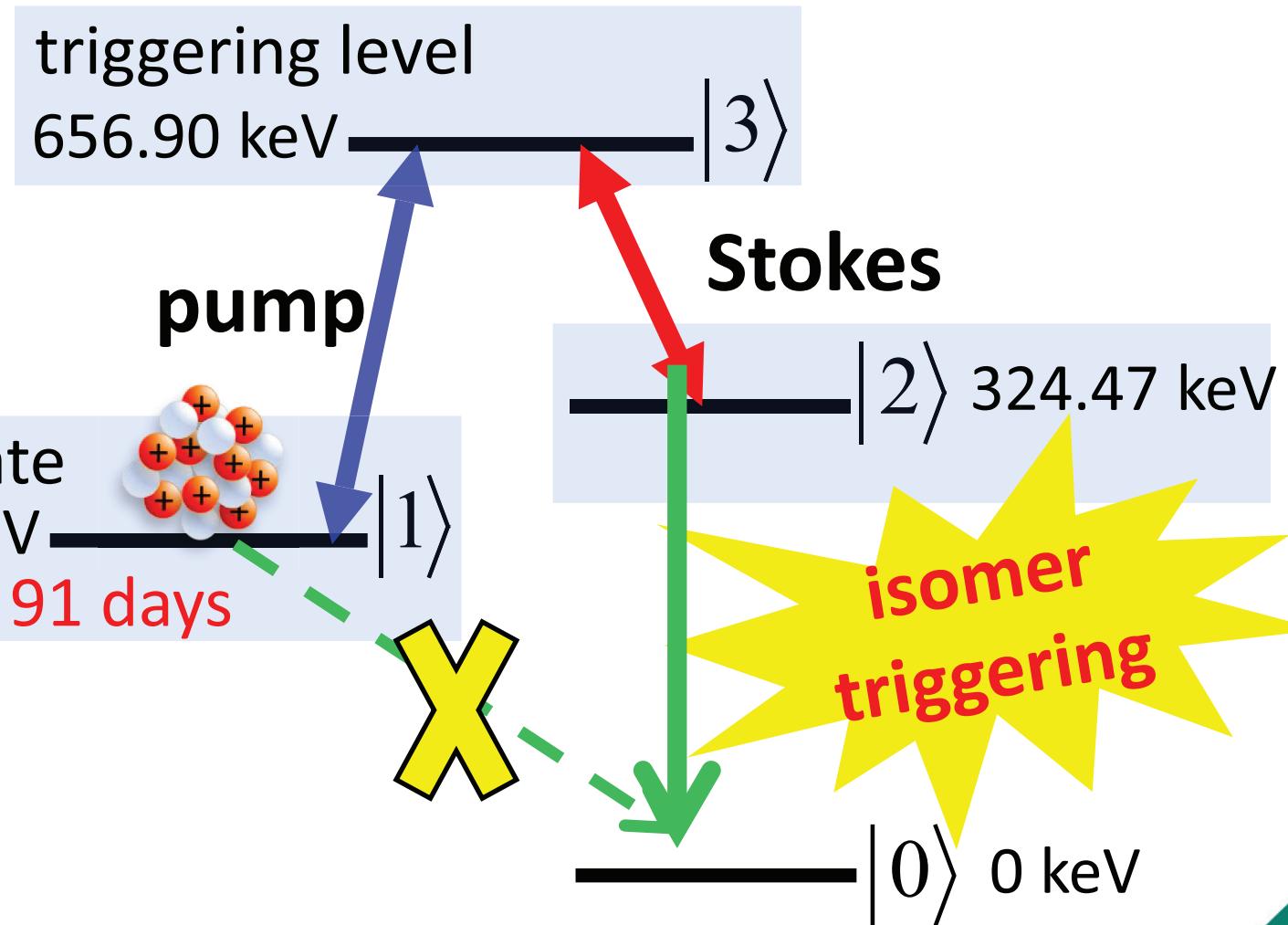


Nuclear Coherent Population Transfer (NCPT)



