Towards realization of the E-P-R experiment for atoms created *via* molecular dissociation in pulsed supersonic beam
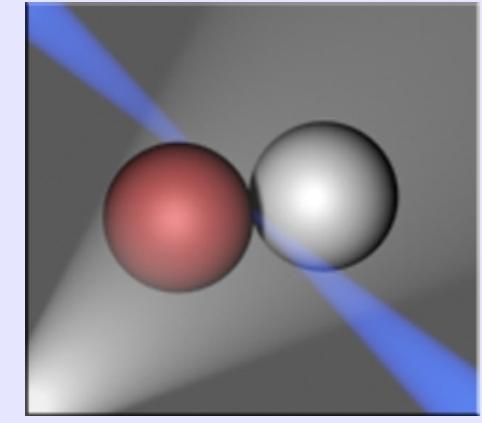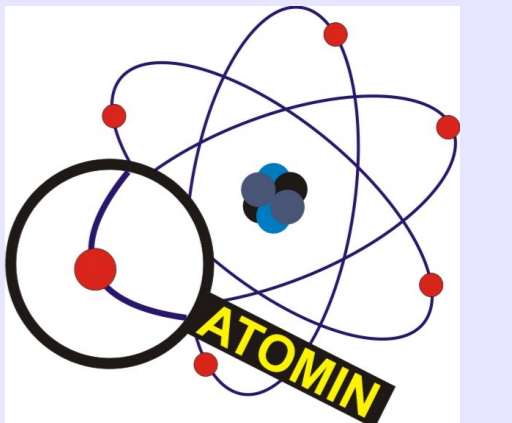
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Molecular Spectroscopy and Quantum Information

Atomic Scale Science for Innovative Economy

Introduction

An idea of realization of the Einstein-Podolsky-Rosen experiment [1] for two spin-1/2 ^{111}Cd atoms is presented. The concept is based on the proposal of Fry *et al*. formulated for ^{199}Hg [2]. In the experiment presented here, the Cd_2 molecules are produced in a pulsed supersonic beam. Next, the $^{111}Cd_2$ molecules are irradiated by two laser pulses and dissociated in a process of stimulated Raman passage. As a result, two entangled ^{111}Cd atoms with anti-parallel nuclear spins are produced. Orientation of the nuclear spins is recorded using spin-state-selective two-photon excitation-ionization method [3]. Current status of the preparation stage of the experiment is reported.
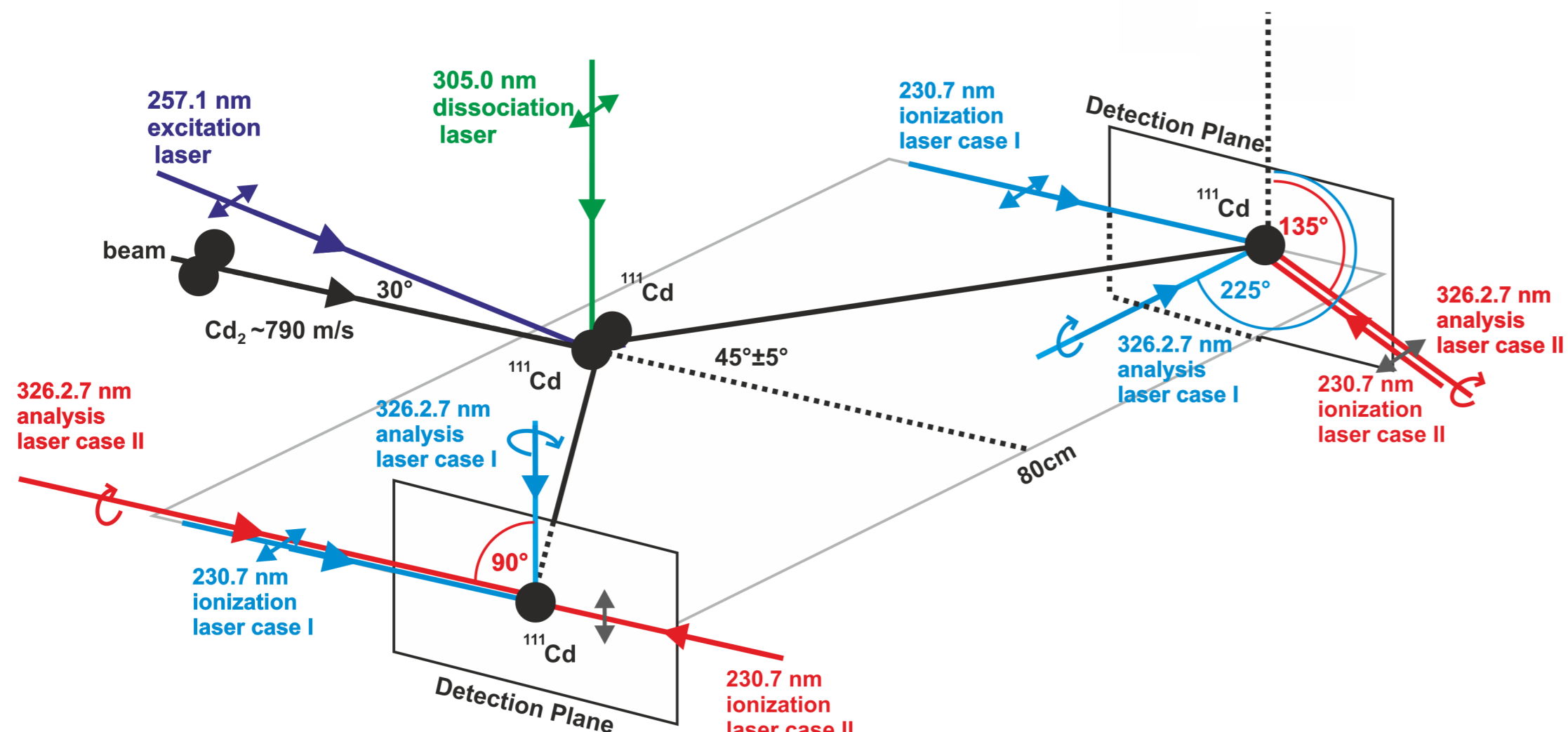
General scheme of the experiment

