united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics

SMR 1302 - 15

WINTER SCHOOL ON LASER SPECTROSCOPY AND APPLICATIONS

19 February - 2 March 2001

Molecular Matter Wave Interferometry

Eberhard TIEMANN
University Hannover, Institute of Quantum Optics
D-30167 Hannover, Germany

These are preliminary lecture notes, intended only for distribution to participants.

strada costiera, 11 - 34014 trieste italy - tel. +39 040224011 1 fax +39 040224163 - sci_info@ictp.trieste.it - www.ictp.trieste.it

Molecular matter wave interferometry

Eberhard Tiemann

University Hannover, Institute of Quantum Optics

- Matter wave interferometry as a high precision spectroscopic tool
- Beam splitters and mirrors with light fields
- Interferometer of the Ramsey-Bordé type
- Realisation with K_2
- Beam splitters and mirrors with STIRAP method
- Studying cold collisions in a molecular beam

Matter waves

wave length (de Broglie)
of a free particle with momentum p:

$$\lambda_{DB} = \frac{h}{p}$$

or with kinetic energy w_{kin}

$$\lambda_{DB} = \frac{h}{\sqrt{2m w_{kin}}}$$

electron with 1 eV : $\lambda_{DB} = 12$ Å
neutron with 1 eV : $\lambda_{DB} = 0.28$ Å
atom ^{23}Na at 300K : $\lambda_{DB} = 0.37$ Å = 37 pm

particle beam with velocity spread gives
a wave packet with width Δx :

$$\Delta x \approx \frac{h}{m \cdot \Delta v}$$

number of periods :

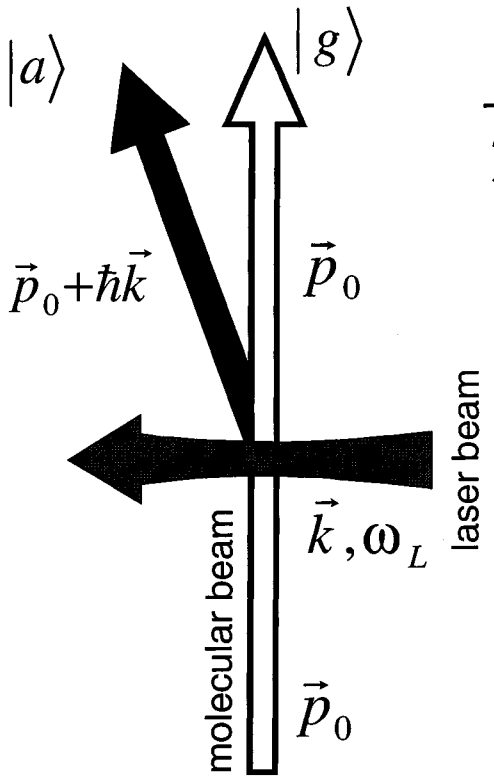
$$n = \frac{\Delta x}{\lambda} = \frac{v}{\Delta v}$$

thermal n = 1.7

for thermal beam ^{23}Na at 300K:

$v \approx 466$ m/s $\Delta v \approx 274$ m/s and $\Delta x \approx 0.63$ Å

Conservation of momentum and energy in the interaction zone of laser and matter wave



$$\frac{\vec{p}_0^{\,2}}{2m}+\hbar\omega_L=\frac{\left(\vec{p}_0+\hbar\vec{k}\right)^2}{2m}+\hbar\omega_0 \quad \text{with} \quad \vec{k}=\frac{\omega_L}{c}$$

$$\frac{\vec{k}\cdot\vec{p}_0}{2m}=\Delta-\delta \qquad \Delta=\omega_L-\omega_0 \quad \text{detuning}$$

$$\delta=\frac{\hbar\vec{k}^{\,2}}{m} \quad \text{recoil}$$

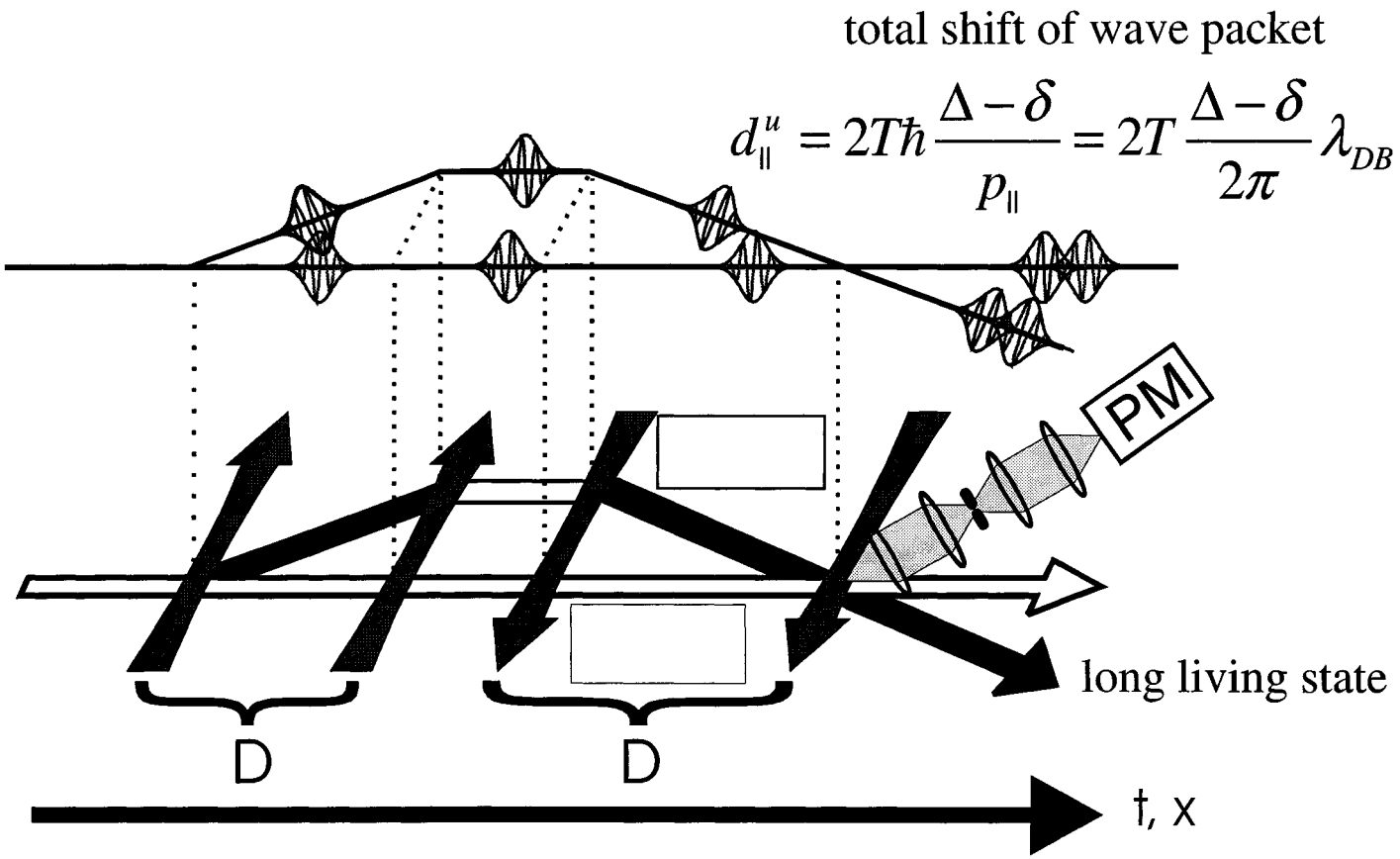
longitudinal momentum transfer

acceleration for phase shift

$$d_{\parallel}=T\frac{\hbar(\Delta-\delta-\mathrm{v}_{\perp}k_{\perp})}{p_{\parallel}}$$