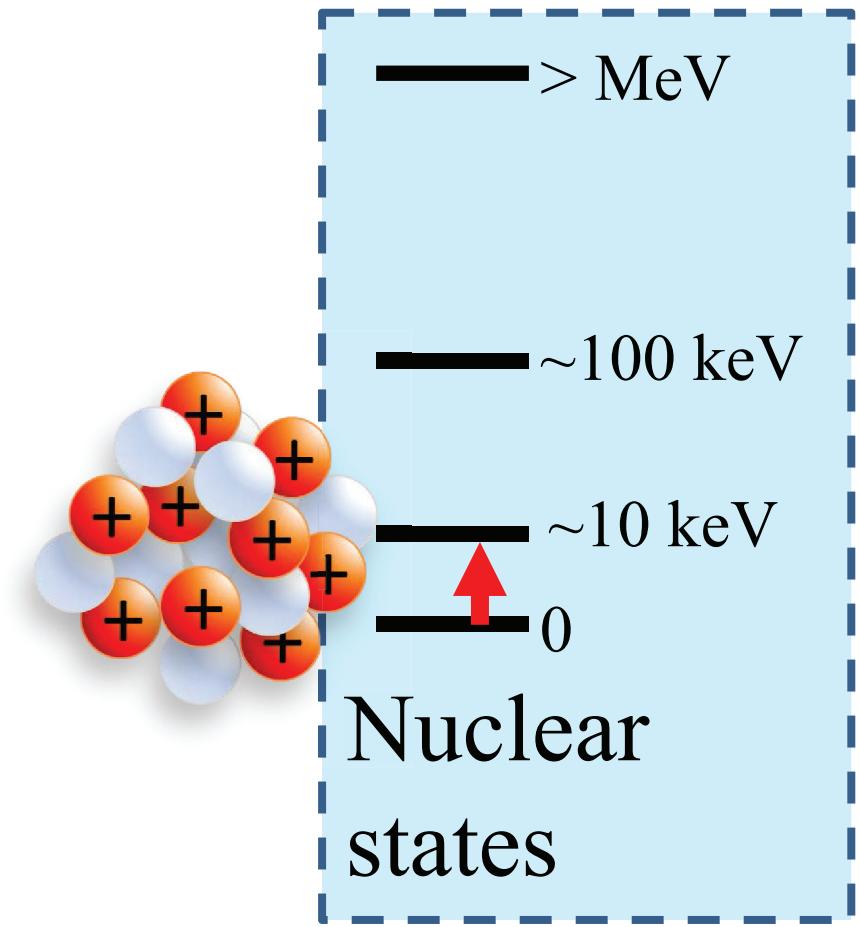
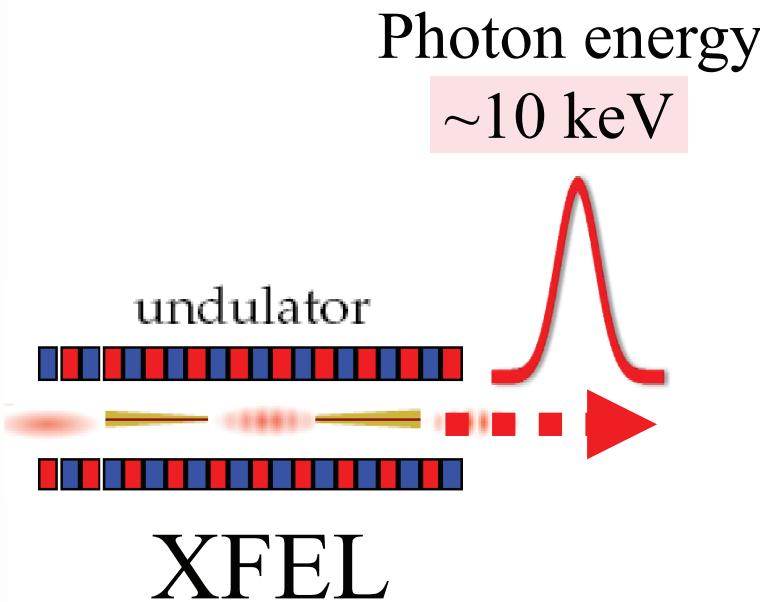
# Motivation-Isomer Triggering