Fig. 1

The $^{111}Cd_2$ molecule in pulsed supersonic beam is dissociated into two ^{111}Cd atoms (black solid lines). In two parallel detection planes, a spin selective detection of ^{111}Cd atoms is taking place. The detection relies on a two-photon excitation-ionization method. Angles between vertical direction perpendicular to the plane in which the atoms are propagating, and analysis and ionization beams are selected in the way which ensures the maximum violation of Bell inequality (for details see Ref. [3]).

Creation of entangled cadmium atoms

In the experiment, ^{111}Cd -^{111}Cd pairs of entangled atoms are produced using laser dissociation of $^{111}Cd_2$ dimers produced in a pulsed supersonic beam (see Fig. 1). Laser dissociation of $^{111}Cd_2$ takes place due to the stimulated Raman transition (SRT) from the $X^10_g^+(5^1S_0)$ ground *via* the $A^10_u^+(5^1P_1)$ excited and back to the repulsive part of the $X^10_g^+$ state (see Fig. 2). Due to the momentum conservation principle, in the process a pair of entangled atoms - each in $(5s)^1S_0$ ground state - is created. It is crucial, that the ^{111}Cd isotope in its ground state possess only one non-zero angular momentum (nuclear spin I=1/2, while S, L and J are all zero). Because in the $^{111}Cd_2$ molecule in the $X^10_g^+(^1\Sigma_g^+)$ state all momenta are zero, it leads to the conclusion that the nuclear spins of the two ^{111}Cd atoms (oriented in opposite directions) are entangled. In the SRT process it is imperative to excite the $^{111}Cd_2$ molecule only to one strictly specified $A^10_u^+$ state J' rotational level. The $A^10_u^+(v'$=40,J'=5)$\leftarrow X^10_g^+(v''$=0,J''=6) transition (257.1nm, 20MHz) was chosen. After the dissociating transition (305.0nm, 2GHz), the separation angle between the two ^{111}Cd atoms should be equal to 90 ± 10°.
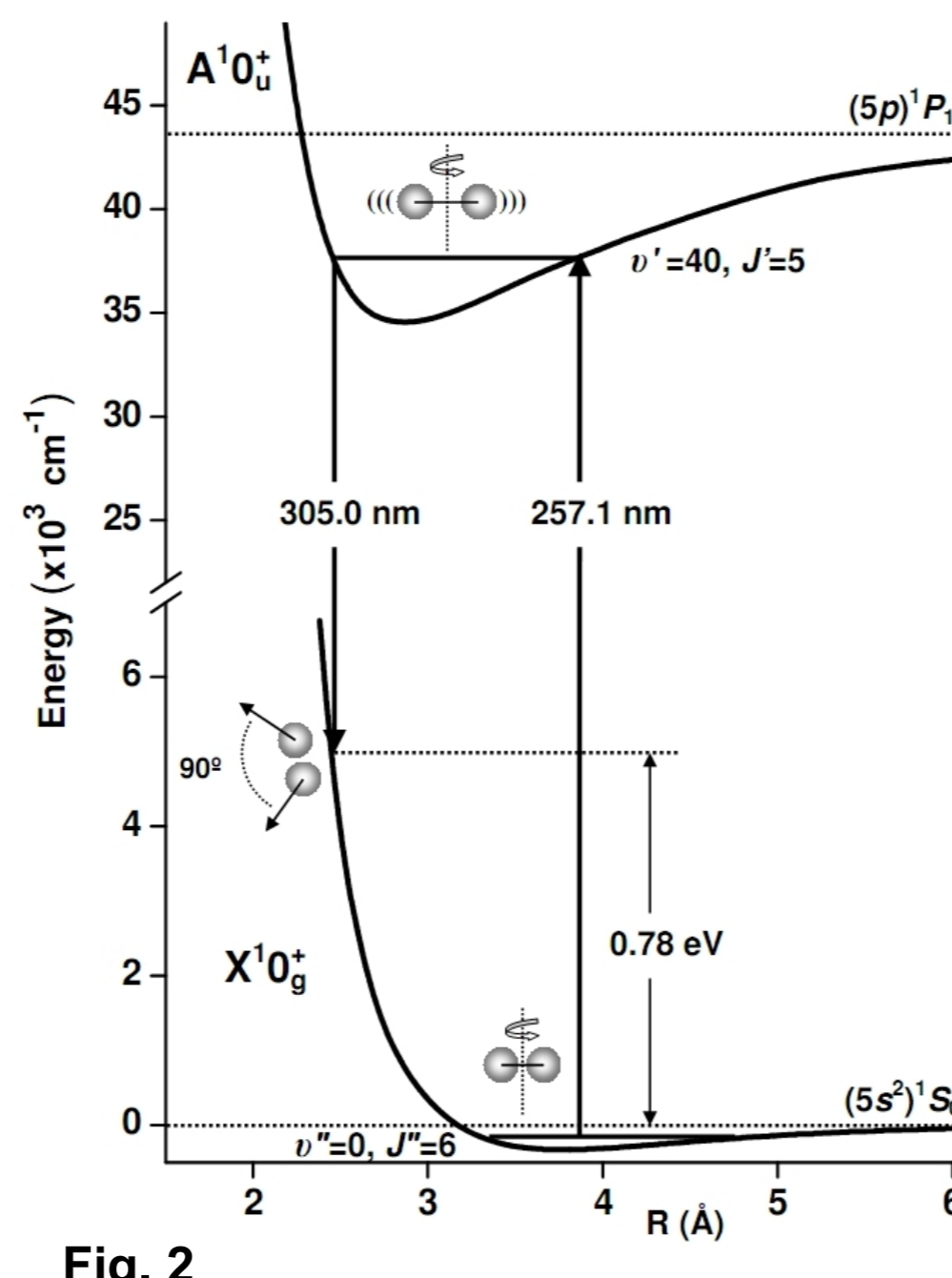