path difference for one zone with traveling time T

Ramsey-Bordé interferometer

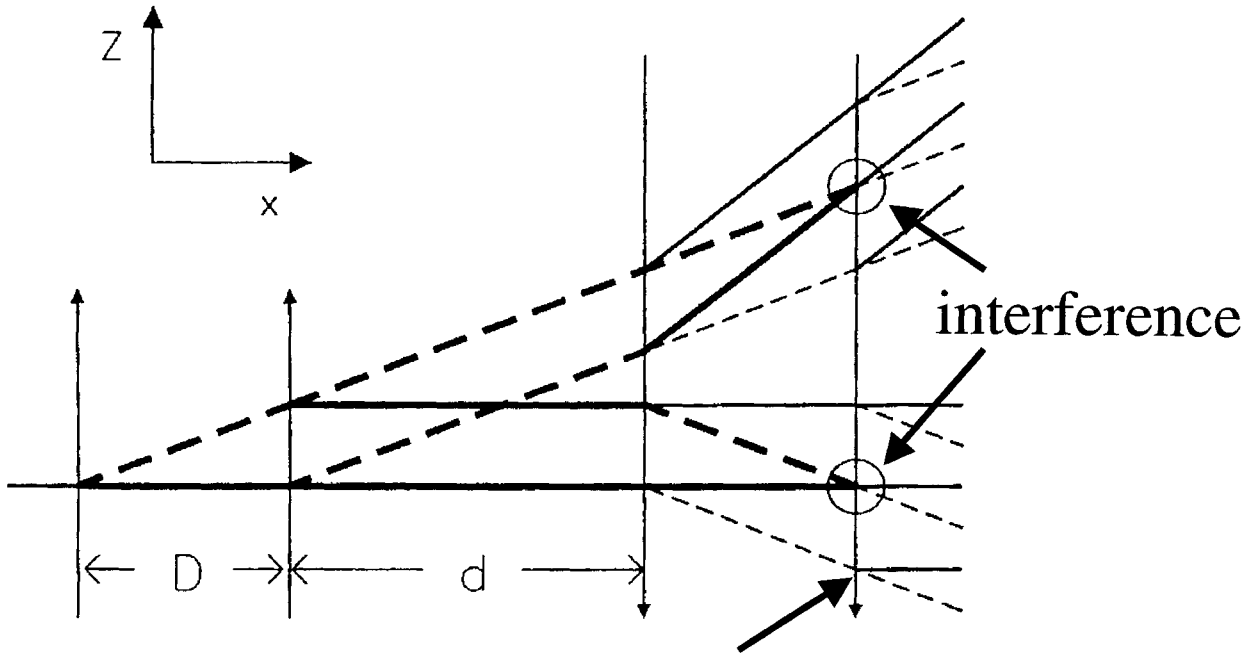


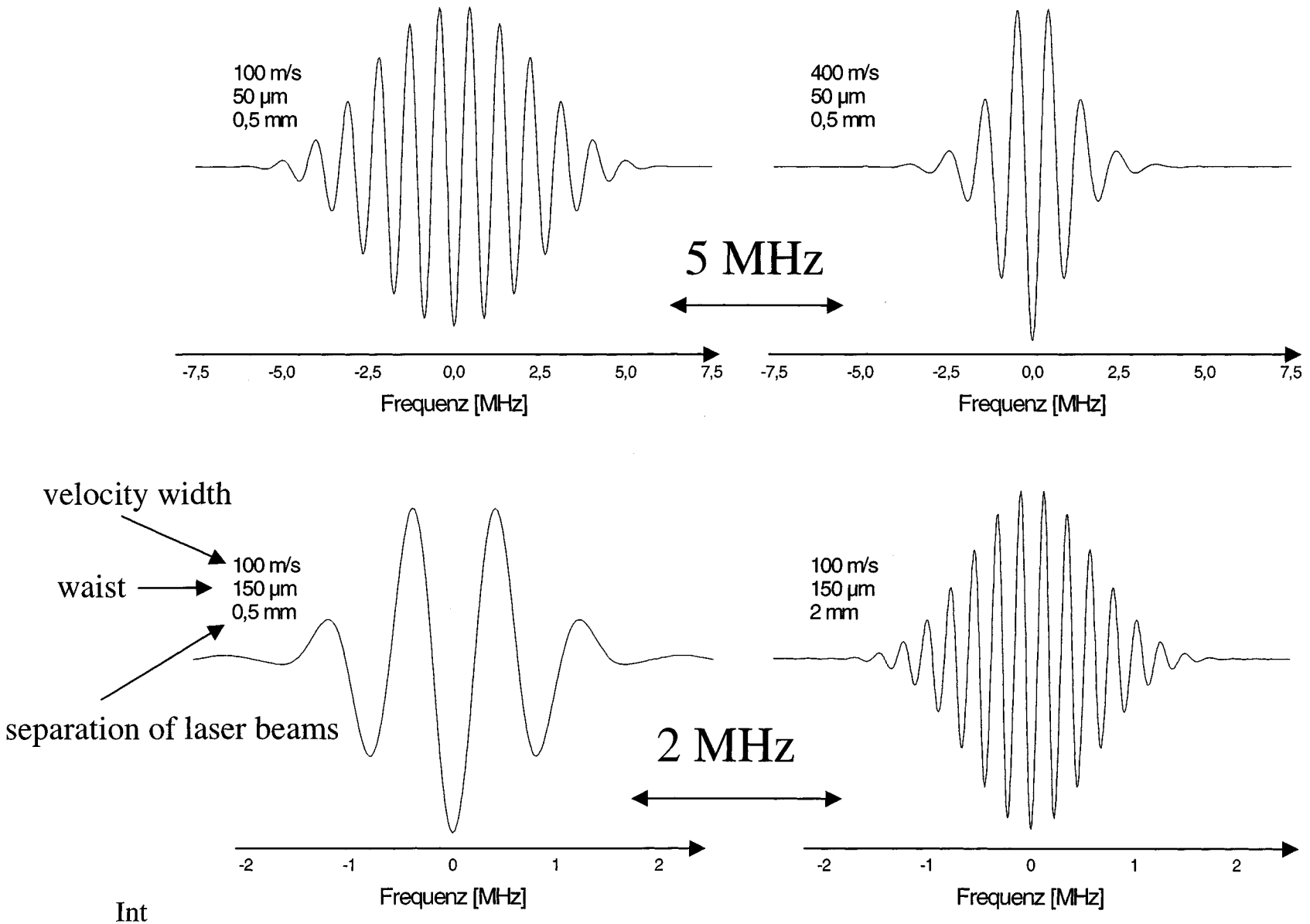
interference: $P_b \propto \cos(\phi) = \cos((\Delta-\delta)\cdot 2T)$

detuning

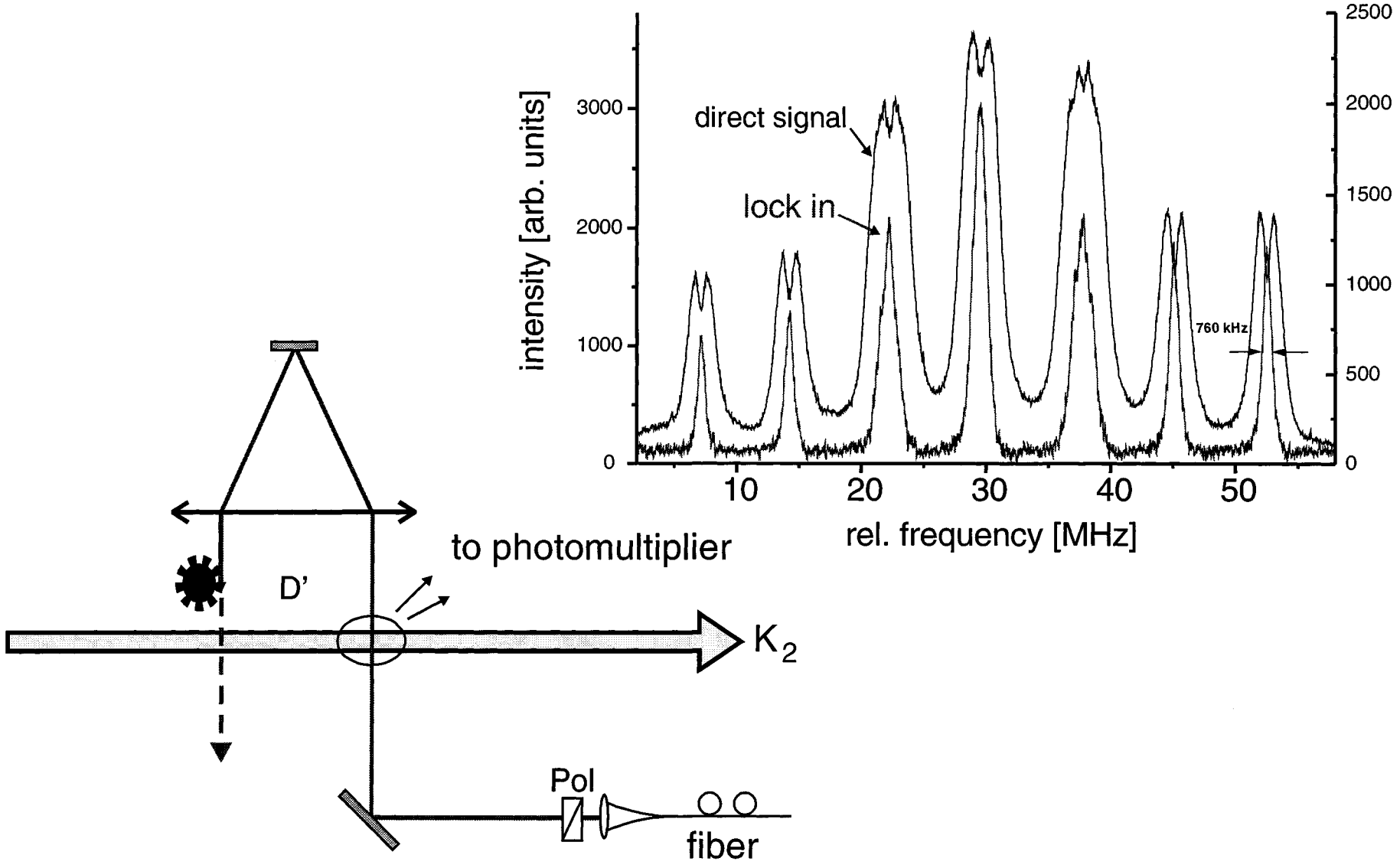
traveling time in D

Different exit ports of the Ramsey-Bordé setup

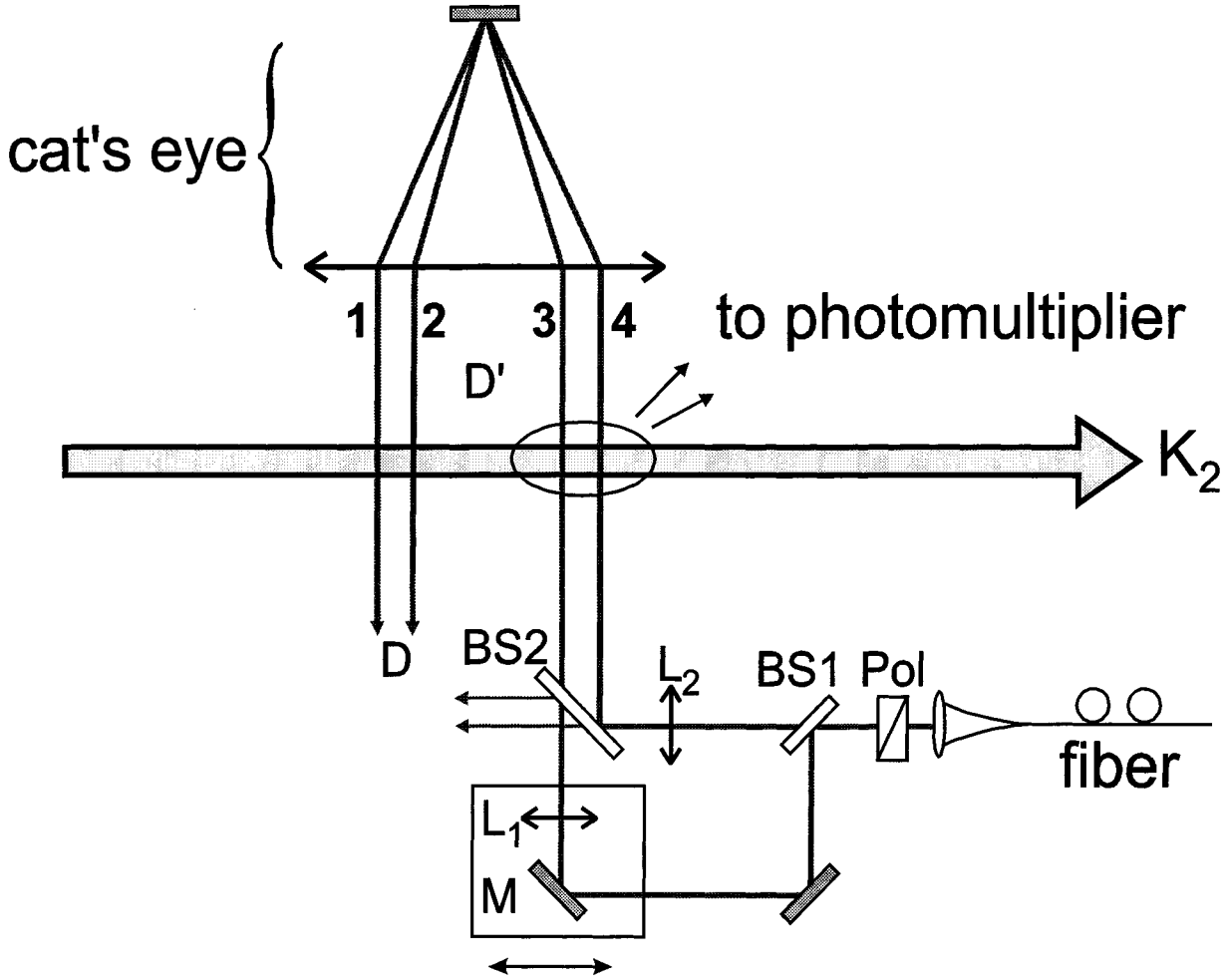



100 m/s
50 µm
0,5 mm
400 m/s
50 µm
0,5 mm
5 MHz
-7,5 -5,0 -2,5 0,0 2,5 5,0 7,5
Frequenz [MHz]
-7,5 -5,0 -2,5 0,0 2,5 5,0 7,5
Frequenz [MHz]
velocity width
waist
100 m/s
150 µm
0,5 mm
separation of laser beams
100 m/s
150 µm
2 mm
2 MHz
-2 -1 0 1 2
Frequenz [MHz]
-2 -1 0 1 2
Frequenz [MHz]