$^{97}\text{Tc}$



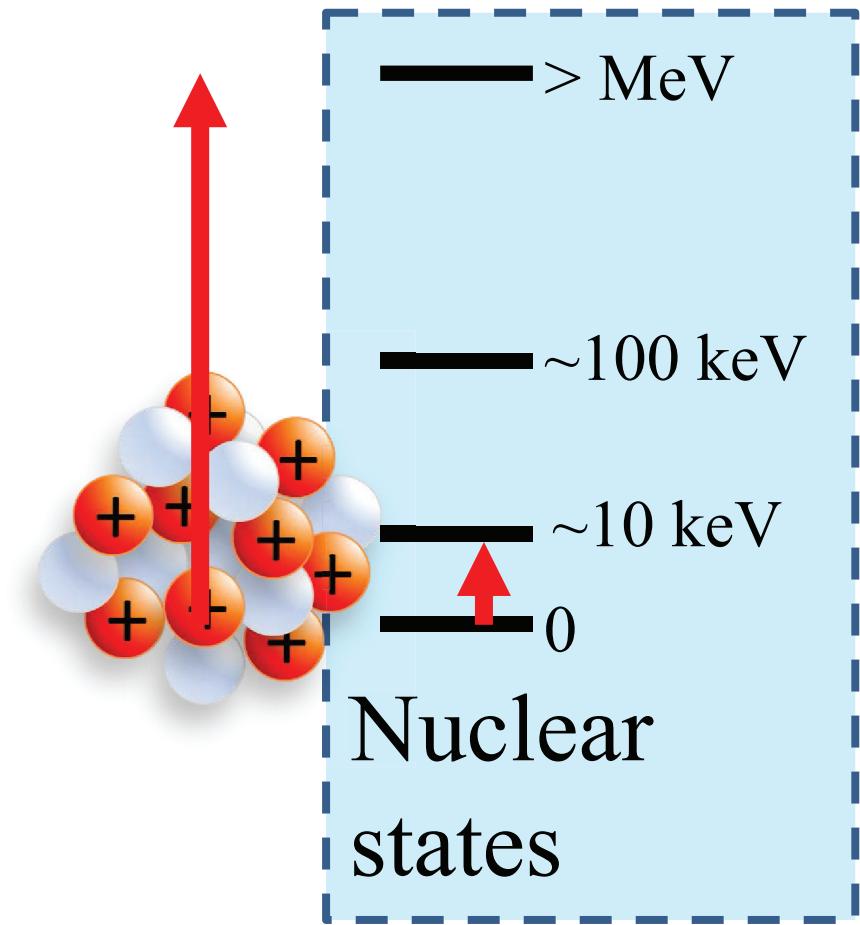
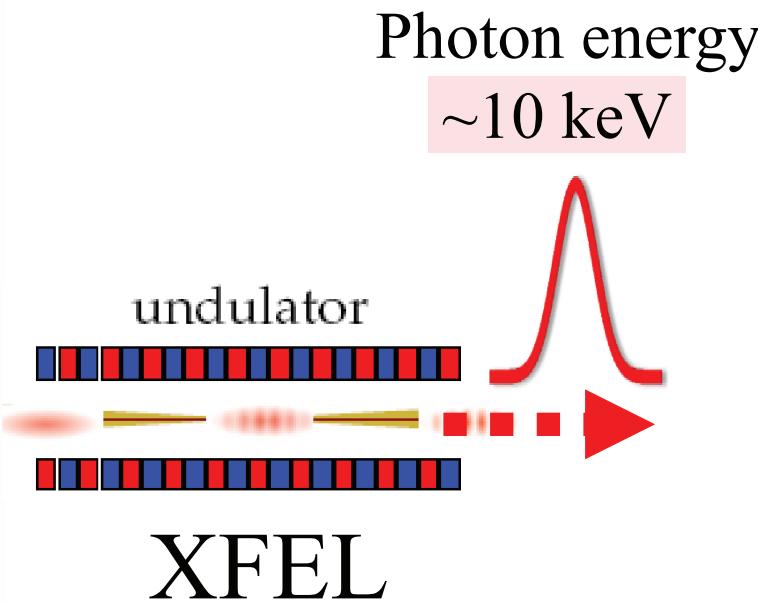
Nuclear Coherent Population Transfer (NCPT)