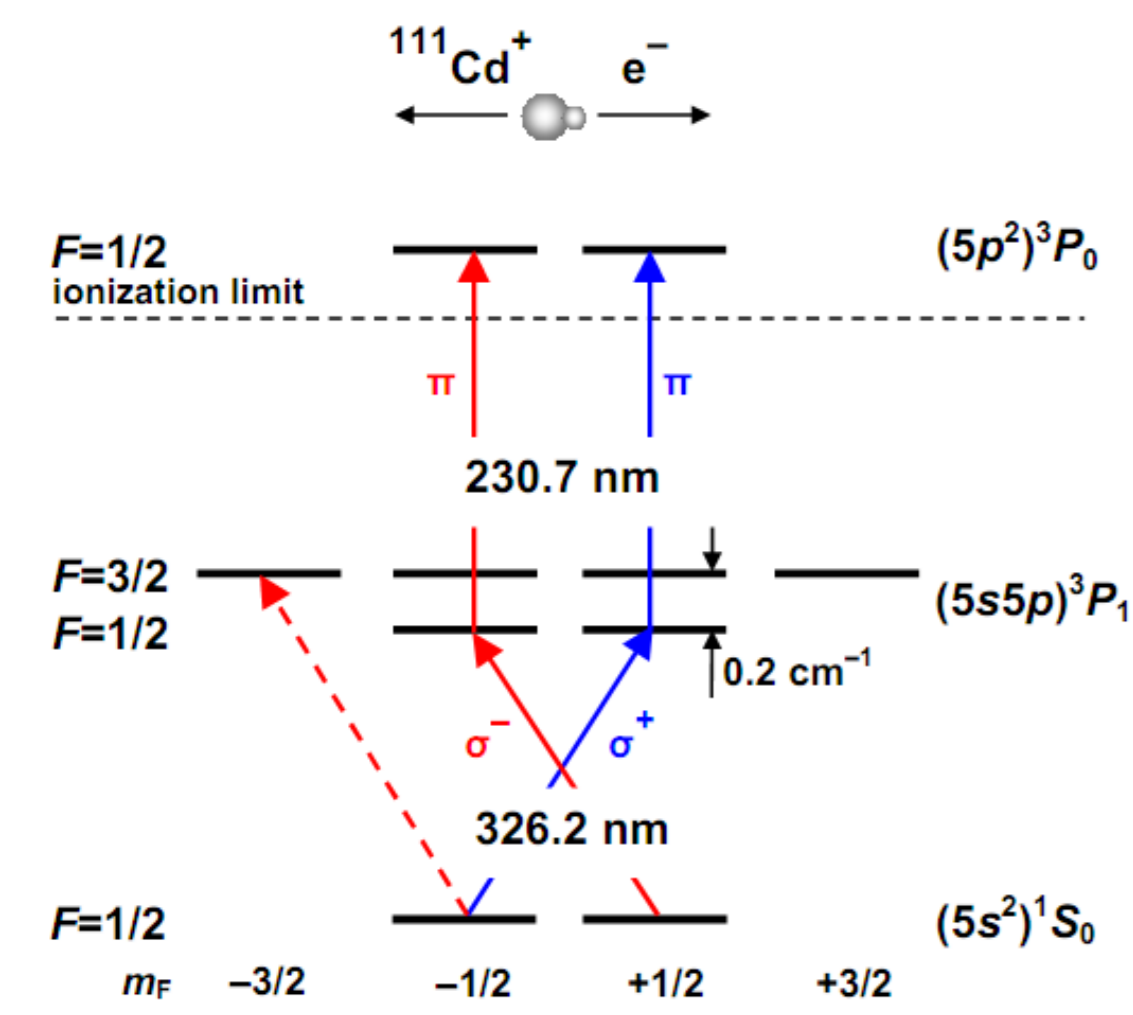**Fig. 2**

Spin selective detection of atoms

Fig. 3a

To selectively detect orientation of ^{111}Cd nuclear spin a two-photon excitation-ionization method [2,3] is used. Circularly polarized analysis-laser beam (326.2 nm, 2GHz) can selectively excite only one F level in the hyperfine structure (HFS) of the 5^3P_1 state (see Fig. 3a). The HFS splitting is about 6GHz. Because