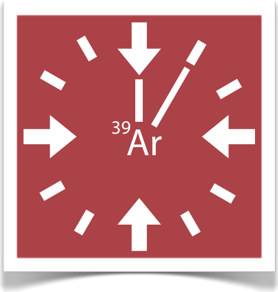
Rare Noble Gas Isotopes: Dating Ice and Water



Sven Ebser
Kirchhoff-Institute for Physics, Group Oberthaler
Heidelberg University

May 27, 2016

ATTA Collaboration in Heidelberg

IUP

Werner Aeschbach-Hertig

Arne Kersting

Stefan Beyersdorfer

Emeline Mathouchanh

Florian Ritterbusch
USTC

KIP

Sven Ebser

Markus K. Oberthaler

Lisa Ringena

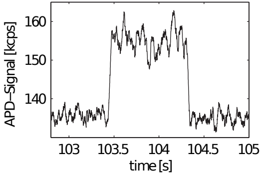
Zhongyi Feng

LAndreas Kamrad

Water sampling

Argon extraction

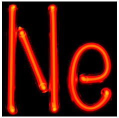
Single ^{39}Ar atom counting



Rare Noble Gas Isotopes

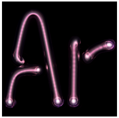
Studying exotic nuclear structure, testing QED

^{6}He and ^{8}He or ^{3}He and ^{4}He



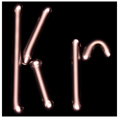
Searching for physics beyond the standard model

Rare Neon isotopes



Dating of ice and water

^{39}Ar



Monitoring of the Nuclear Non-Proliferation Treaty

^{85}Kr

Krypton contamination in Xenon Dark Matter detectors

Kr contamination in Xe

Rare Noble Gas Isotopes

Studying exotic nuclear structure, testing QED

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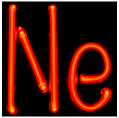
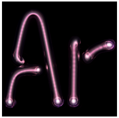


Searching for physics beyond the standard model

Rare Neon isotopes



Dating of ice and water

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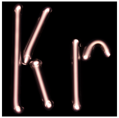

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Dating Water and Ice

Groundwater

- Water resource management
- Climate reconstruction

Dating Water and Ice

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Ocean

- Circulations (Global Conveyor Belt, North Atlantic Current, ...)
- Mixing processes (CO_2 uptake by oceans,...)

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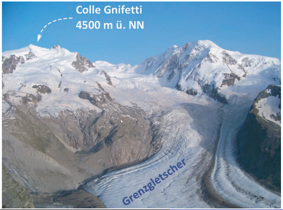


Ice

- Climate reconstruction
- Glaciological studies

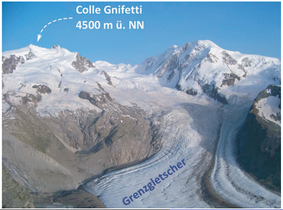
decreasing sample size

Groundwater

- Water resource management
- Climate reconstruction

Ocean

- Circulations (Global Conveyor Belt, North Atlantic Current, ...)
- Mixing processes (CO_2 uptake by oceans,...)



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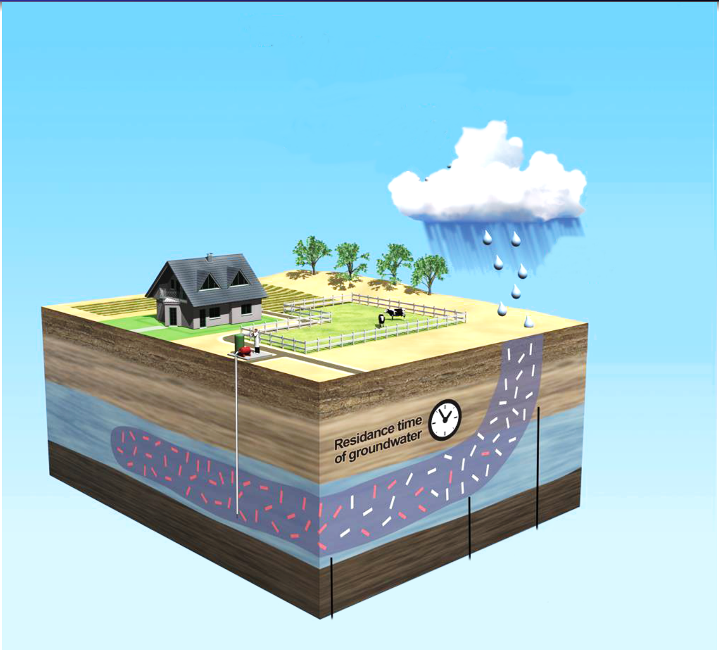
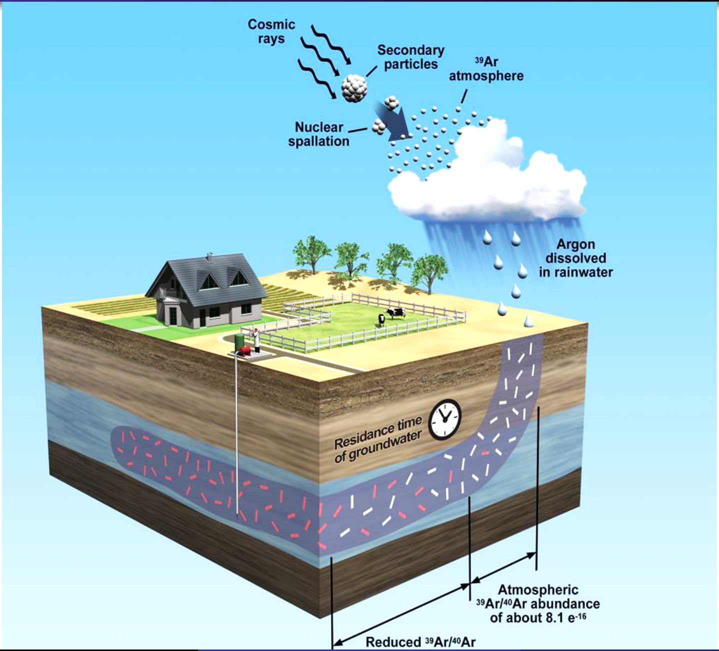
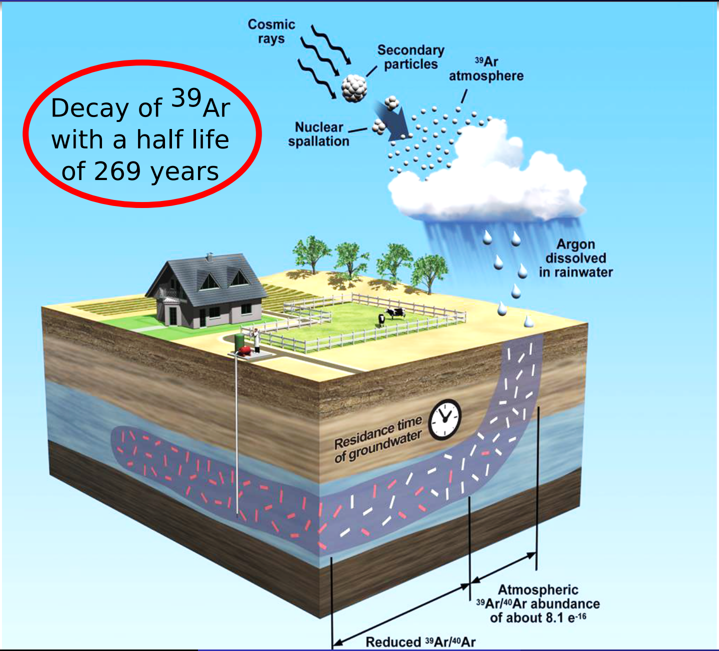
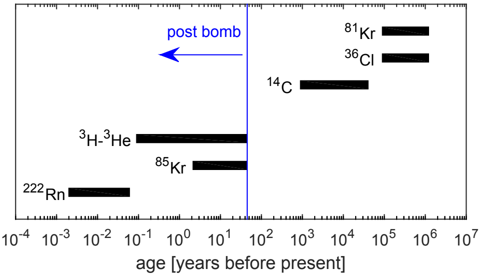