# Drive MeV transition with 10keV photon



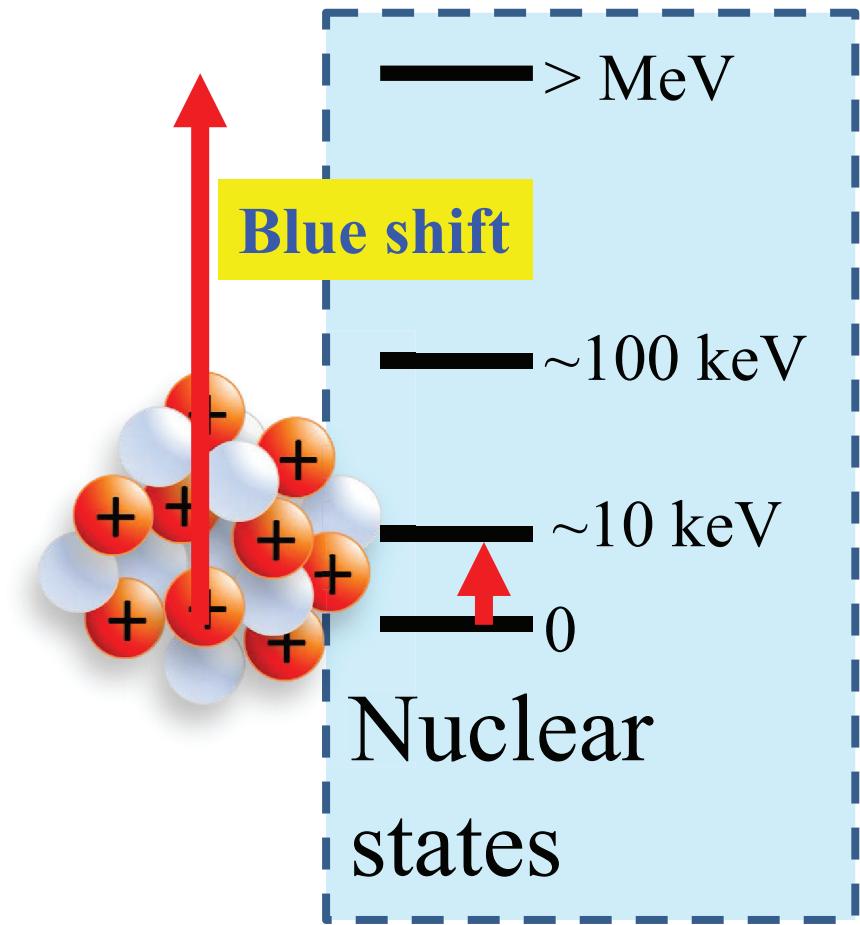
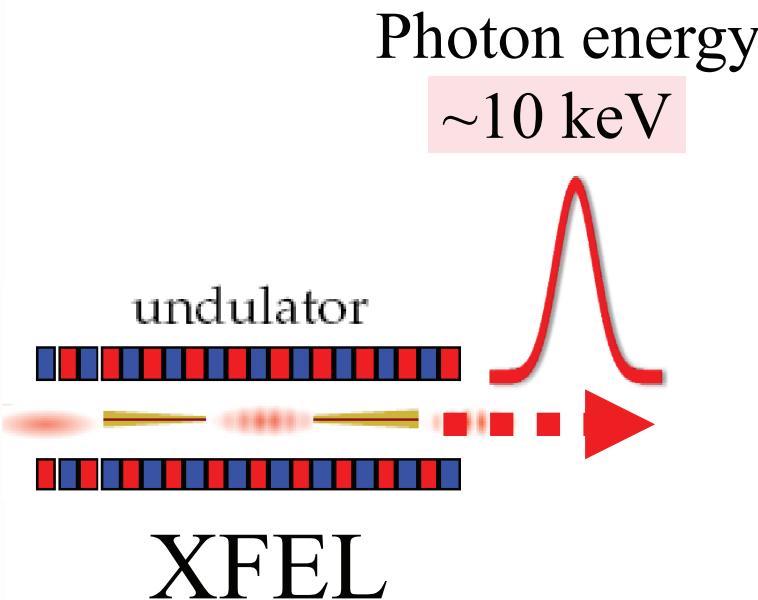
- T. Tajima, *Report on the ELI Science*, p.14 (2009).  
T. J. Bürvenich, J. Evers and C. H. Keitel, PRL 96, 142501 (2006).  
W.-T. Liao, A. Pálffy, C. H. Keitel, Phys. Lett. B 705, 134 (2011).