Saturation Spectroscopy on molecular beam

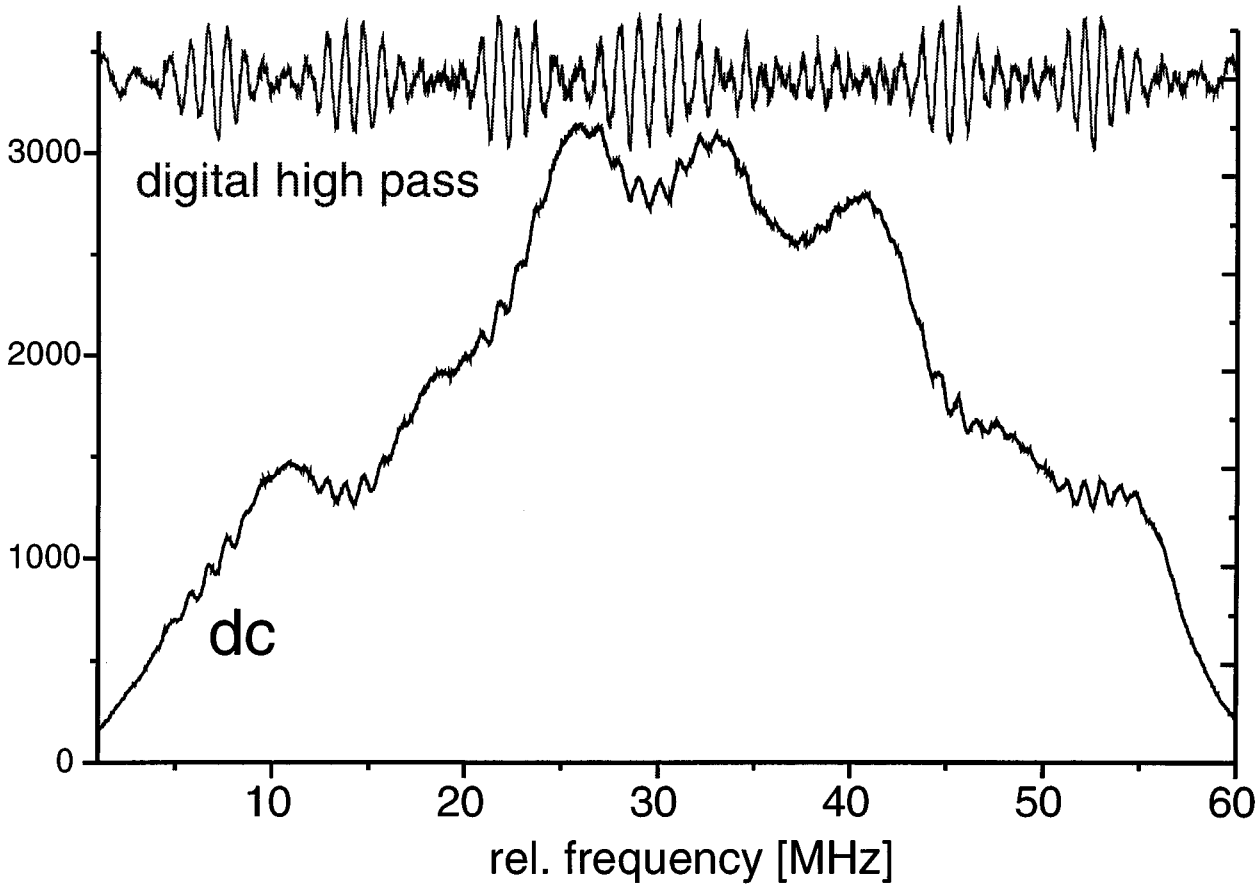


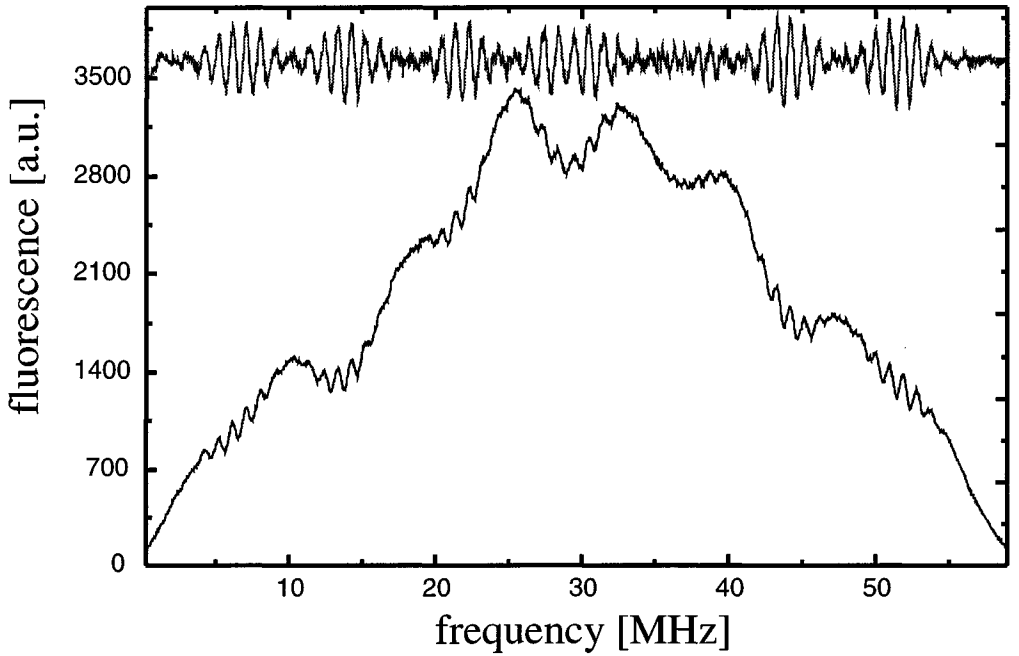
Setup for matterwave interferometer in Ramsey-Bordé configuration