Residance time
of groundwater

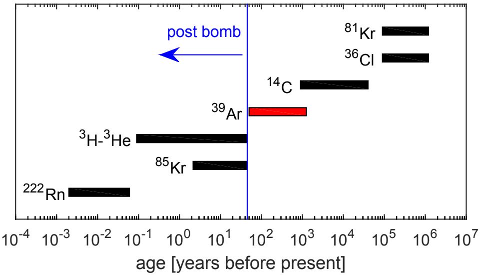
Radioisotope Dating




Decay of ^{39}Ar with a half life of 269 years
Cosmic rays
Secondary particles
^{39}Ar atmosphere
Nuclear spallation
Argon dissolved in rainwater
Residance time of groundwater
Atmospheric $^{39}Ar/^{40}Ar$ abundance of about 8.1 e-16
Reduced $^{39}Ar/^{40}Ar$



isotope	half life
^{222}Rn	3.824 d
^{3}H	12.32 a
^{85}Kr	10.76 a
^{14}C	5730 a
^{81}Kr	232 ka
^{36}Cl	301 ka



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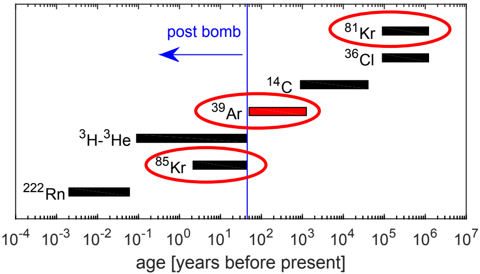

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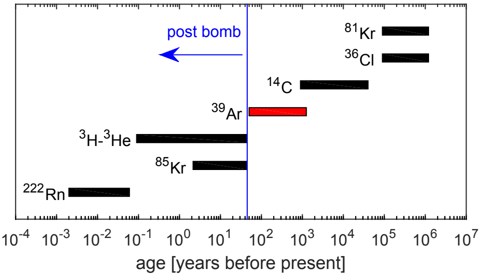
- Conservative tracer not involved in chemical processes



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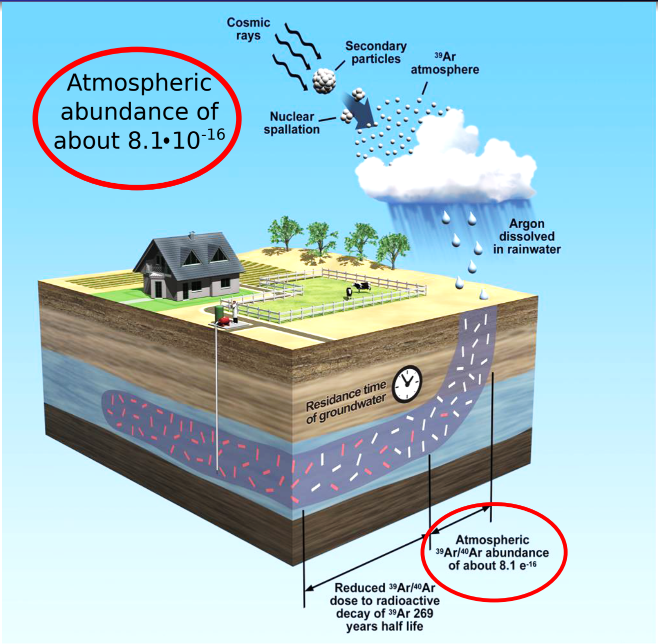
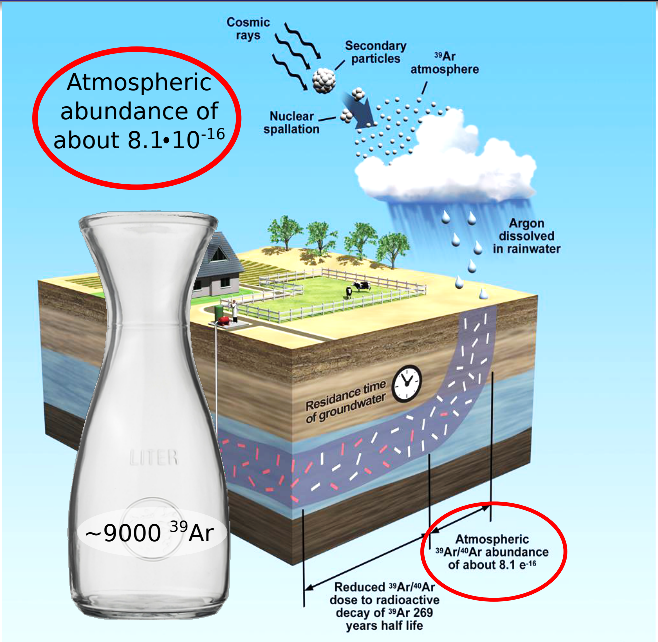
- Conservative tracer not involved in chemical processes
- Anthropogenic contribution $< 5\,\%$
- Variations in atmospheric ^{39}Ar concentration during the last 1000 years $< 7\,\%$


Atmospheric abundance of about 8.1•10-16
Cosmic rays
Secondary particles
39Ar atmosphere
Nuclear spallation
Argon dissolved in rainwater
Residance time of groundwater
Atmospheric 39Ar/40Ar abundance of about 8.1 e-16
Reduced 39Ar/40Ar dose to radioactive decay of 39Ar 269 years half life


Atmospheric abundance of about 8.1•10-16
Cosmic rays
Secondary particles
39Ar atmosphere
Nuclear spallation
Argon dissolved in rainwater
LITER
~9000 39Ar
Residance time of groundwater
Atmospheric 39Ar/40Ar abundance of about 8.1 e-16
Reduced 39Ar/40Ar dose to radioactive decay of 39Ar 269 years half life

$^{39}Ar : {}^{40}Ar = 1 : 1\,000\,000\,000\,000\,000$

Public debit of the USA in US-cents

$^{39}Ar : {}^{40}Ar = 1 : 1\ 000\ 000\ 000\ 000\ 000$

Public debit of the USA in US-cents

^{39}Ar:^{40}Ar = 4000 times to the moon and there is one cent different!

Detection methods for ^{39}Ar

- **Radioactivity:**
  Low-Level-Counting (LLC): $^{39}\text{Ar} \rightarrow {}^{39}\text{K} + e^- + \bar{\nu}_e$
  Only large samples (1-3 tons of water)

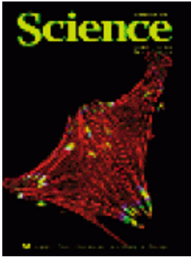
- **Mass:**
  Accelerator Mass Spectrometry (AMS):
  Possible, but difficult for noble gases

- **Atomic spectrum:**
  Atom Trap Trace Analysis (ATTA)
  Complement for rare and long-lived noble gases

Ultrasensitive Isotope Trace Analyses with a Magneto-Optical Trap

C. Y. Chen,[1] Y. M. Li,[1] K. Bailey,[1] T. P. O'Connor,[1] L. Young,[2] Z.-T. Lu[1]*

SCIENCE VOL 286 5 NOVEMBER 1999



	^{85}Kr	^{81}Kr	^{39}Ar
half life	10.76 a	232 ka	269 a
relative abundance	$2 \cdot 10^{-11}$	$6 \cdot 10^{-13}$	$8 \cdot 10^{-16}$

ATTA for Rare Krypton Isotopes

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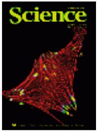

One million year old groundwater in the Sahara revealed by krypton-81 and chlorine-36

N. C. Sturchio,[1] X. Du,[2,3] R. Purtschert,[4] B. E. Lehmann,[4] M. Sultan,[5] L. J. Patterson,[1] Z.-T. Lu,[2] P. Müller,[2] T. Bigler,[4] K. Bailey,[2] T. P. O'Connor,[2] L. Young,[6] R. Lorenzo,[4] R. Becker,[5] Z. El Alfy,[7] B. El Kaliouby,[8] Y. Dawood,[8] and A. M. A. Abdallah[8]