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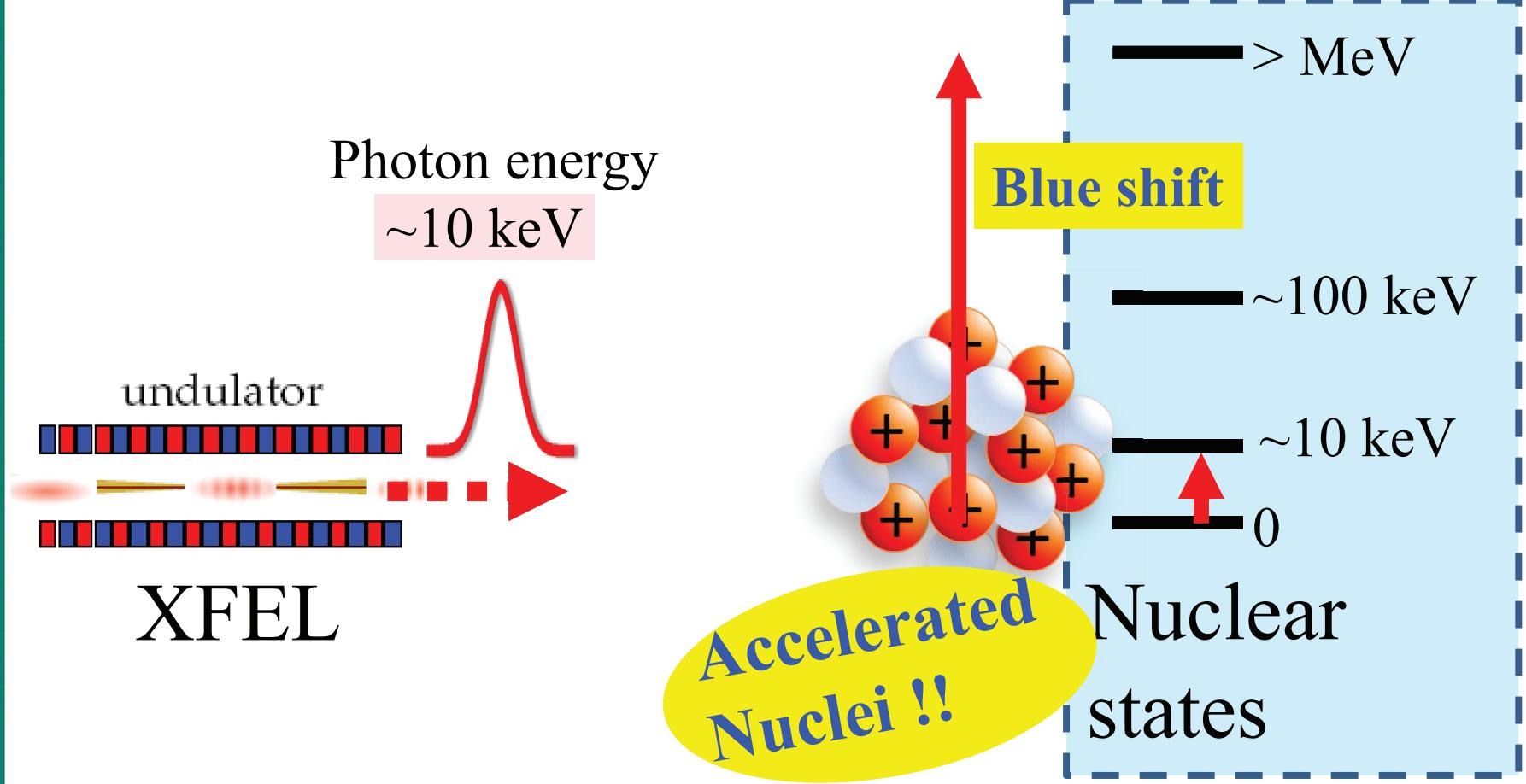
- T. Tajima, *Report on the ELI Science*, p.14 (2009).