hyperfine structure of $b\,^3\Pi_u\,0^+$

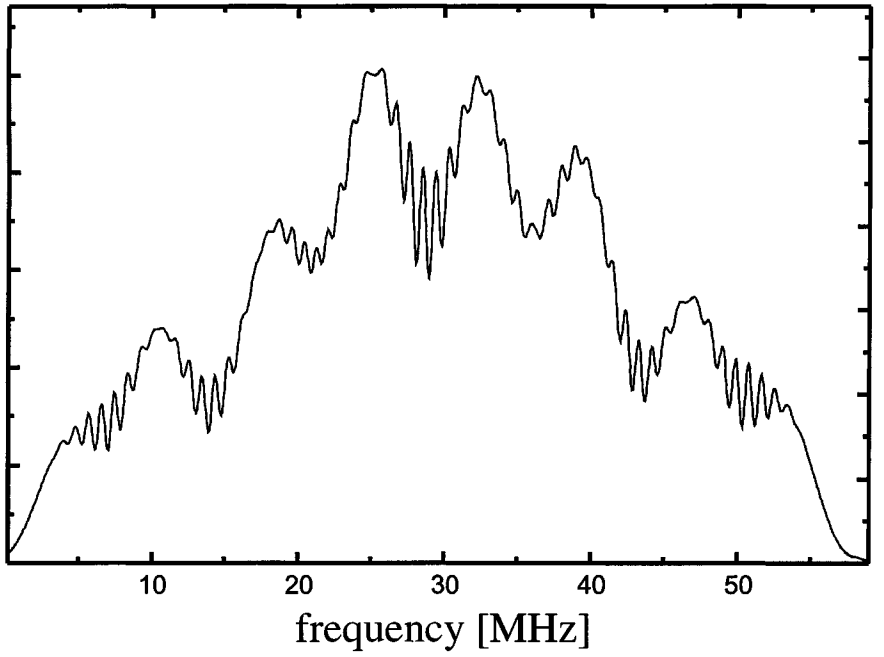
with interference pattern



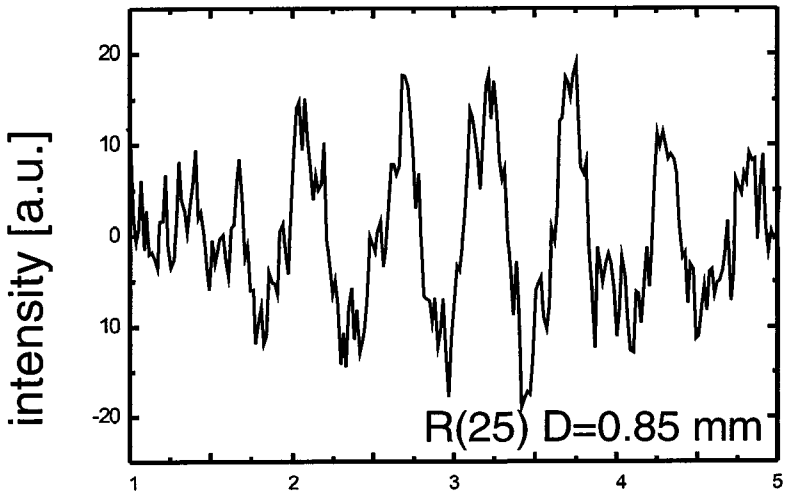


digital filtering

observation



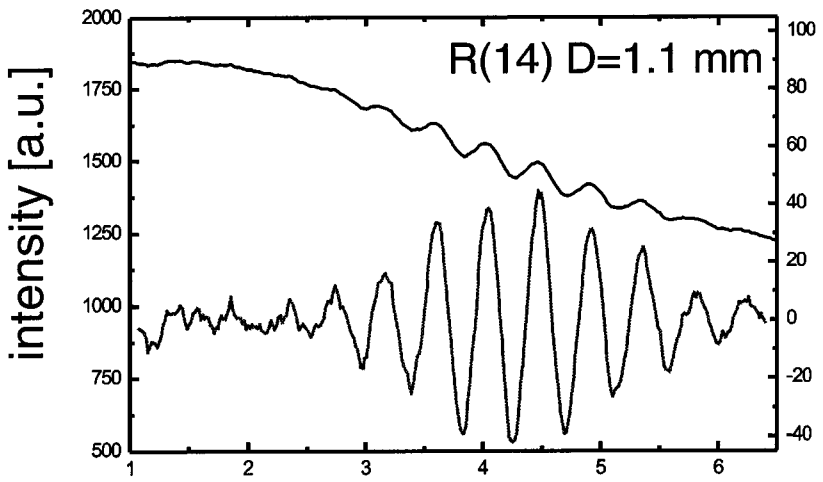
simulation

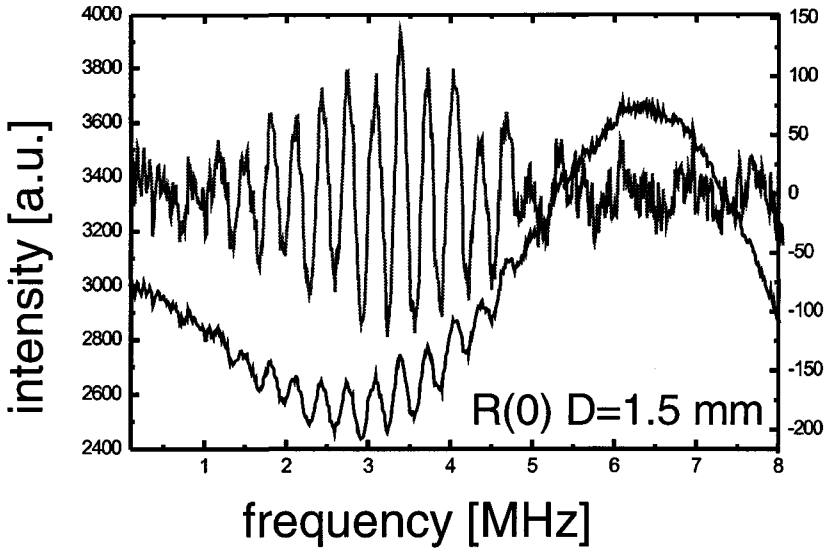


Variation of angular momentum
giving variation of life time

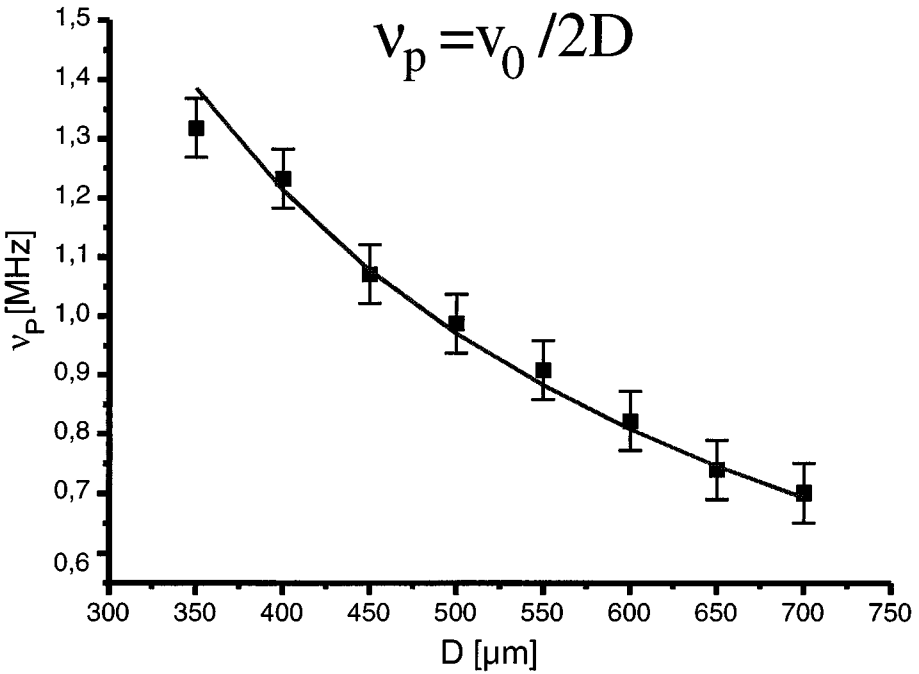
here about a factor of 2

Variation of beam separation

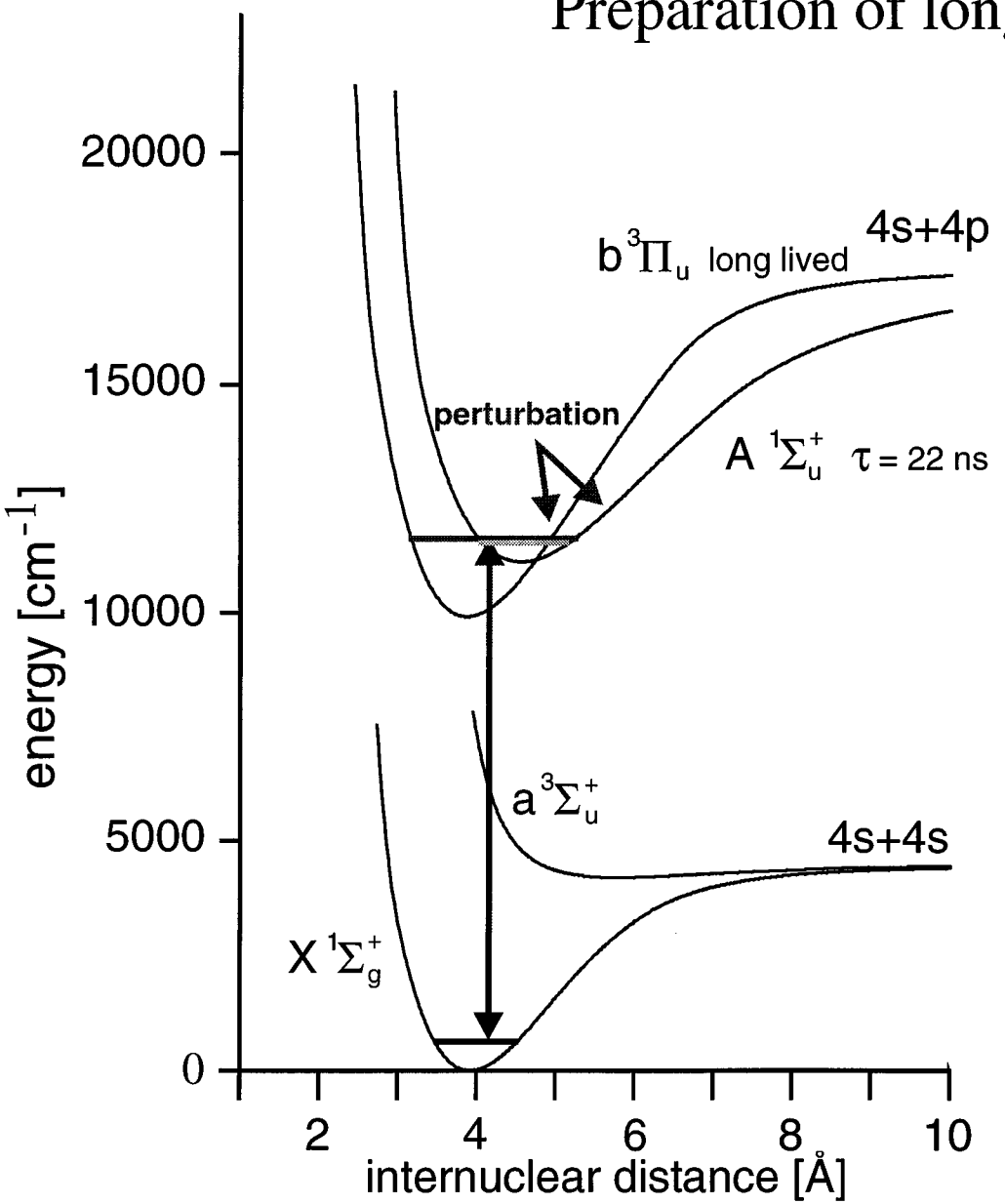




Dependence of oscillation frequency on D