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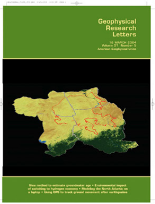

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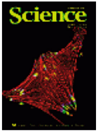

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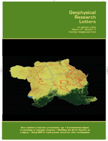


PRL 106, 103001 (2011) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2011

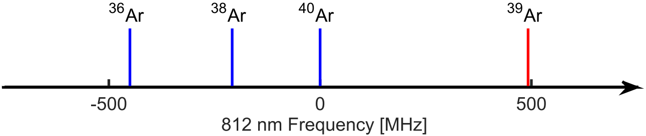
^{39}Ar Detection at the 10^{-16} Isotopic Abundance Level with Atom Trap Trace Analysis

W. Jiang,[1] W. Williams,[1] K. Bailey,[1] A. M. Davis,[2,3] S.-M. Hu,[4] Z.-T. Lu,[1,2,5] T. P. O'Connor,[1] R. Purtschert,[6] N. C. Sturchio,[7] Y. R. Sun,[4] and P. Mueller[1]

	^{85}Kr	^{81}Kr	^{39}Ar
half life	10.76 a	232 ka	269 a
relative abundance	$2 \cdot 10^{-11}$	$6 \cdot 10^{-13}$	$8 \cdot 10^{-16}$

Principle of ATTA

Isotope shifts:



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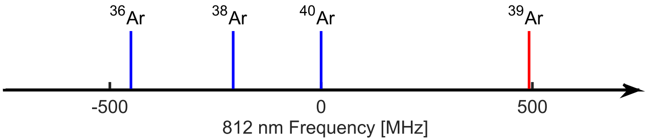
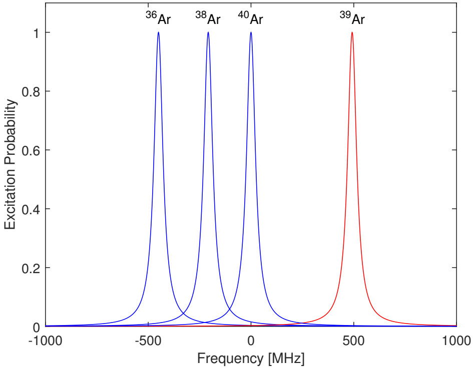


Transition rate: $\sim 10^7$ Hz



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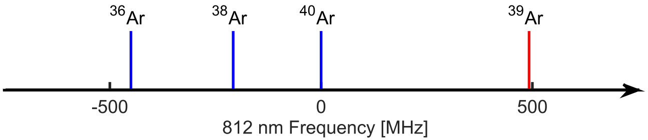
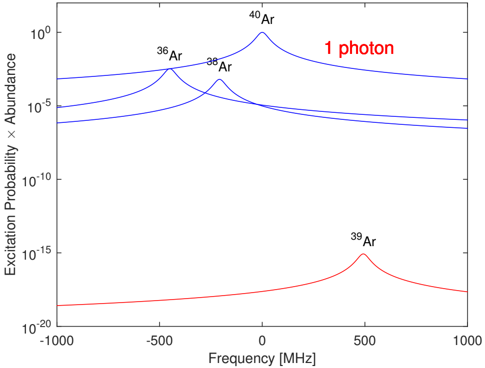


$(\text{Rate})^1 \times \text{Iso. abundance}$



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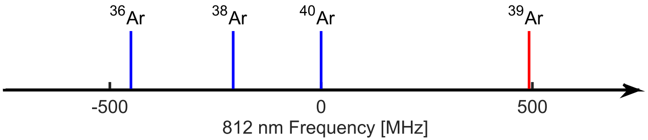
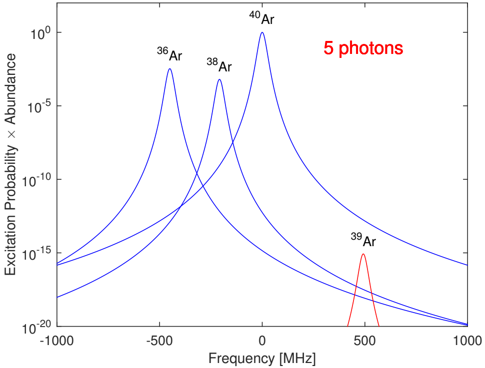
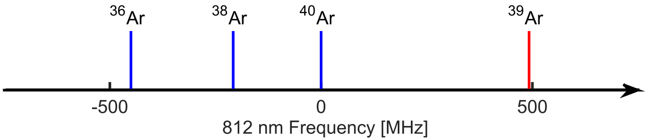


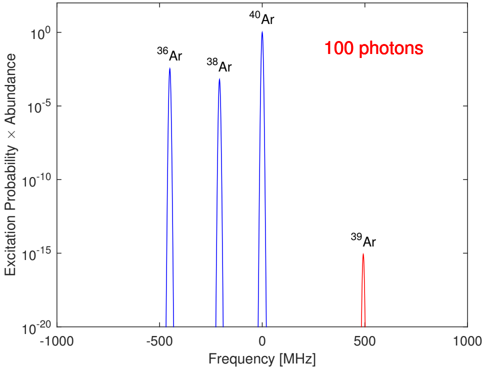
$(\text{Rate})^5 \times$ Iso. abundance



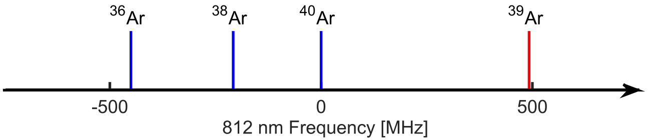
Isotope shifts:

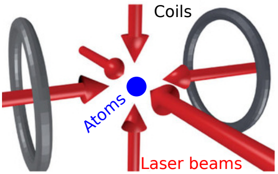


(Rate)^{100} $\times$ Iso. abundance



Isotope shifts:

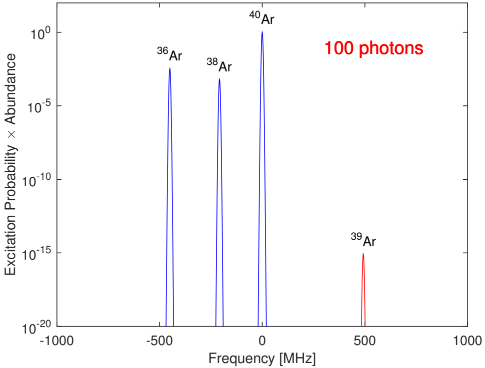




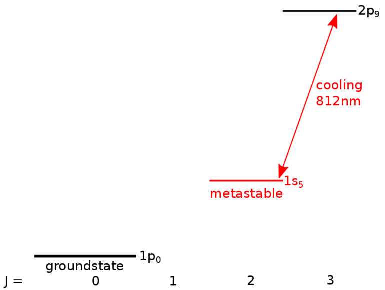
Key characteristics:

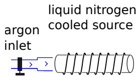
Resonance & repetition

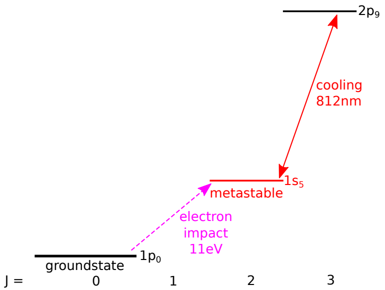
→ Zero background

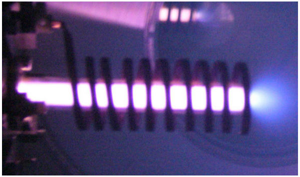


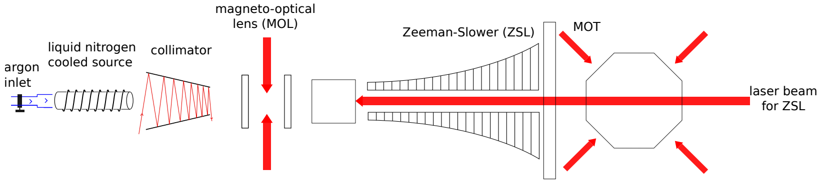
^{39}Ar-ATTA System

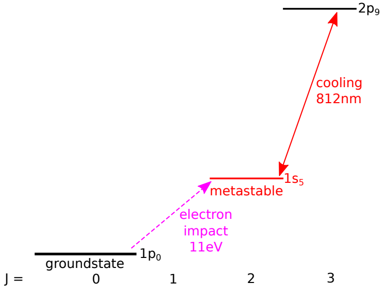



liquid nitrogen
cooled source
argon
inlet


2p9
cooling
812nm
1s5
metastable
electron
impact
11eV
1p0
groundstate
J =
0
1
2
3




magneto-optical
lens (MOL)
liquid nitrogen
cooled source
collimator
Zeeman-Slower (ZSL)
MOT
argon
inlet
laser beam
for ZSL