- T. J. Bürvenich, J. Evers and C. H. Keitel, PRL 96, 142501 (2006).
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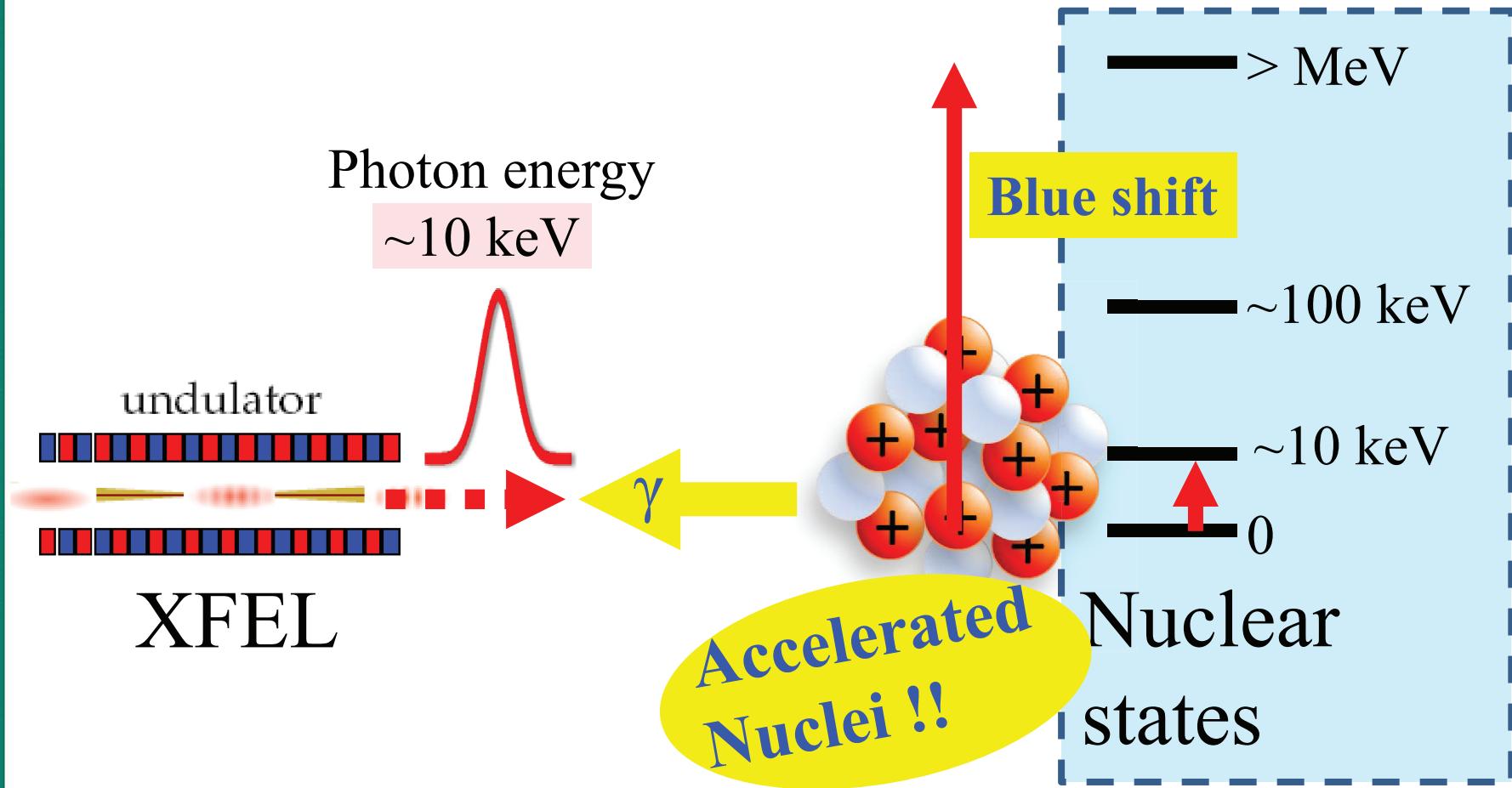