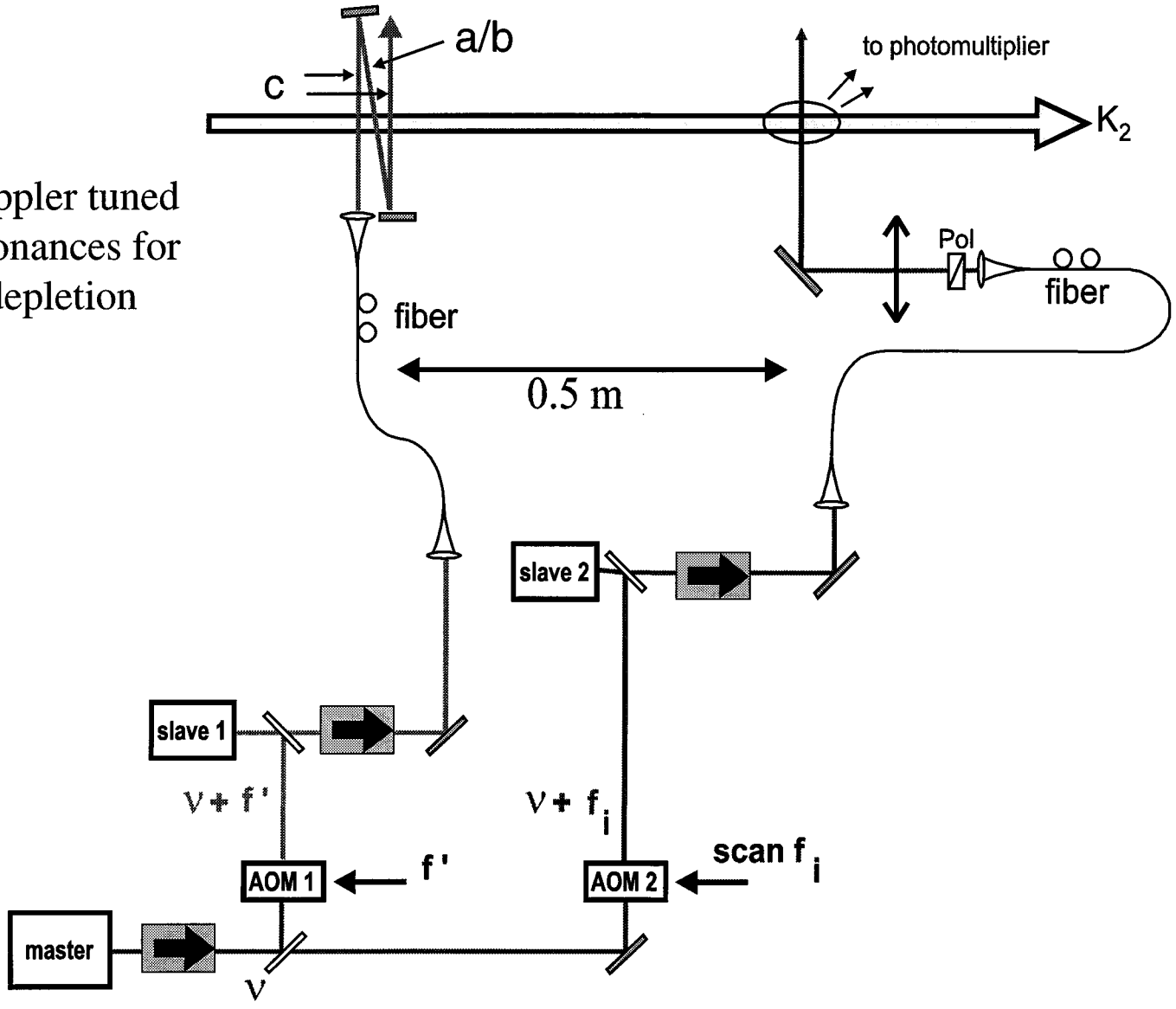


Preparation of long living states

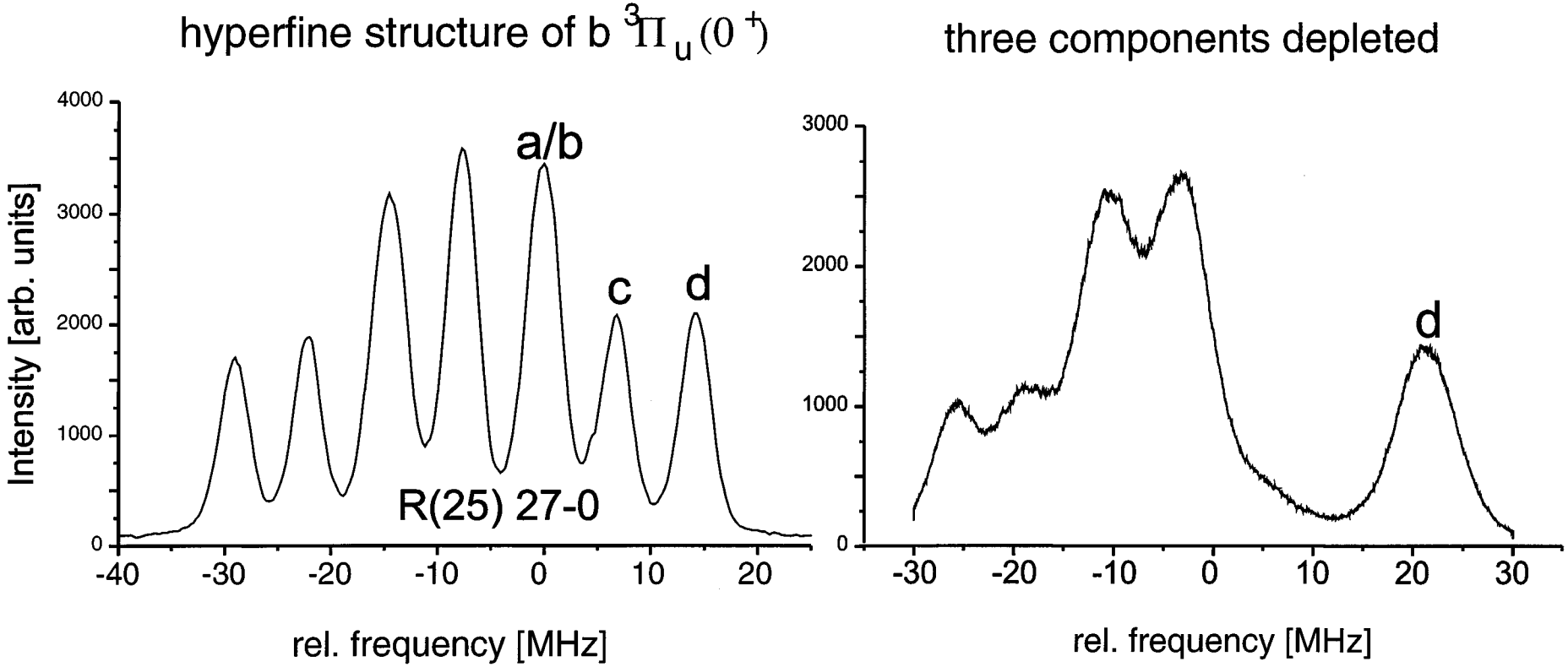


depletion of hyperfine components

Doppler tuned resonances for depletion

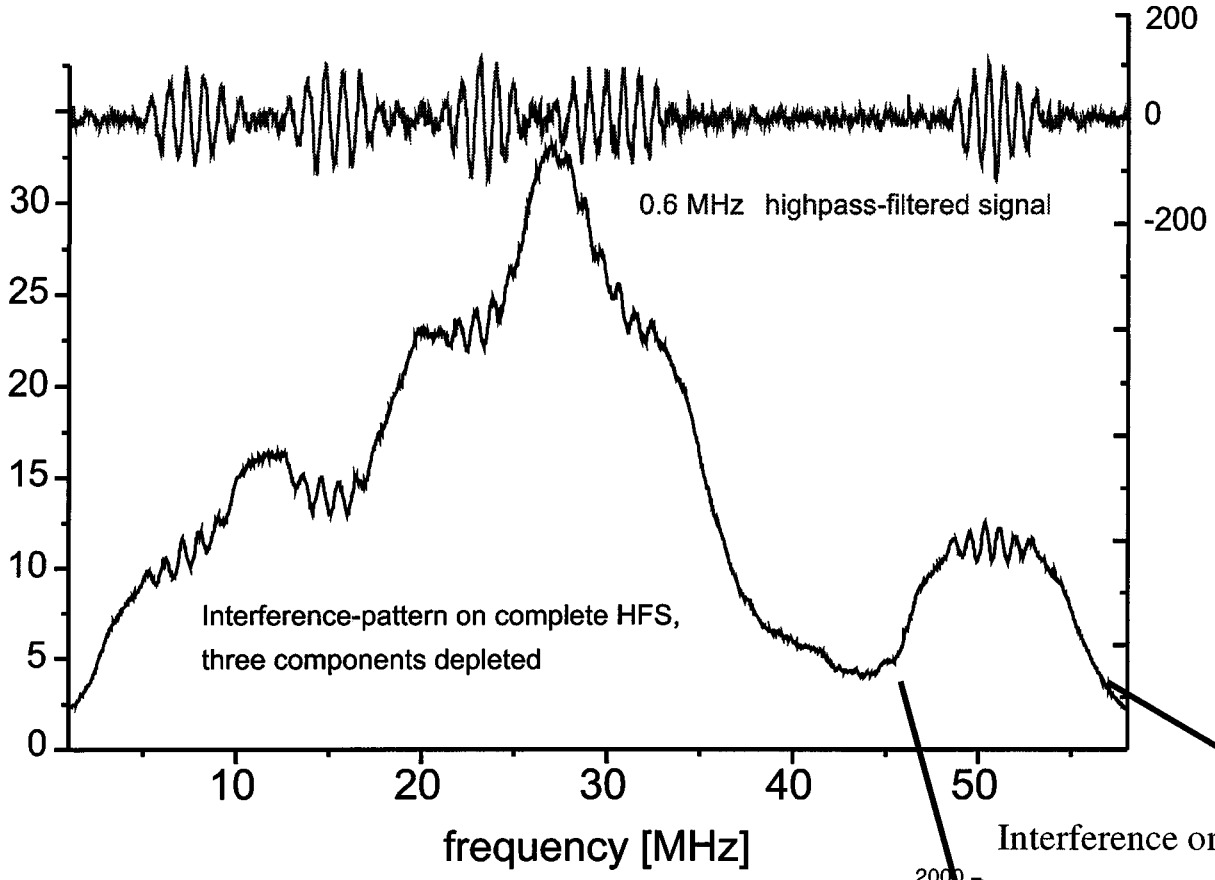


Depletion of hyperfine components

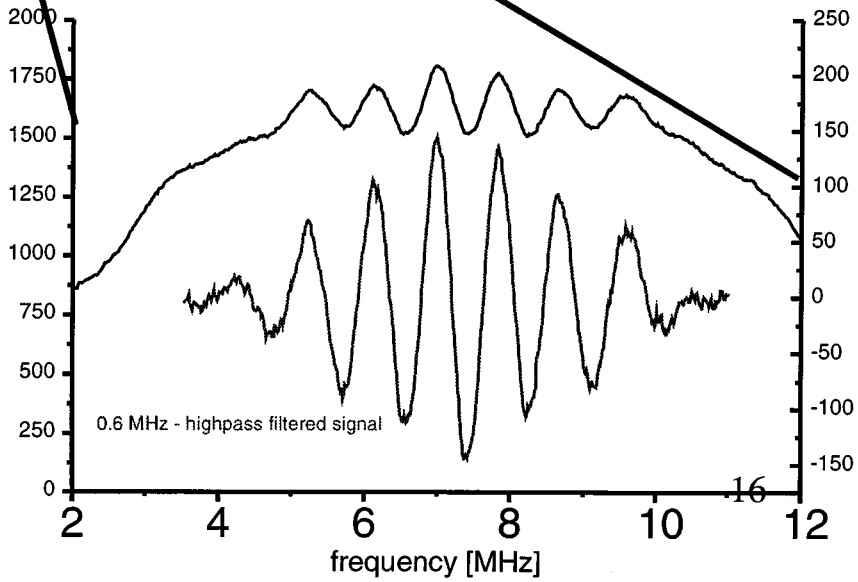


The different line widths result from transient line broadening.

laser beam waist



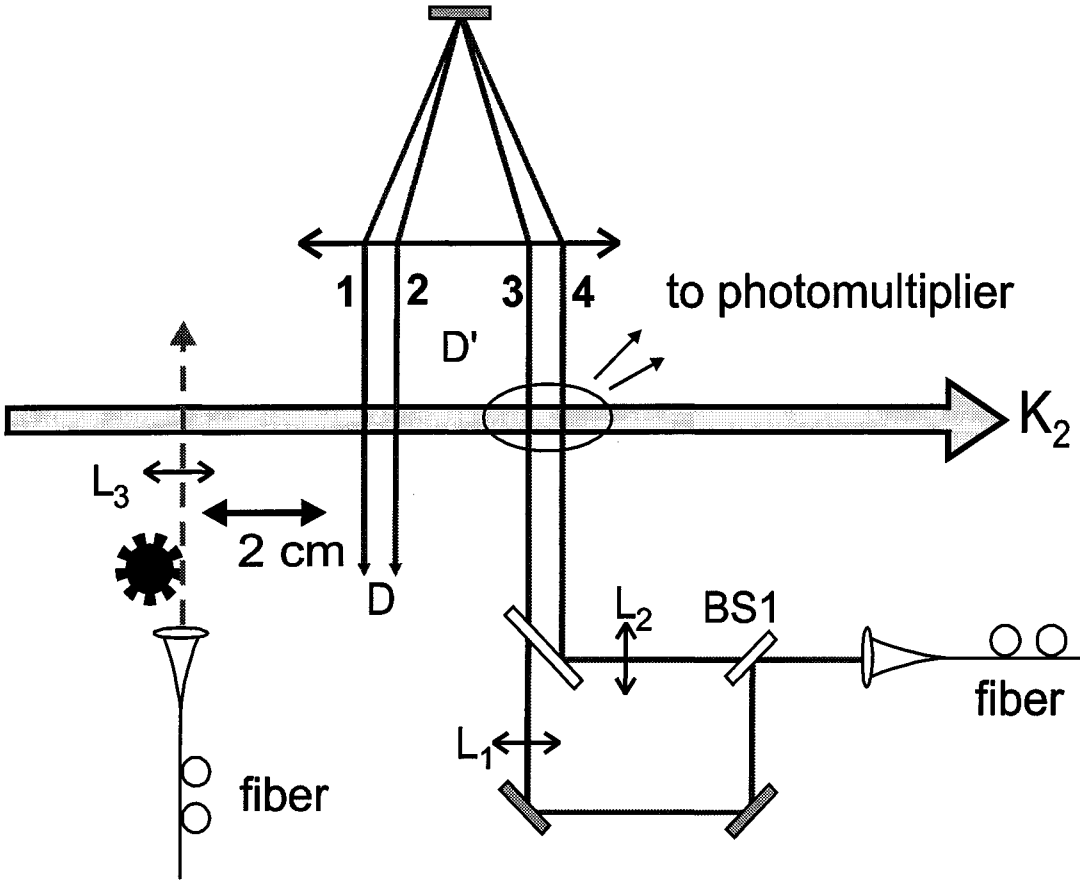
Interference on isolated hyperfine component