the only non-zero angular momentum in the $(5s)^1S_0$ state of ^{111}Cd is the nuclear spin I, the excitation of the ^{111}Cd is possible only if orientation of the nuclear spin is properly correlated with circular polarization of the analysis-laser beam (σ^+ and σ^- can only excite atoms with m_F=-1/2 and m_F= +1/2, respectively). The second, ionization-laser beam (230.7nm, 2GHz) is linearly polarized (π) and ionizes the excited ^{111}Cd to the $(5p^2)^3P_0$ state in the ionization continuum. After focusing by electrostatic lenses, products of the ionization process (ion and electron) can be detected by channeltrons. Figure 3b presents detector of ions and electrons designed for this experiment and installed in detection chambers (see Fig. 4).
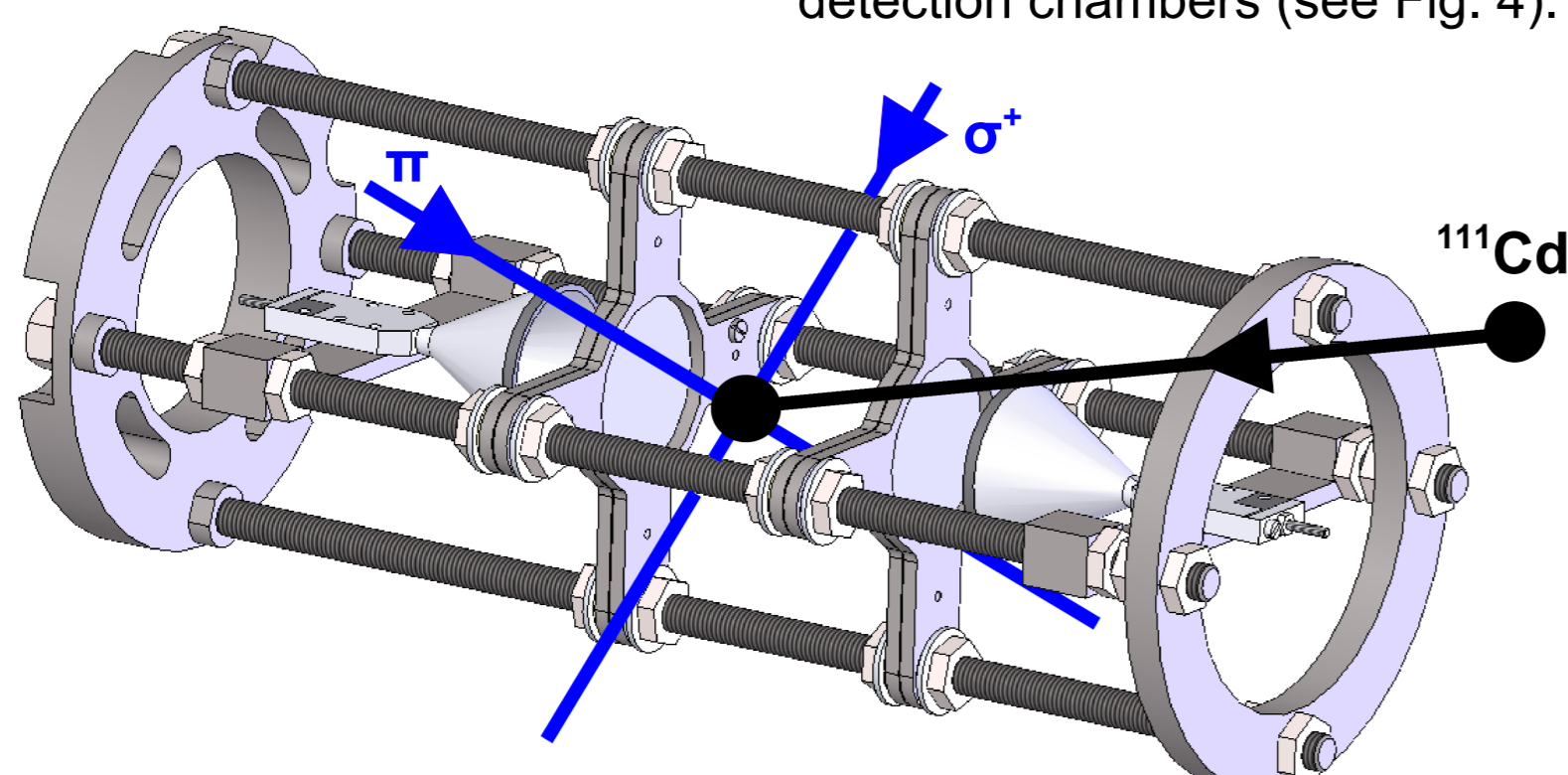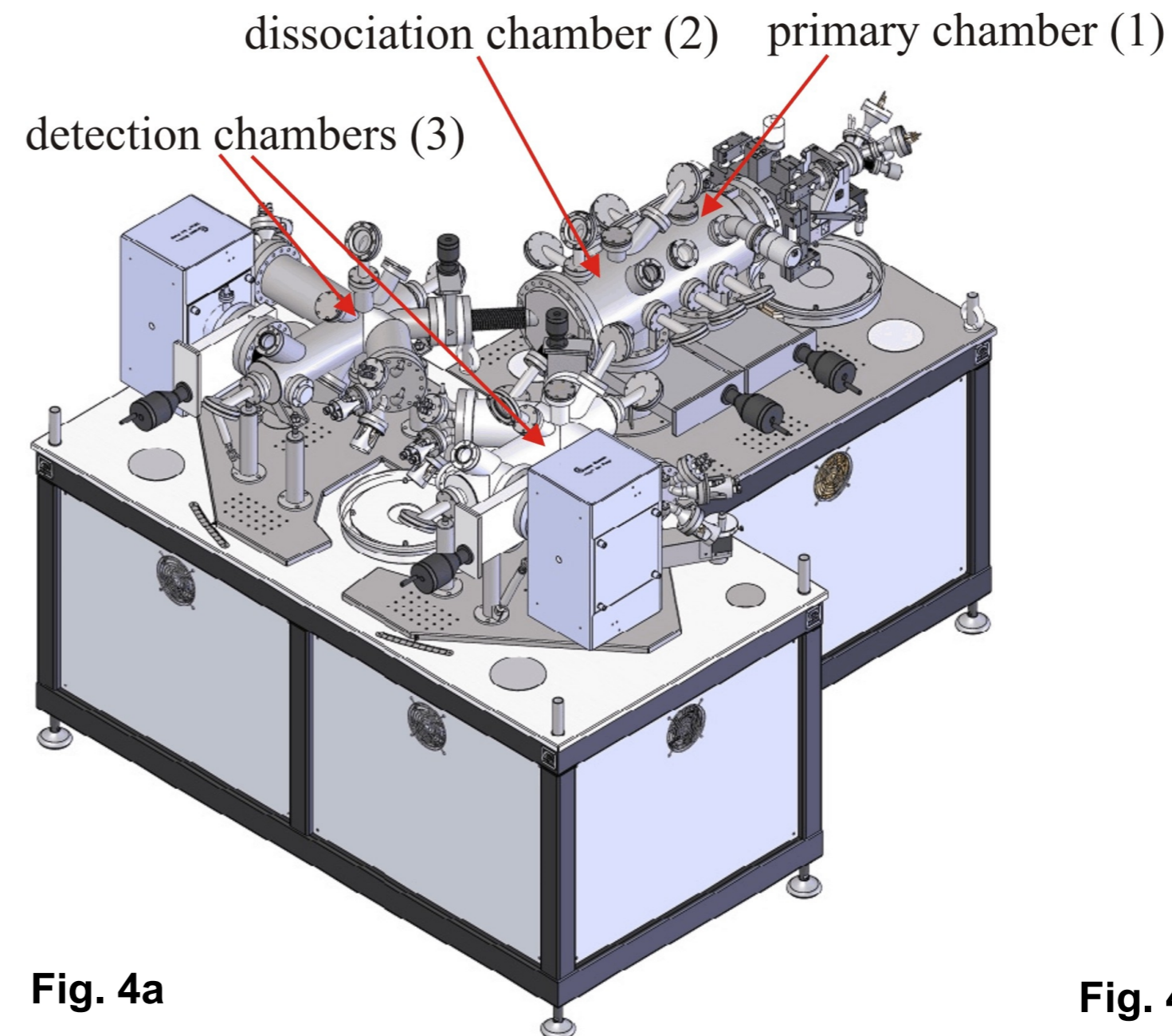