2p9
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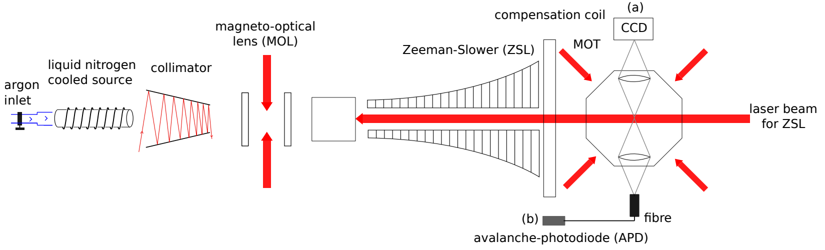
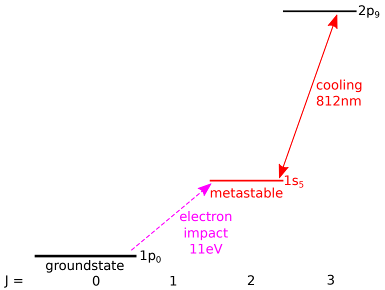
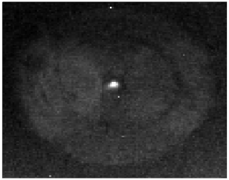
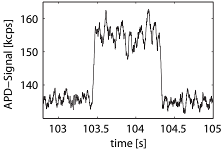




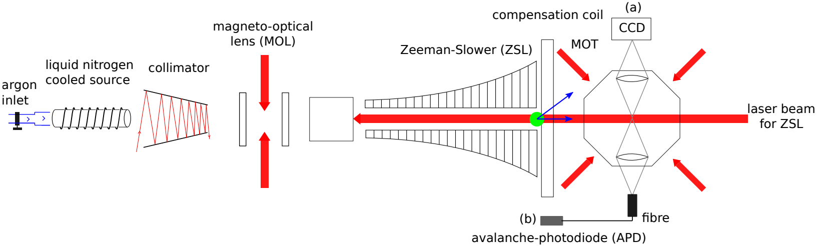
a) ^{39}Ar atom on CCD

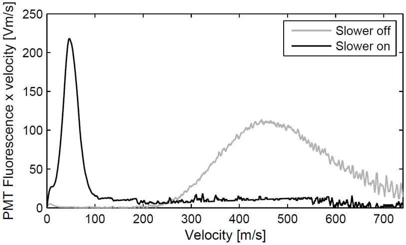


b) ^{39}Ar atom on APD



^{39}Ar-ATTA System





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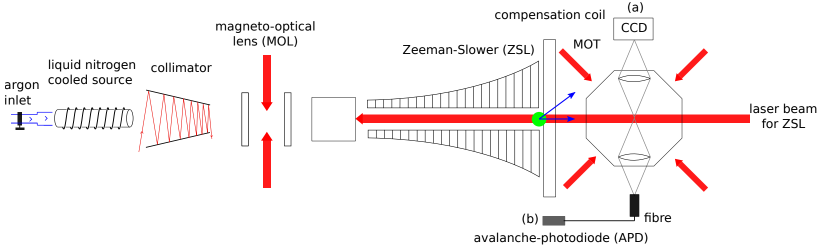
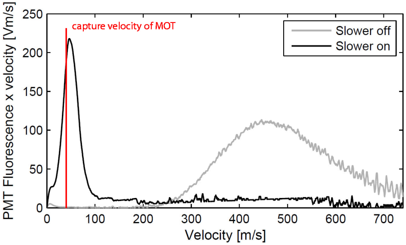
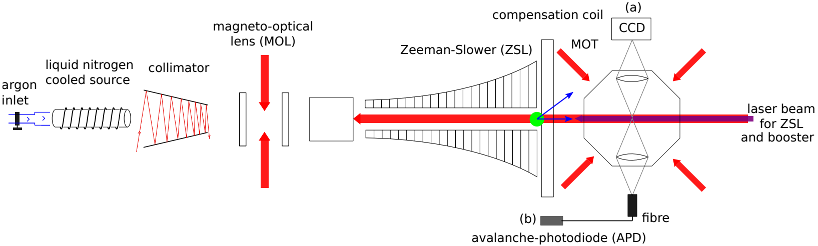
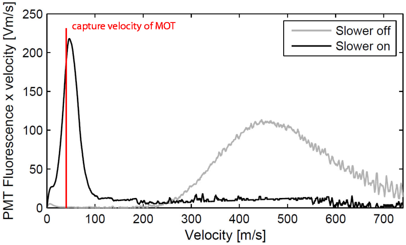
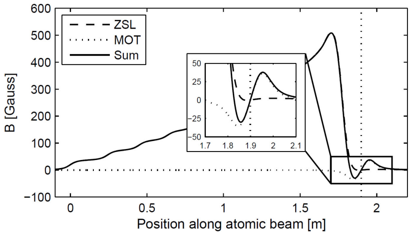




^{39}Ar-ATTA System







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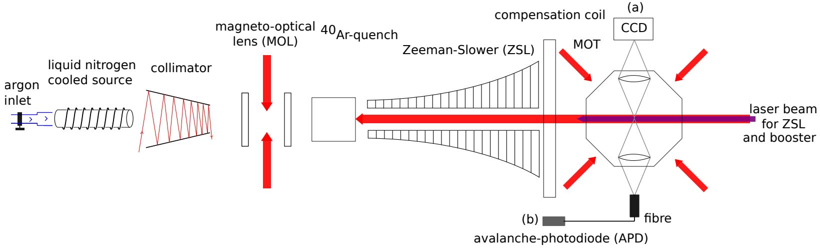