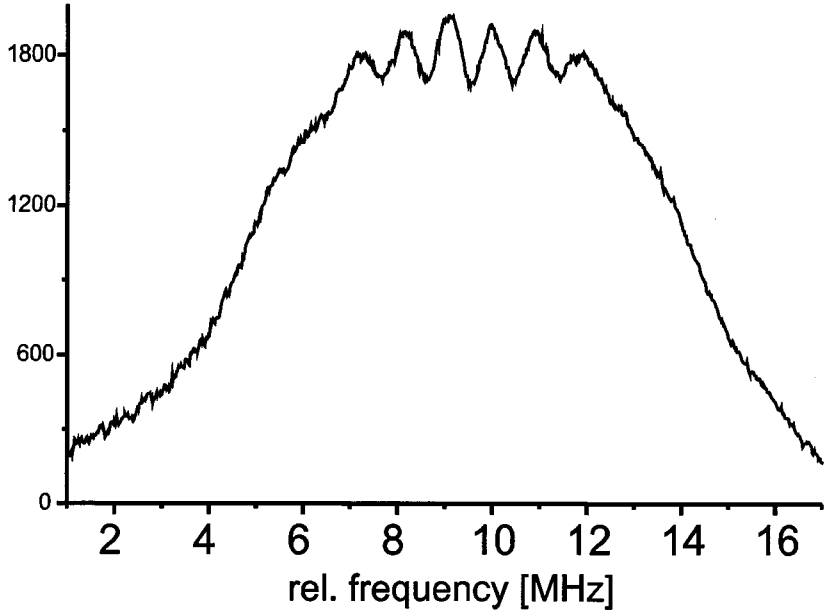


depletion of hyperfine components

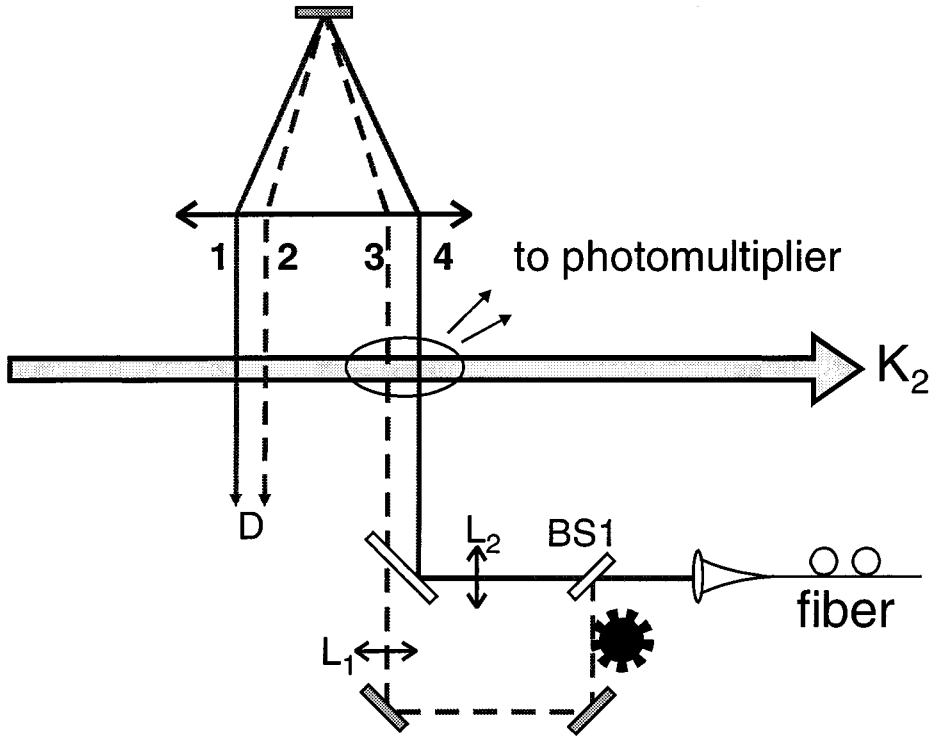
Int

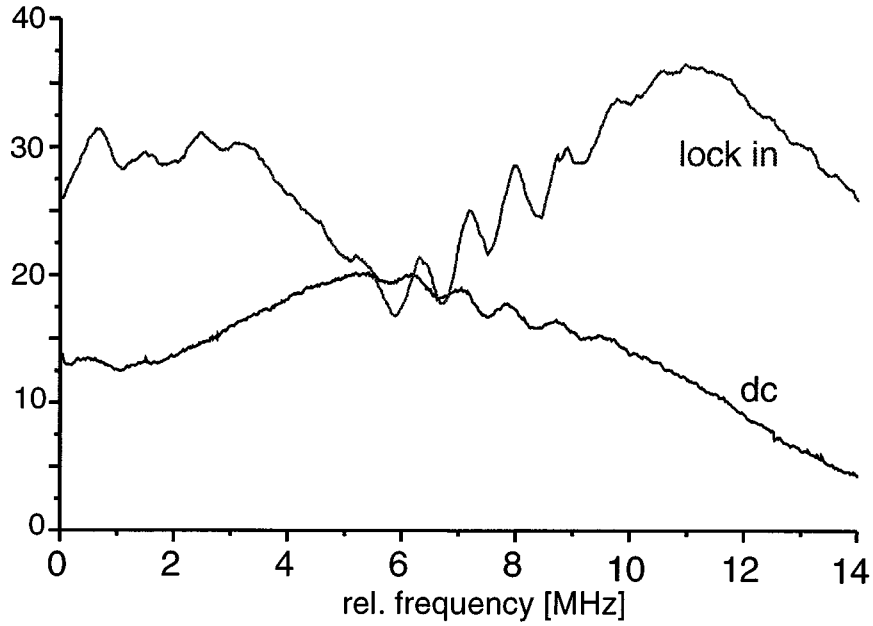
chopped depletion laser



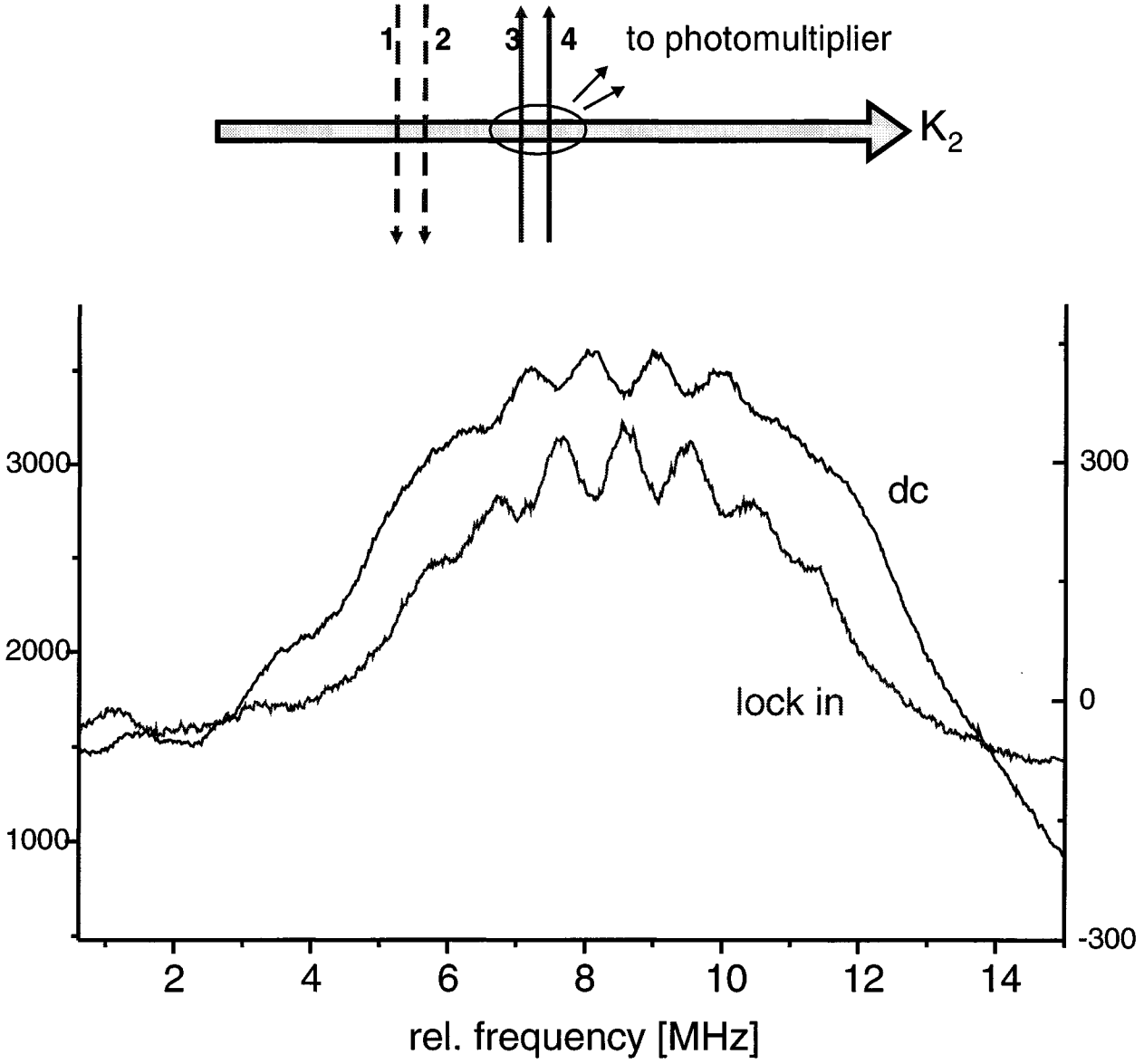


Chopped laser beams in the interferometer

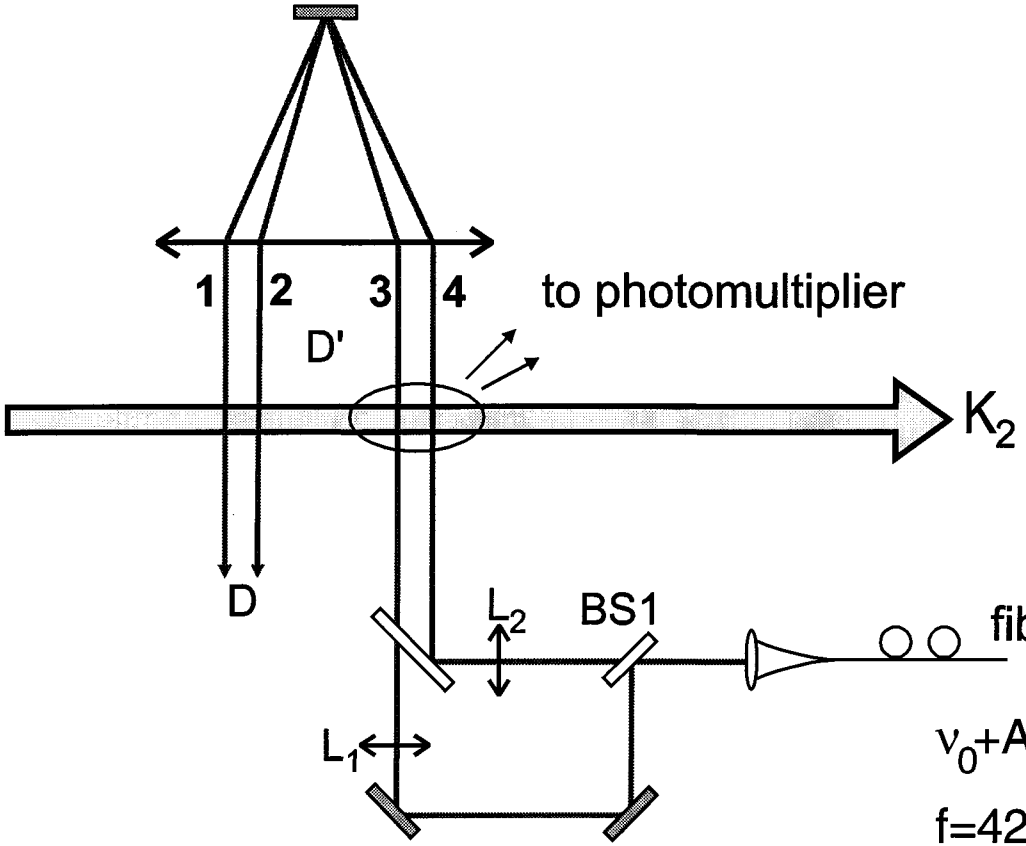


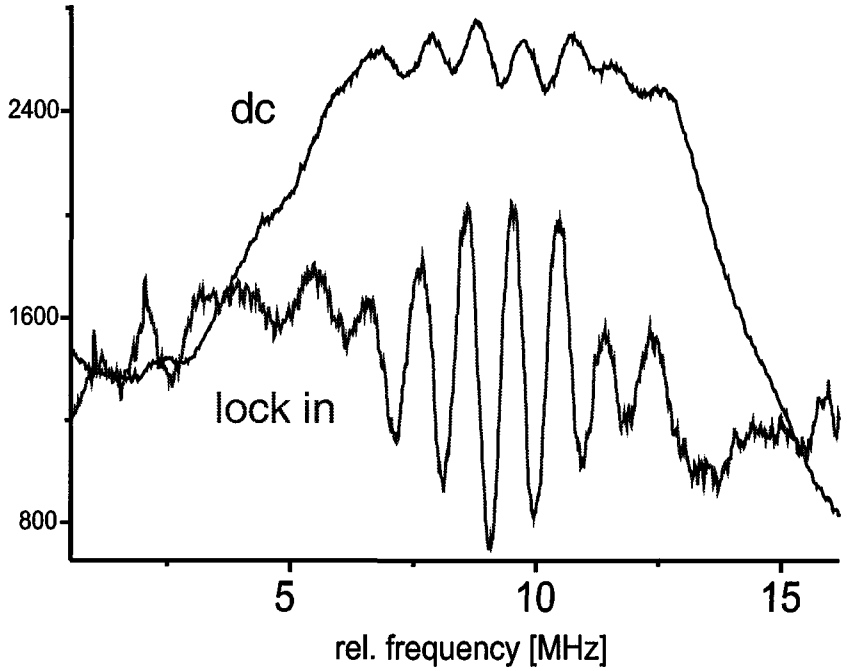


1.+2. laserbeam in the interferometer chopped



frequency modulation of all laserbeams in the interferometer





ν_0+A·sin 2πft

f=420 Hz