Fig. 3b

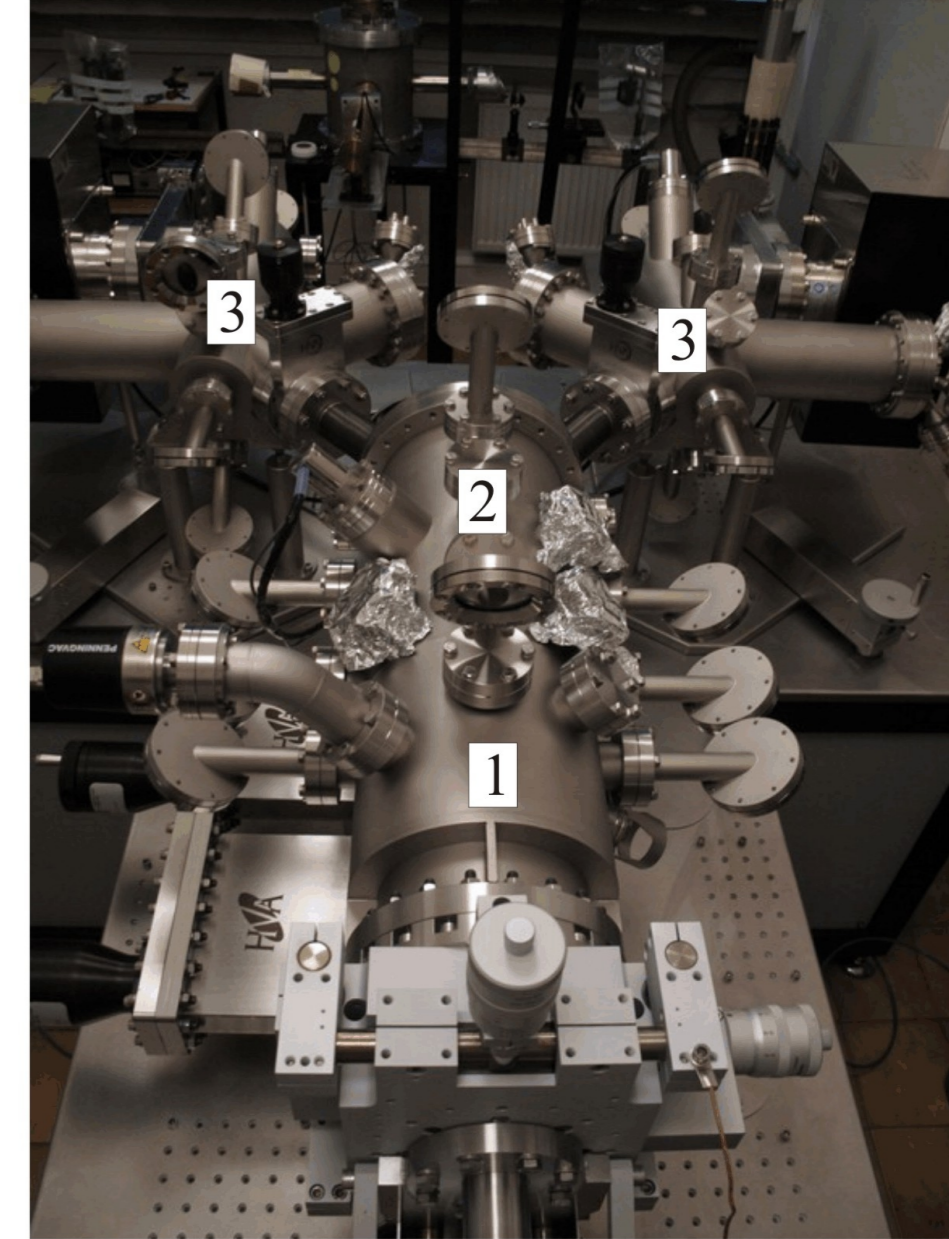## Experimental set-up

Fig. 4a

Fig. 4b

Visualization (Fig. 4a) and laboratory set-up of the vacuum chambers (Fig. 4b). Primary chamber (1) in which the pulsed source of supersonic beam is located. Dissociation chamber (2) is separated from the primary chamber by a skimer (1mm in diameter). Both primary and dissociation chambers are pumped down to 10^{-6} mbar of ultimate pressure. Detection chambers (3) in which nuclear spin selective detection of entangled atoms is performed. Both detection chambers are equipped with ion pumps (ultimate pressure down to 10^{-10} mbar).

Pulsed source of supersonic beam

Cd_2 molecules are produced using a high-temperature high-pressure pulsed source of vdW dimers developed in present study [4] (see Fig. 5). Cadmium metal (natural abundance) is heated in the reservoir (1) up to 1000 K ($Cd_{meltpoint}$=594K). Cadmium vapour (partial pressure 0.2 bar) enter the mixing chamber (2) in which are mixed with carrier gas (argon). The mixing chamber ends with a nozzle (with D=0.15mm orifice) through which the mixture expands to the vacuum chamber forming a supersonic beam of Cd_2. The pulsed operation of the nozzle is ensured by a titanium plunger (3) attached to the armature of an electrically driven solenoid valve (4, Parker-General Series 9). Parts of the pulsed source: water shield (5), carrier gas supplies (6), reservoir heater (7), source body heater (8), nozzle cartridge (9), orifice (10), nozzle cartridge heater (11).
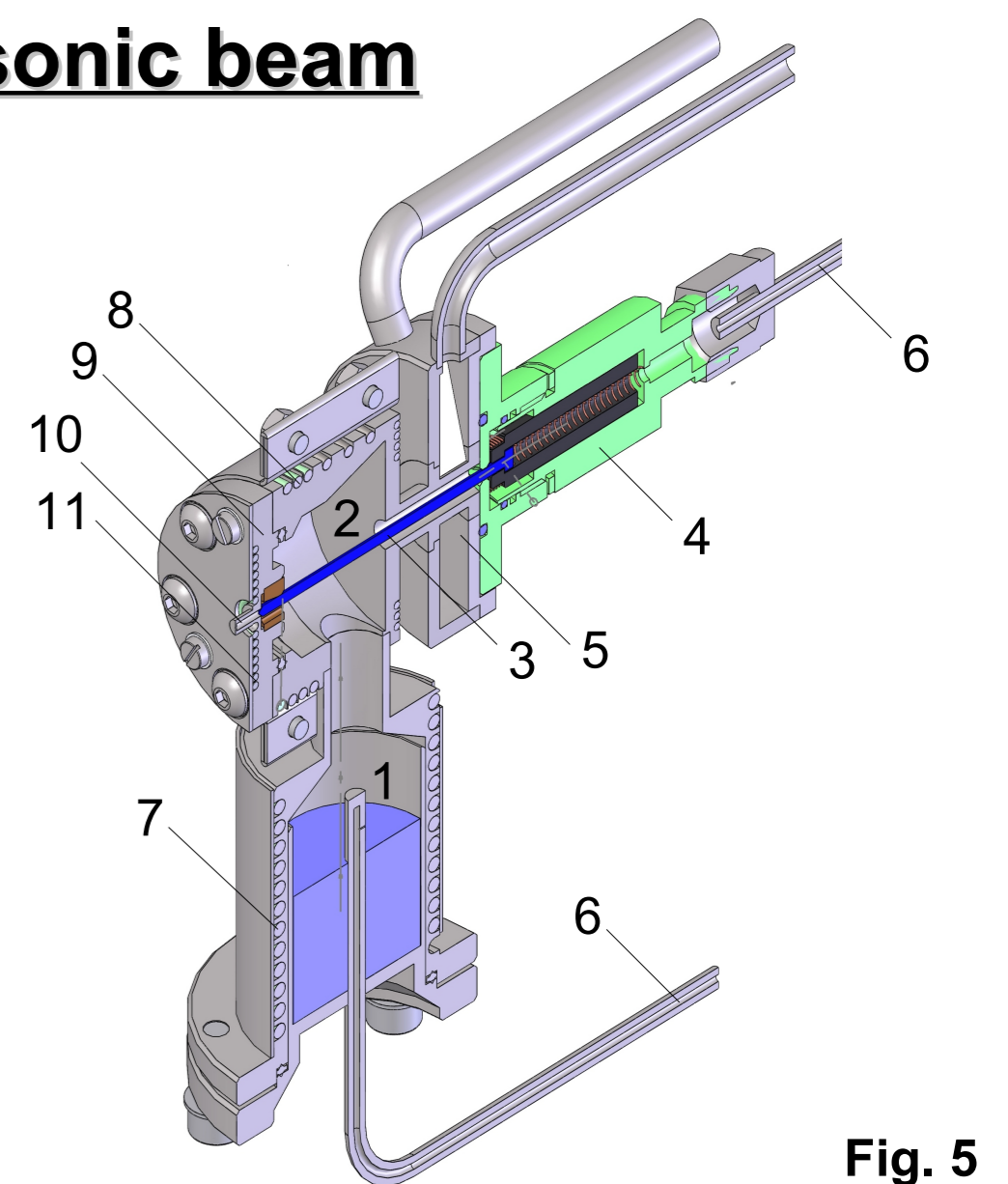