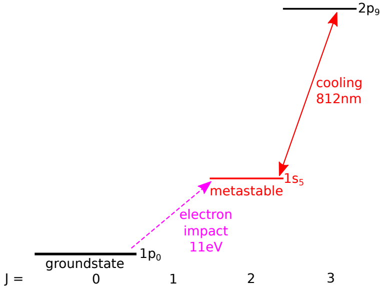

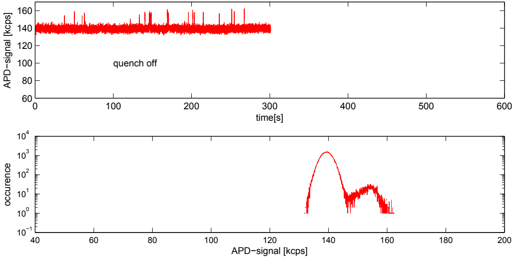

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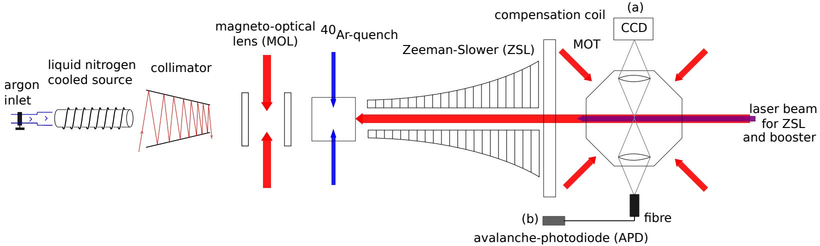
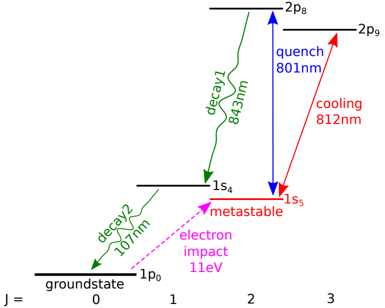
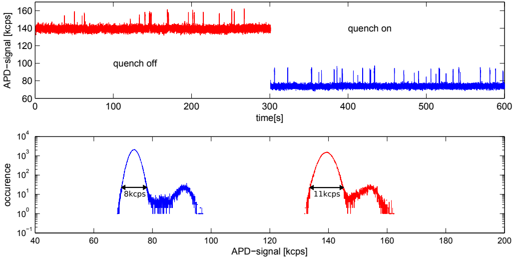
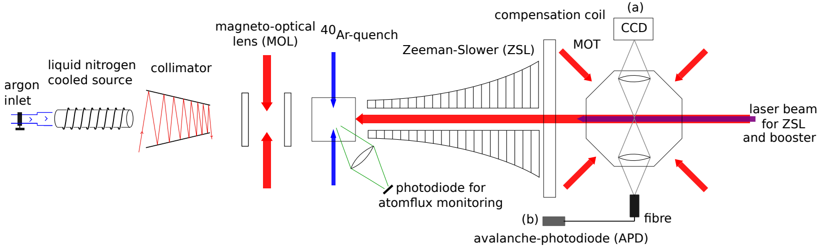
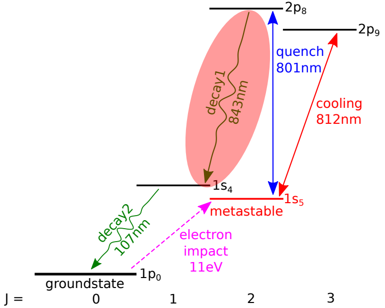
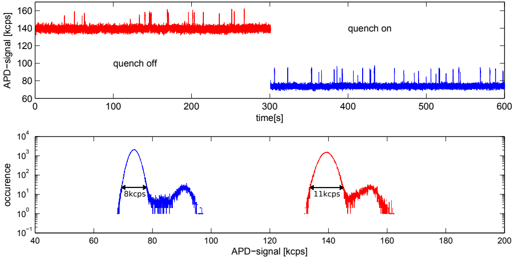


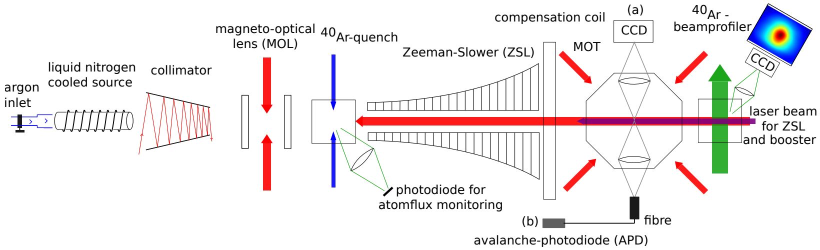





argon
inlet
liquid nitrogen
cooled source
collimator
magneto-optical
lens (MOL)
40Ar-quench
Zeeman-Slower (ZSL)
compensation coil
(a)
CCD
MOT
laser beam
for ZSL
and booster
photodiode for
atomflux monitoring
(b)
fibre
avalanche-photodiode (APD)


2p8
2p9
quench
801nm
cooling
812nm
decay1
843nm
1s4
1s5
metastable
decay2
107nm
electron
impact
11eV
1p0
groundstate
J =
0
1
2
3


APD−signal [kcps]
quench on
quench off
time[s]
occurence
8kcps
11kcps
APD−signal [kcps]


argon
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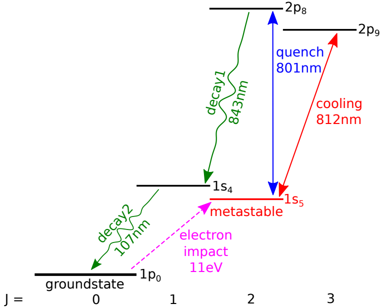
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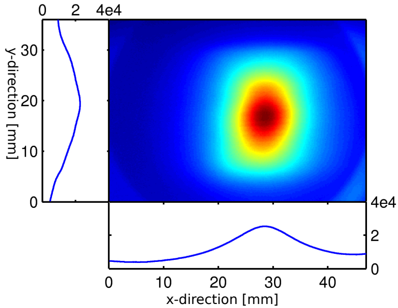
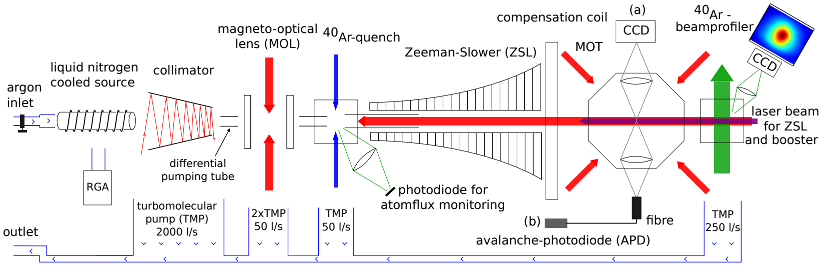

0
2
4e4
y-direction [mm]
30
20
10
0
4e4
2
0
0
10
20
30
40
x-direction [mm]

^{39}Ar-ATTA System



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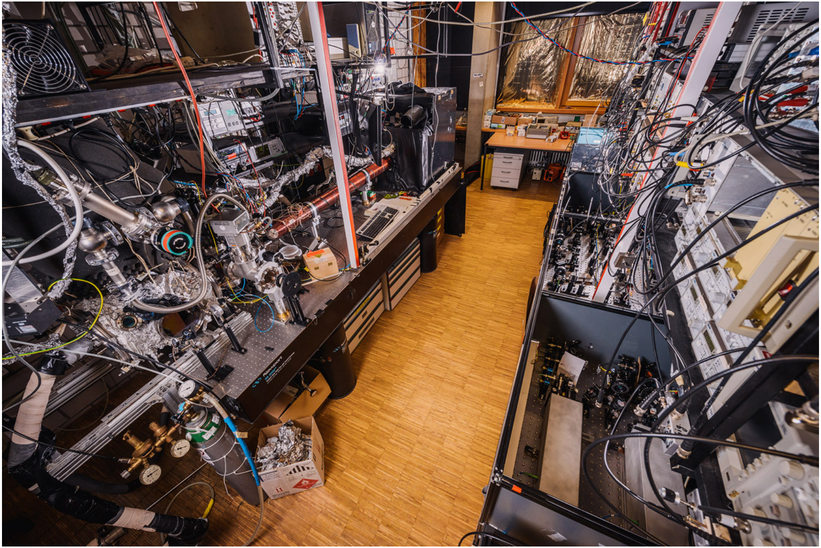

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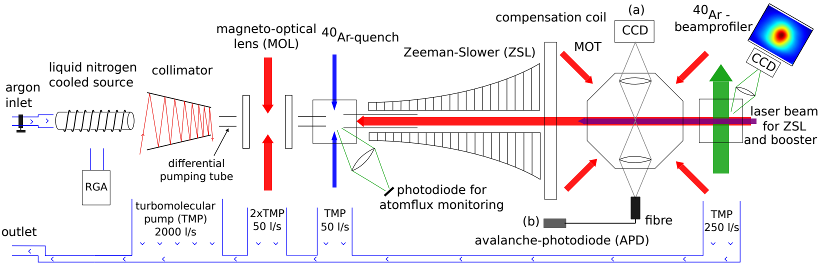

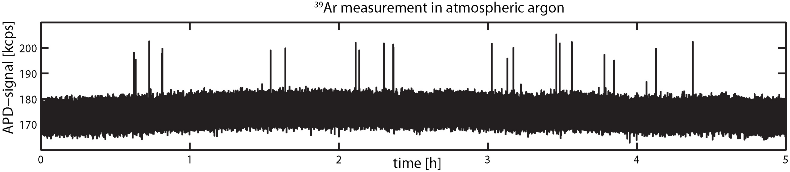

Atmospheric ^{39}Ar count rate:

3.6 atoms/h

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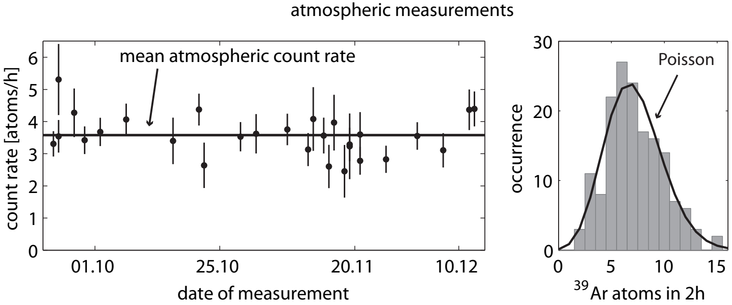

F. Ritterbusch et al. (2014), Groundwater dating with Atom Trap Trace Analysis of ^{39}Ar, Geophys. Res. Lett., 41

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AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2014GL061120

Key Points:
- First dating of groundwater with Atom Trap Trace Analysis of Argon-39
- Argon-39-ATTA has the potential for Argon-39 analysis of small water and ice samples

Groundwater dating with Atom Trap Trace Analysis of ^{39}Ar

F. Ritterbusch[1], S. Ebser[1], J. Welte[1], T. Reichel[2], A. Kersting[2], R. Purtschert[3], W. Aeschbach-Hertig[2], and M. K. Oberthaler[1]

[1]Kirchhoff-Institute for Physics, Heidelberg University, Heidelberg, Germany, [2]Institute of Environmental Physics, Heidelberg University, Heidelberg, Germany, [3]Climate and Environmental Physics, University of Bern, Bern, Switzerland

Abstract We report on the realization of Atom Trap Trace Analysis for ^{39}Ar and its first application to dating of groundwater samples. The presented system achieves an atmospheric ^{39}Ar count rate as high as

F. Ritterbusch et al. (2014), Groundwater dating with Atom Trap Trace Analysis of ^{39}Ar, Geophys. Res. Lett., 41

First Groundwatersamples: Results

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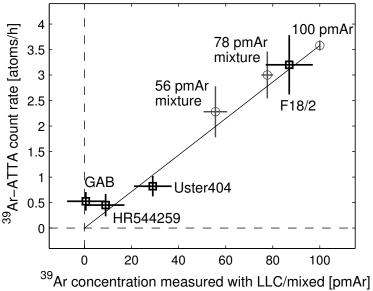

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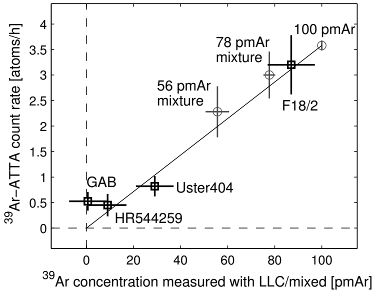

	F18/2	*Uster404*	*HR544259*
NGT [°C]	7.8 ± 0.6	7.3 ± 0.5 [a]	4.3 ± 1.1
^{3}H [TU]	7.40 ± 0.16	0.4 ± 0.1[a]	0.6 ± 0.9
^{14}C [pmC]	84.03 ± 0.24	22.1 ± 0.4[a]	0.025 ± 0.020
^{39}Ar age ATTA [a]	46 ± 71	574 ± 95	> 652

[a] values from *Beyerle et. al, 1998*

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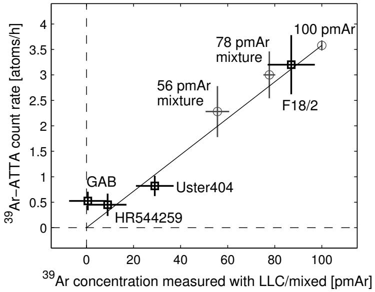

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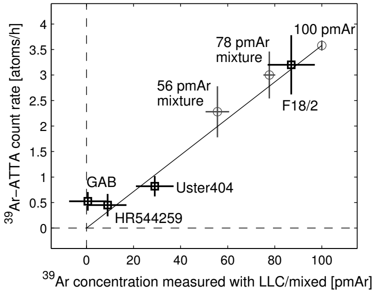

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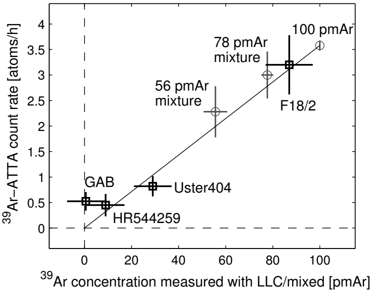

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→ Groundwater dating with ^{39}Ar-ATTA demonstrated

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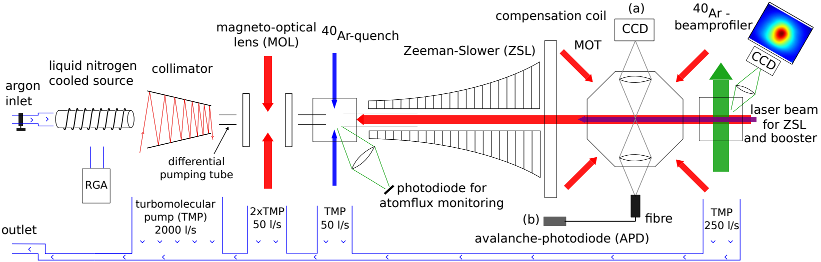
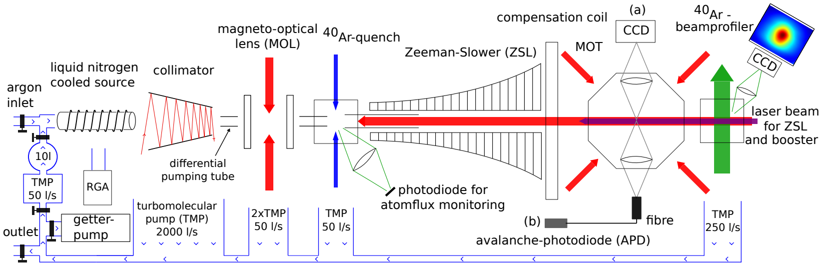


Throughput configuration

Required sample size: 30 mL/h

0.5 -1 L STP argon ↔ 1000 - 2500 kg water or 500 - 1000 kg ice



Throughput configuration

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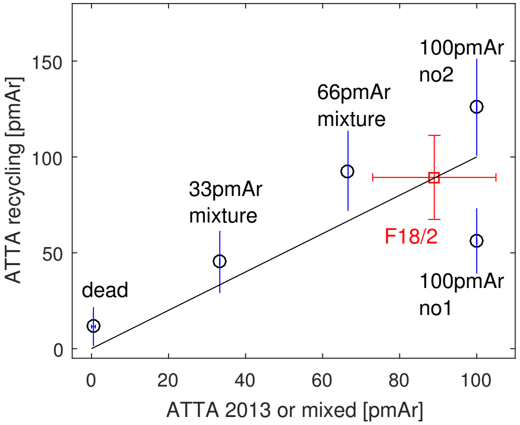
Recycling configuration

Required sample size due to contamination:

4 -10 mL STP argon $\leftrightarrow$ 10 - 25 L water or 4 - 10 kg ice

First Results with 4 ml Samples (Preliminary)



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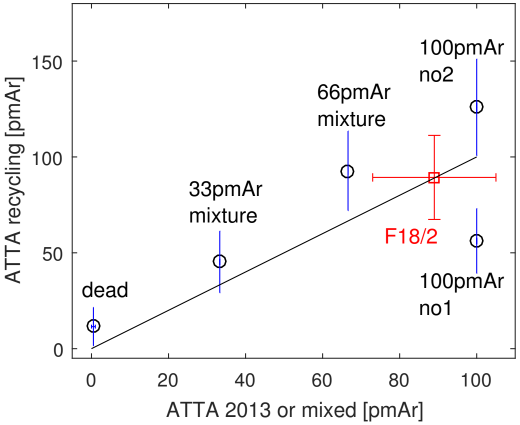

Reduction of the needed sample size by more than a factor 100!