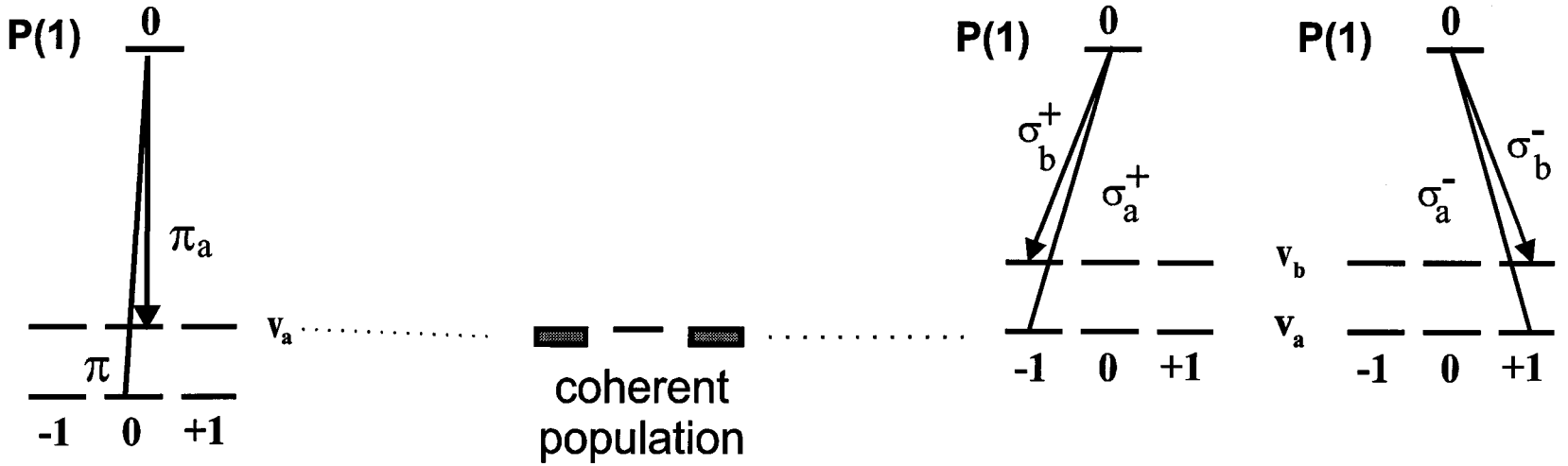
A~0.4 MHz

STIRAP for preparation

STIRAP for beamsplitter / mirror

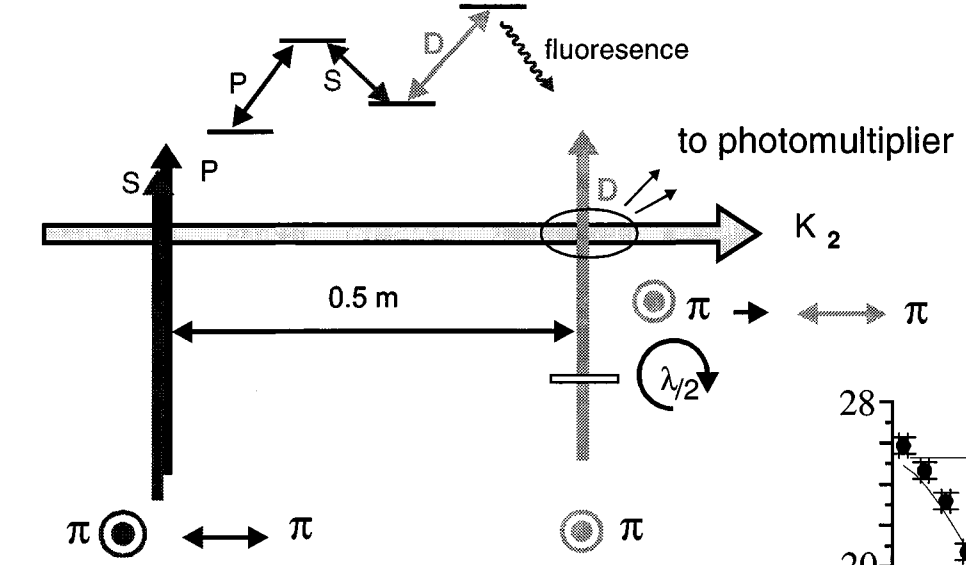
quantization parallel to molecular beam

quantization perpendicular to molecular beam



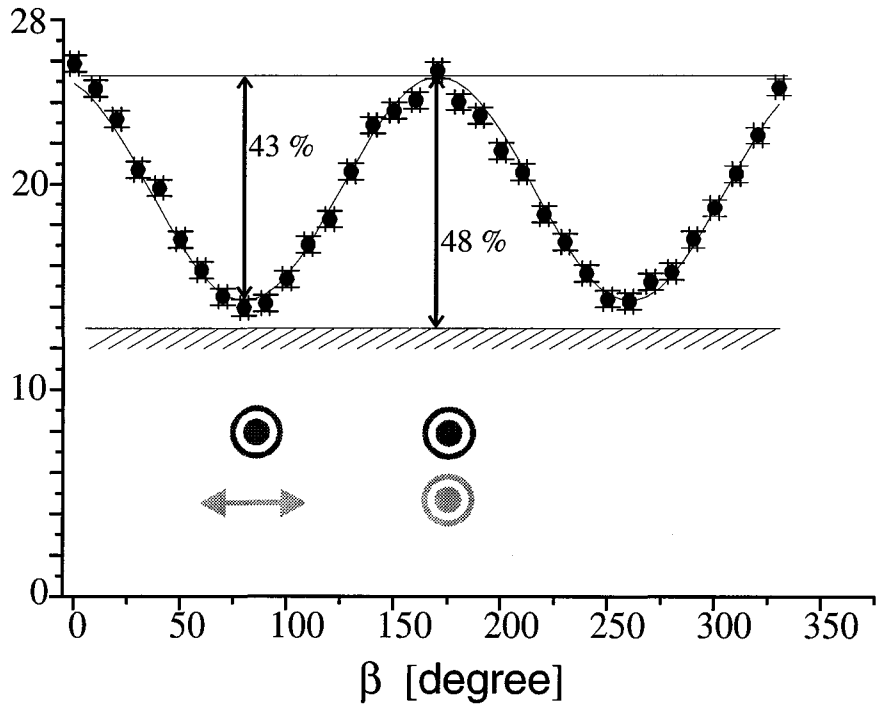
additional influence of ground state hyperfine structure

Alignment



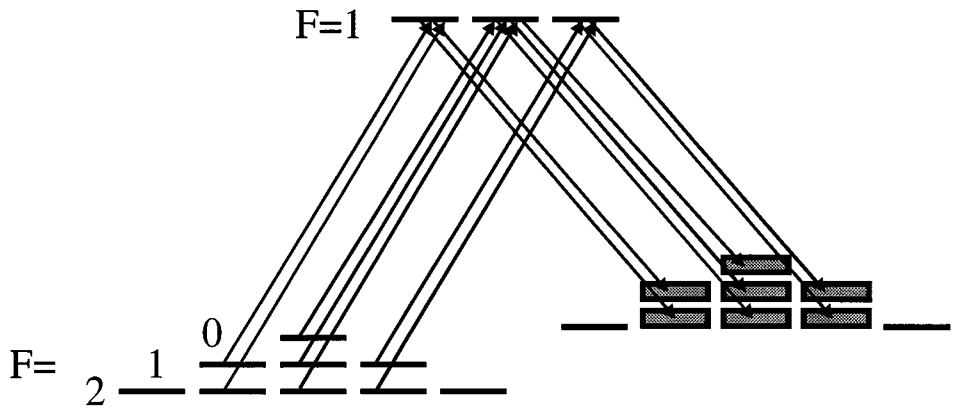
preparation by STIRAP

probe



Extended system due to HFS

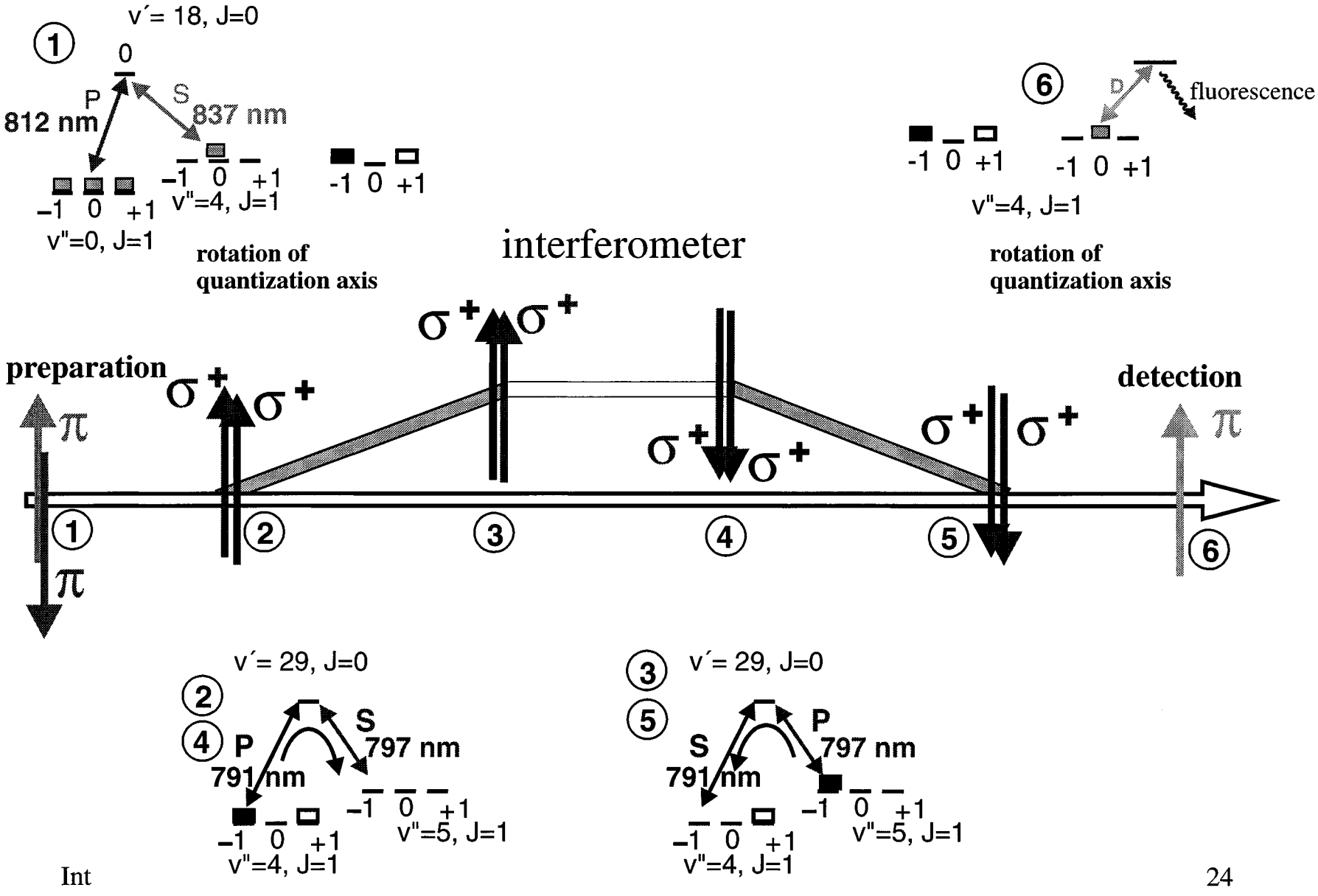
e.g. I=1 (I=3 also present for J=1 !)