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T. J. Bürvenich, J. Evers and C. H. Keitel, PRL 96, 142501 (2006).

W.-T. Liao, A. Pálffy, C. H. Keitel, Phys. Lett. B 705, 134 (2011).

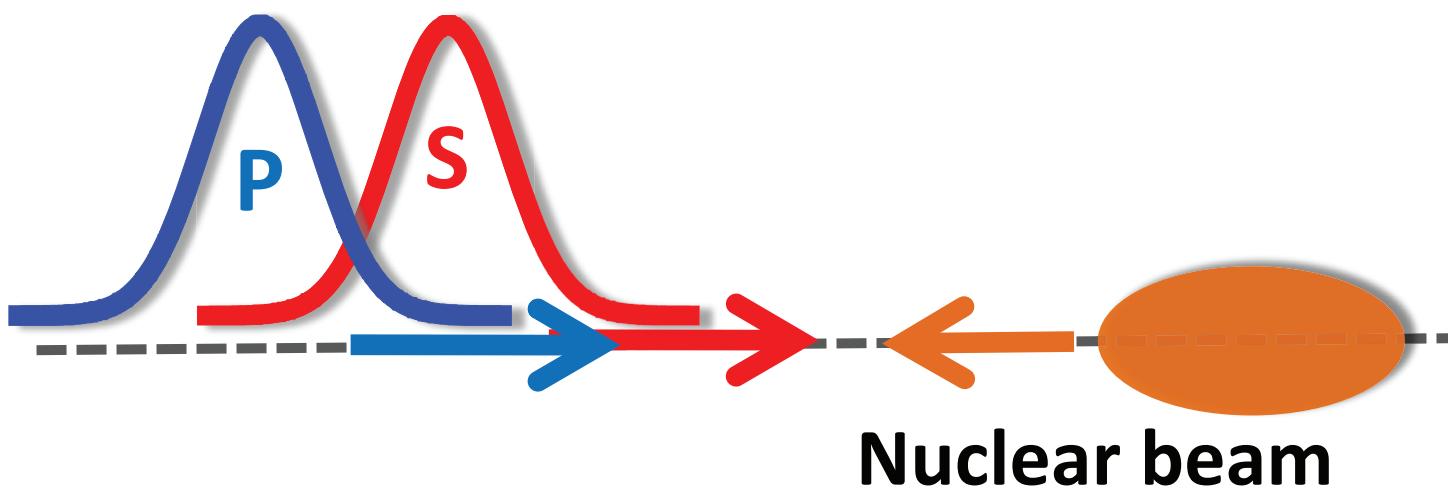
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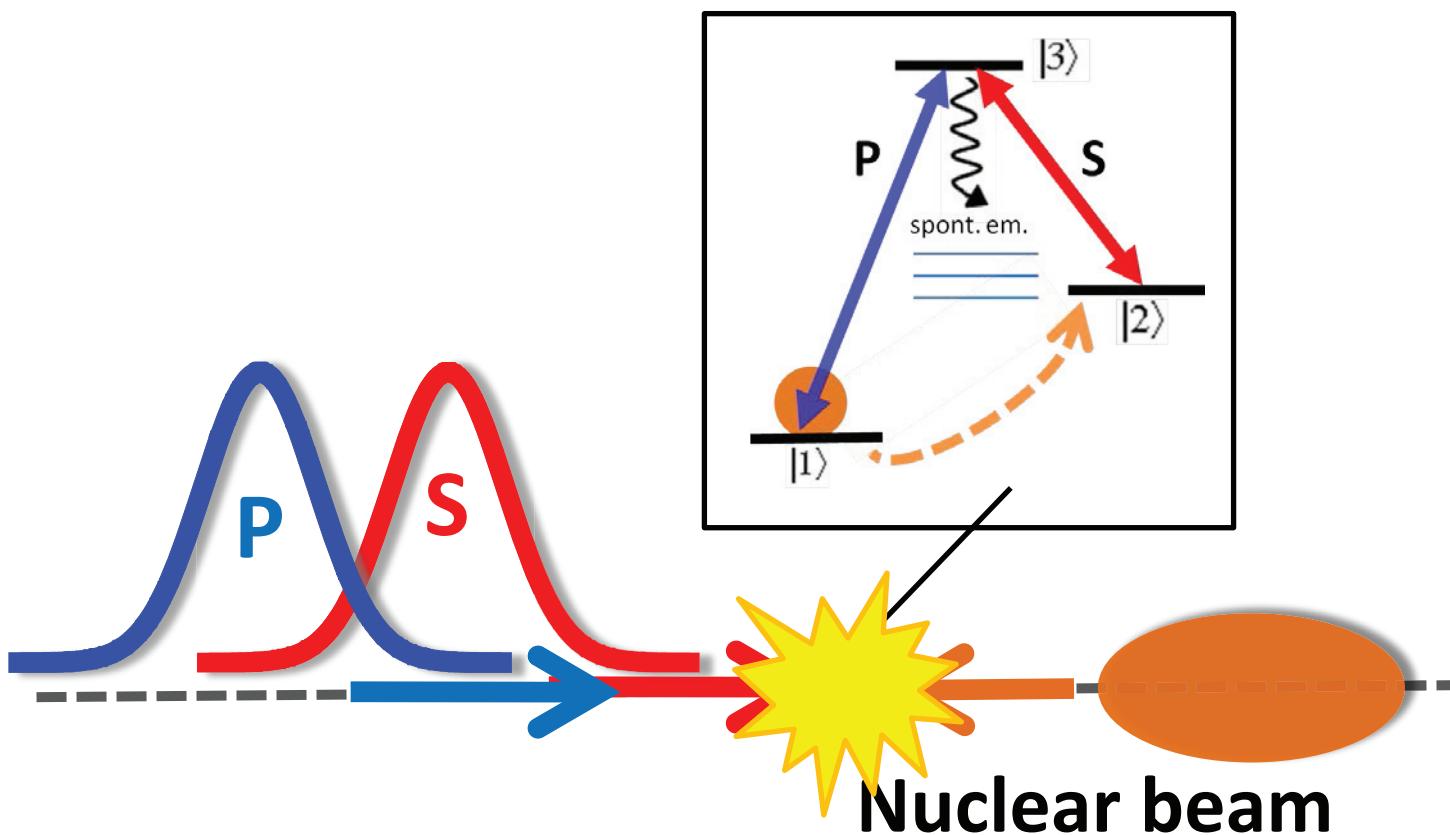
T. J. Bürvenich, J. Evers and C. H. Keitel, PRL 96, 142501 (2006).