In Progress: ^{39}Ar Dating of Glacier Ice and Ocean Water

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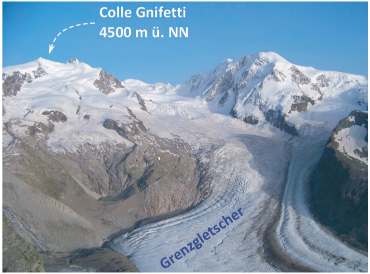
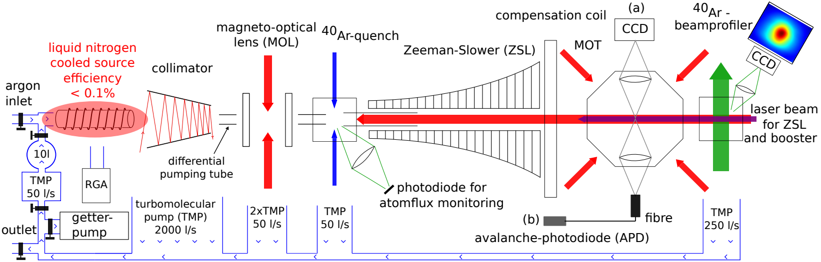


Optical Pumping



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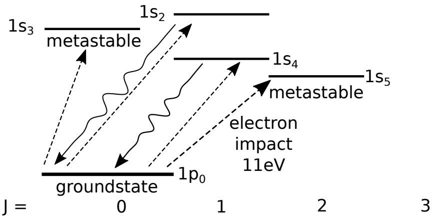

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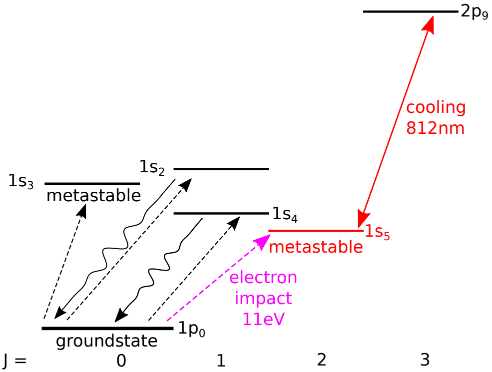

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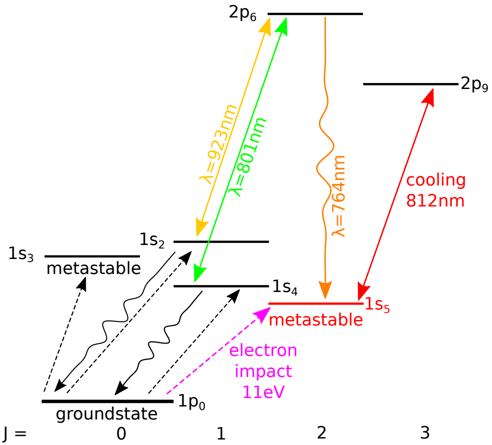

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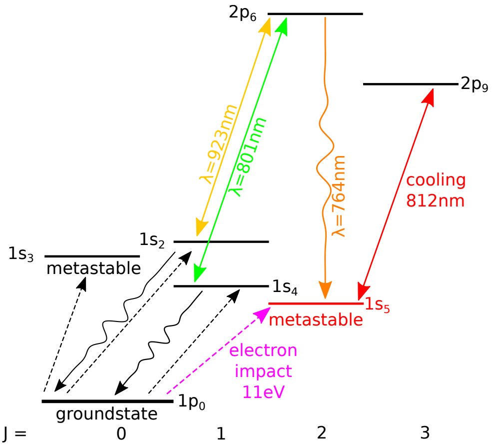
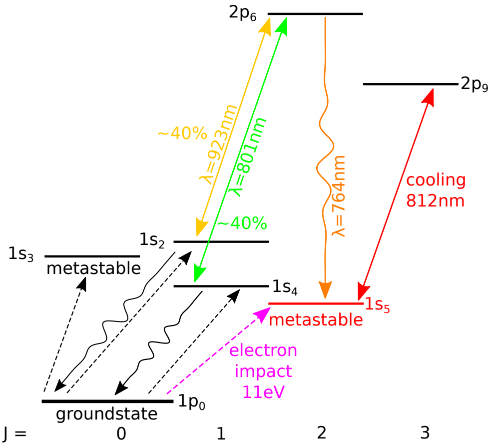


Anika
Frölian

Maurus
Hans

see: www.matterwave.de



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Maurus Hans

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In an ^{40}Ar spectroscopy cell: 40% are gained by each transition, together 80%

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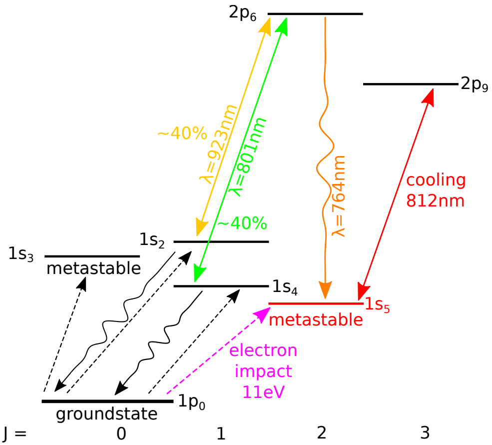

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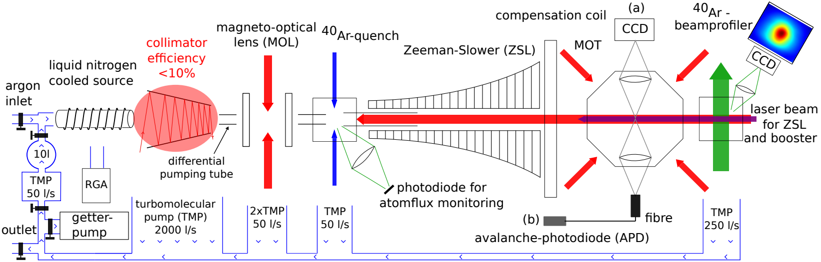
A realisation for ^{39}Ar has to be investigated

Precollimator



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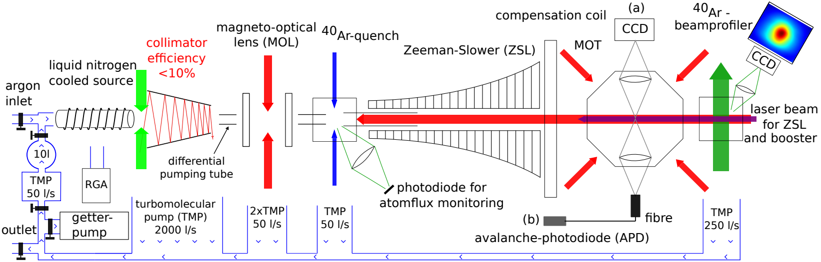
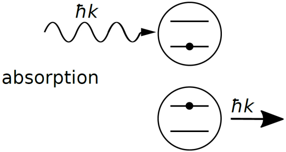


Bichromatic Force: Basic Principle

Radiative force



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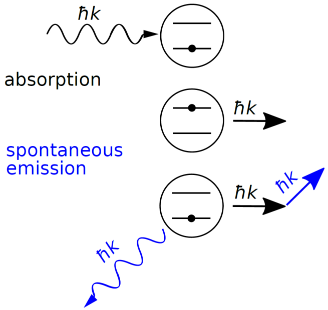
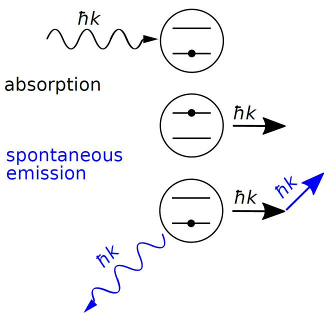


Force is limited: $F_{rad} < \hbar k \frac{\gamma}{2}$

Radiative force



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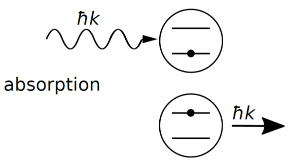