$\Rightarrow$ reduced alignment

$\Rightarrow$ reduced contrast in interferometer

molecular ground state interferometer



Estimation of the observation of cold collisions between K and K_2

Collisions induce **phase shifts** in the interfering wave-packets, which depend sensitively on the **long-range potential**

phase shift $\Delta\varphi$ of the matter wave:

$$\Delta\varphi = \frac{2\pi}{k_c} N \cdot L \cdot \mathrm{Re}\left(f(k_c)\right)$$

$$k_C = \frac{2\pi}{\lambda_{DB}} : \textit{wave vector in cm-system}$$

N : *collision partner denstity*

L : interaction *length*

$f(k_C)$: *forward scattering amplitude*

$\Delta\varphi$ can be interpreted in terms of index of refraction:

$$n = 1 + \frac{2\pi}{k_C k_{Lab}} N f(k_C)$$

Pritchard [1]

Collision partners:

Na - He, Ne, Ar, ...
CO_2, NH_3, ...
Na_2 - He, Ne, Ar, ...

Experimental conditions:

mechanical gratings
spatially separated arms

L=0.1 m
$N \sim 3 \cdot 10^{13} cm^{-3}$
$\lambda_{DB} \sim 25$ pm
($v_{rel} \sim 1000\ ms^{-1}$)

$\Delta\varphi \sim 0.5...6$ rad

Our experiment

Collision partners:
K_2 - K

Experimental conditions:

light fields as beam splitters
no separation of interferometer arms

L ~ 0.001 m
$N \sim 9 \cdot 10^{12} cm^{-3}$
$\lambda_{DB} \sim$ 150 pm ... 0.5 nm
($v_{rel} \sim 50 ... 15\ ms^{-1}$)
difference between $f(^1\Sigma)$ - $f(^3\Pi) > 10\%$

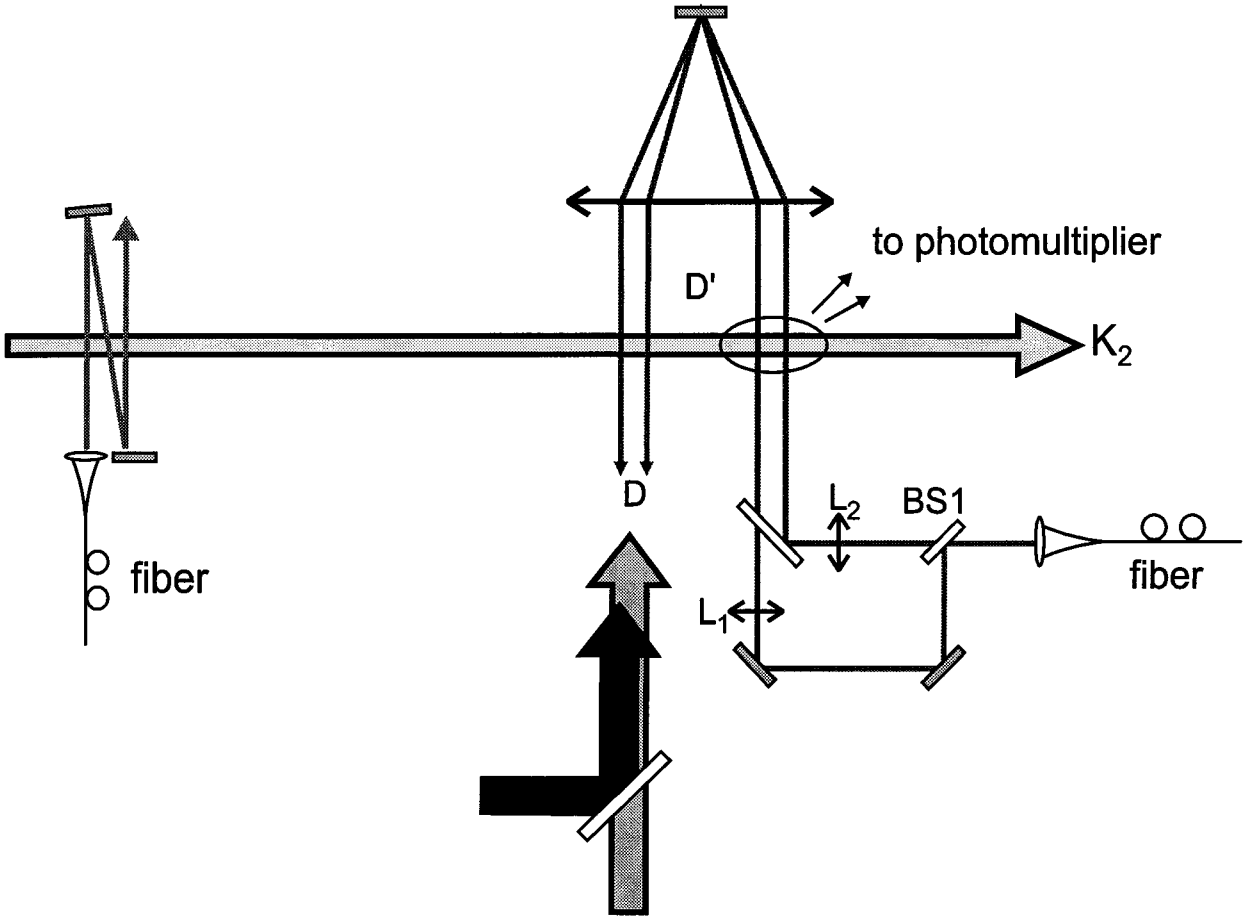
$\Delta\varphi \sim 0.03$ rad

possible gain by exciting
K Rydberg atoms:

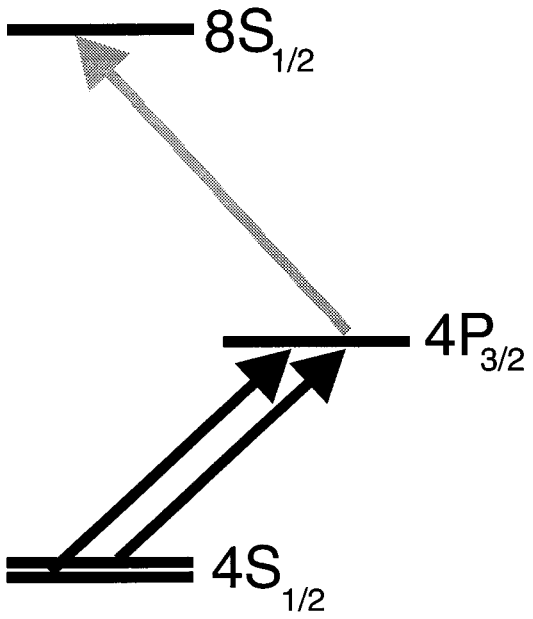
f is function of C_6
$C_6 \sim$ polarisibility $p_k \sim n^{*7}$

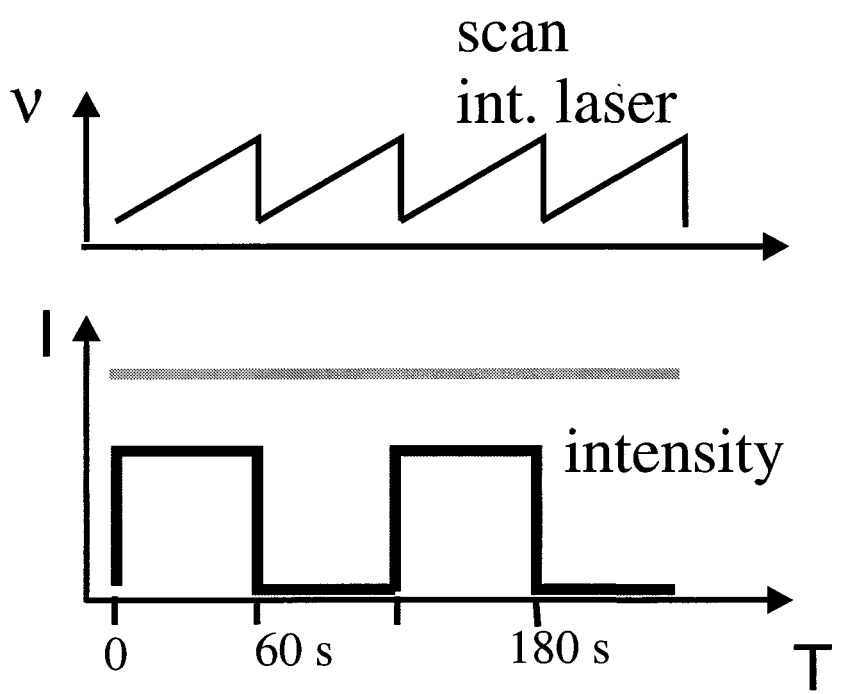
[1] Schmiedmayer *et al.* Phys. Rev. Lett. **74**, 1043 (1995)
Chapman *et al.* Phys. Rev. Lett. **74**, 4783 (1995)

Setup for collision experiments of K_2 with K Rydberg atoms



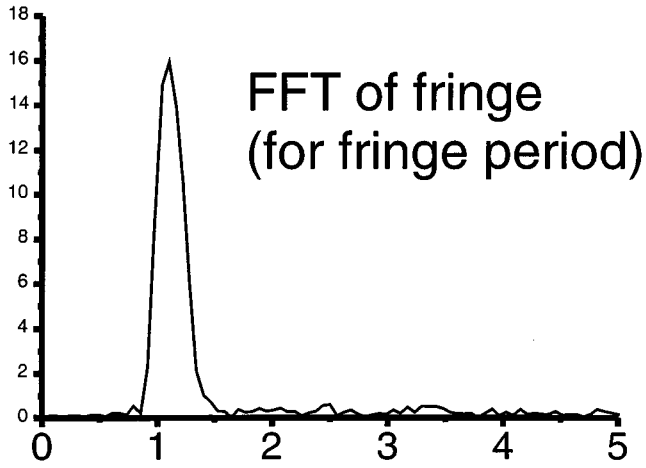
time sequence of the collision experiment

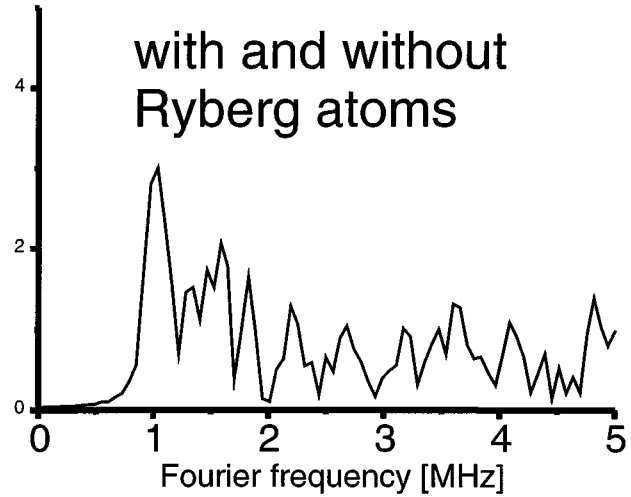




pure interferogram

difference of two recordings





Conclusions

- Ramsey-Bordé interferomter for K_2 realized
- precision molecular spectroscopy, presently observed limit 10kHz
- sensitivity for weak collisions in molecular beams
- new concept for very long living states
- improved sensitivity expected
  - collisions shifts in reference spectra
  - study of weak interactions