W.-T. Liao, A. Pálffy, C. H. Keitel, Phys. Lett. B 705, 134 (2011).



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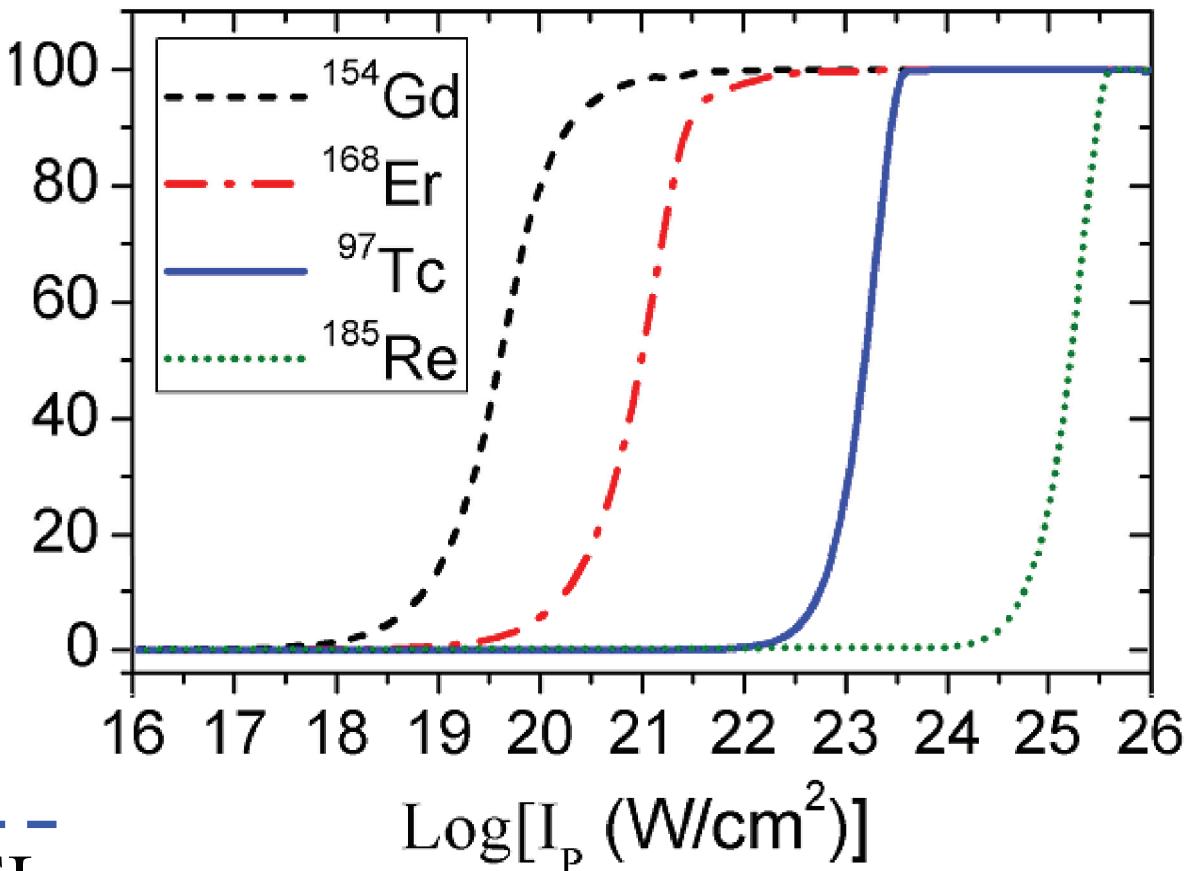
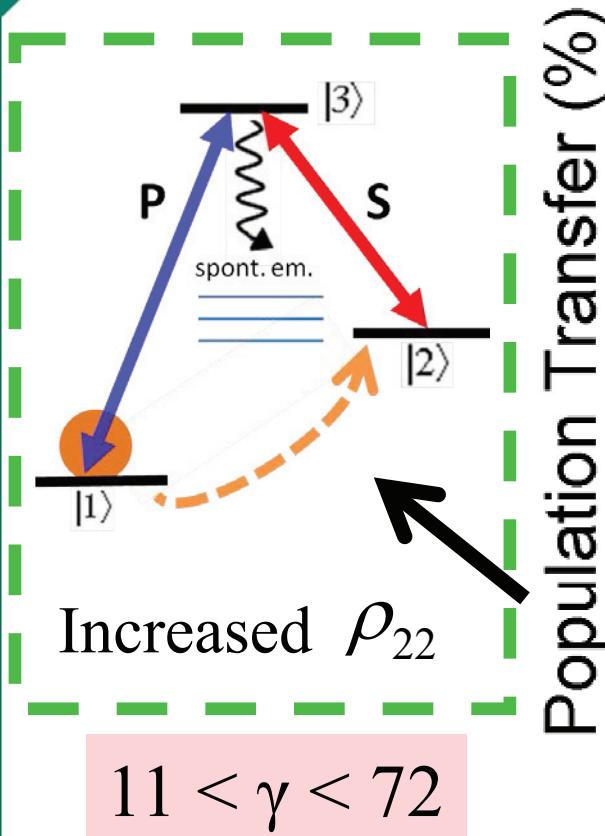
W.-T. Liao, A. Pálffy, C. H. Keitel, Phys. Rev. C 87, 054609 (2013).



W.-T. Liao, A. Pálffy, C. H. Keitel, Phys. Lett. B 705, 134 (2011).

W.-T. Liao, A. Pálffy, C. H. Keitel, Phys. Rev. C 87, 054609 (2013).

# Results



Fully coherent XFEL:

Photon energy = 12.4 keV

Bandwidth = 10 meV

W.-T. Liao, A. Pálffy, C. H. Keitel, Phys. Lett. B 705, 134 (2011).

W.-T. Liao, A. Pálffy, C. H. Keitel, Phys. Rev. C 87, 054609 (2013).

$$\frac{I_p}{I_S} = \frac{I_p^\pi}{I_S^\pi}$$

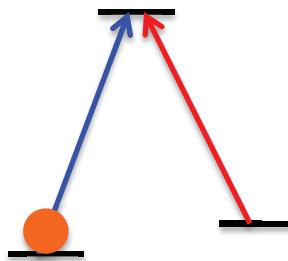


# Summary

1. Iron memory for x-ray photons.



2. mechanics-free method of changing x-ray phase.



3. NCPT can be observed with XFEL peak intensity  $> 10^{18} \text{ (W/cm}^2\text{)} .$



# Acknowledgement



Prof. Christoph H. Keitel  
MPIK, Heidelberg



Dr. Adriana Pálffy  
MPIK, Heidelberg



Dr. Ralf Röhlsberger  
DESY, Hamburg