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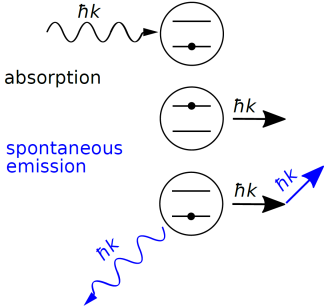

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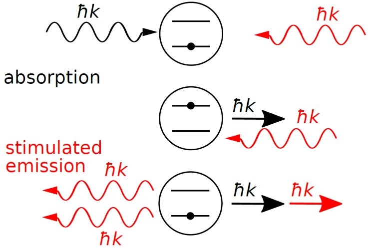

Force is not limited by the spontaneous decay rate

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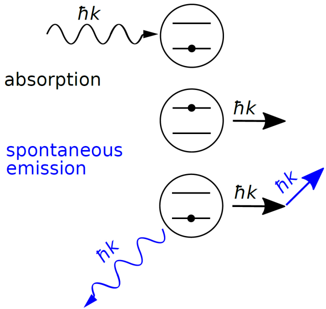
Radiative force



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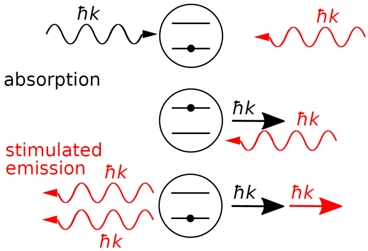
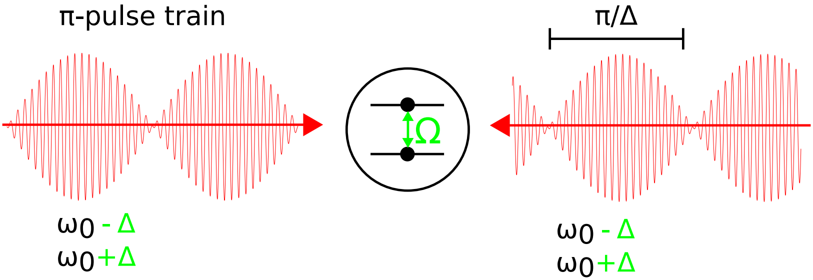


Force is not limited by the spontaneous decay rate

Calculation: Yatsenko (1991, 2004), Cs: J. Söding et. al. (1996), Rb: Williams/Metcalf (1999), He: Cashen/Metcalf (2001)

Bichromatic Force: Realisation



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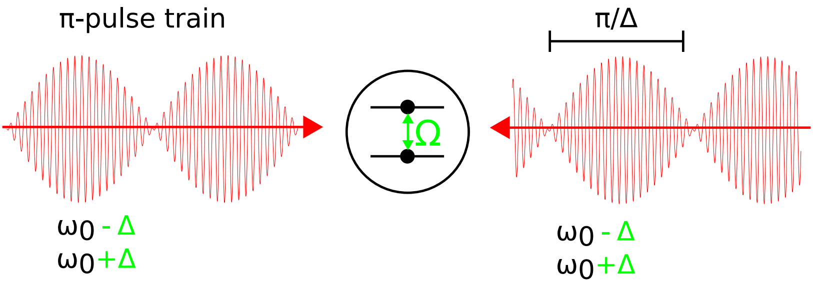
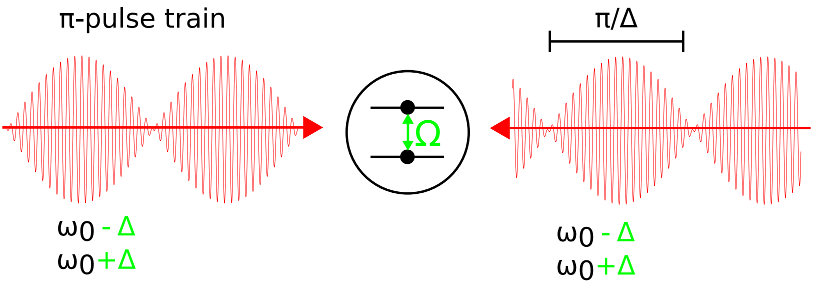


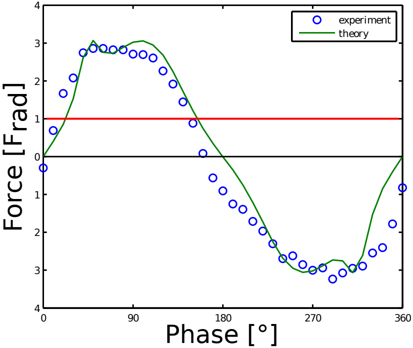
- Average force $\overline{F} = \frac{\hbar k}{\pi}\Delta$ (only limited by power!)

Bichromatic Force: Realisation



- Average force $\overline{F} = \frac{\hbar k}{\pi}\Delta$ (only limited by power!)
- Optimum phase $\phi = \frac{\pi}{2}$

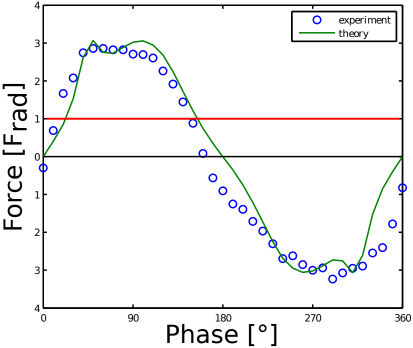
Bichromatic Force: Experimental Results

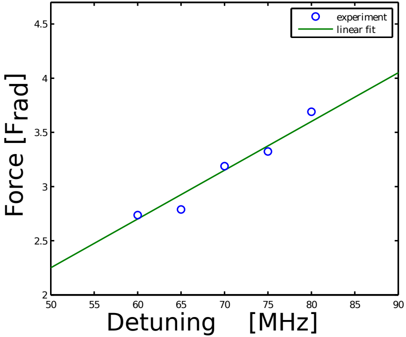


Zhongyi
Feng

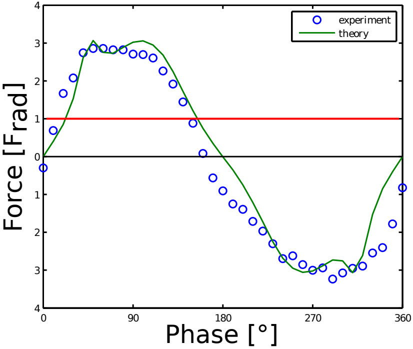
see: www.matterwave.de

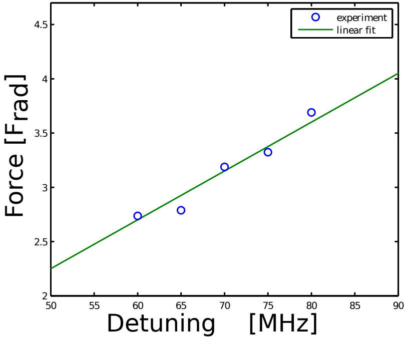
Bichromatic Force: Experimental Results





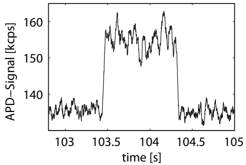
$$\overline{F} = \frac{\hbar k}{\pi} \Delta$$



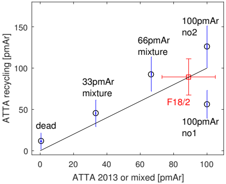


$$\overline{F} = \frac{\hbar k}{\pi} \Delta$$

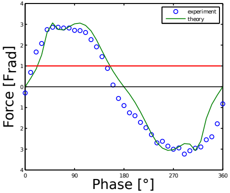
- For ^{39}Ar the realisation of the repumper still has to be investigated



^{39}Ar and Atom Trap Trace Analysis as an application of a rare noble gas



First demonstration of ATTA of ^{39}Ar with groundwater (GRL 2014) and reduction of the sample size down to 4 ml



Study of new techniques for ATTA:

- Optical pumping
- Bichromatic force