Fig. 5

Tests of the pulsed source

LIF excitation spectra of CdAr and Cd_2 recorded using the $B^31(5^3P_1)\leftarrow X^10^+(5^1S_0)$ and $b^30_u^+(5^3P_1)\leftarrow X^10_g^+(5^1S_0)$ transitions, respectively. The apparatus and pulsed source from Figs. 4b and 5, respectively were employed for the production of the molecules using following parameters: a) D=0.15mm, p_{Ar}=5.5bar, $T_{reservoir}$=923K, T_{body}=943K and T_{nozzle}=943K, X=11mm, repetition rate f=10Hz, valve pulse width w=0.7ms, laser pulse delay τ=1ms, time-gating interval 3-5μs. b) D=0.25mm, p_{Ar}=1.5bar, $T_{reservoir}$=903K, T_{body}=948K, T_{nozzle}=948K, the remaining parameters as in a). c) As in a) but with time-gating interval 0.2-0.5μs. d) Simulation of the bound←bound LIF excitation spectrum from a) *i.e.*, recorded using the $B^31\leftarrow X^10^+$, v'=0 transition in CdAr, assuming: ω_e'=11.3cm^{-1}, $\omega_e'x_e'$=0.59cm^{-1}, ω_e''=19.8cm^{-1}, $\omega_e''x_e''$= 0.93cm^{-1}, R_e'=5.01Å, R_e''=4.31Å from previous work, as well as calculated B_e'=0.022808cm^{-1} and B_e''= 0.030818cm^{-1}, and assumed rotational temperature T_{rot}=3K, bandwidth of the laser Δ_L=0.2cm^{-1} and Doppler broadening Δ_G=0.2cm^{-1}. e) Simulation as in d) but for v''=0,1 and T_{rot}=19K. f) Simulation of the free←bound part of the excitation spectrum from (a) assuming: Born-Mayer and Morse representations for the excited- and ground-state potentials, respectively. g) Sum of simulations from d) and f) plotted to reconstruct the spectrum from a). h) Simulation of the bound←bound spectrum from c) but recorded using the $b^30_u^+\leftarrow X^10_g^+$, v''=0 transition in Cd_2, assuming: ω_e'=18.7cm^{-1}, $\omega_e'x_e'$=0.34cm^{-1}, ω_e''=21.4cm^{-1}, $\omega_e''x_e''$=0.35cm^{-1}, R_e'= 4.02Å R_e''=3.78Å from previous work, as well as calculated B_e'=0.01848cm^{-1} and B_e''=0.02090cm^{-1}, and assumed T_{rot}=3K, Δ_L=0.2cm^{-1} and Δ_G=0.2cm^{-1}. i) Sum of simulations d), f) and h) plotted to reconstruct the spectrum from c).
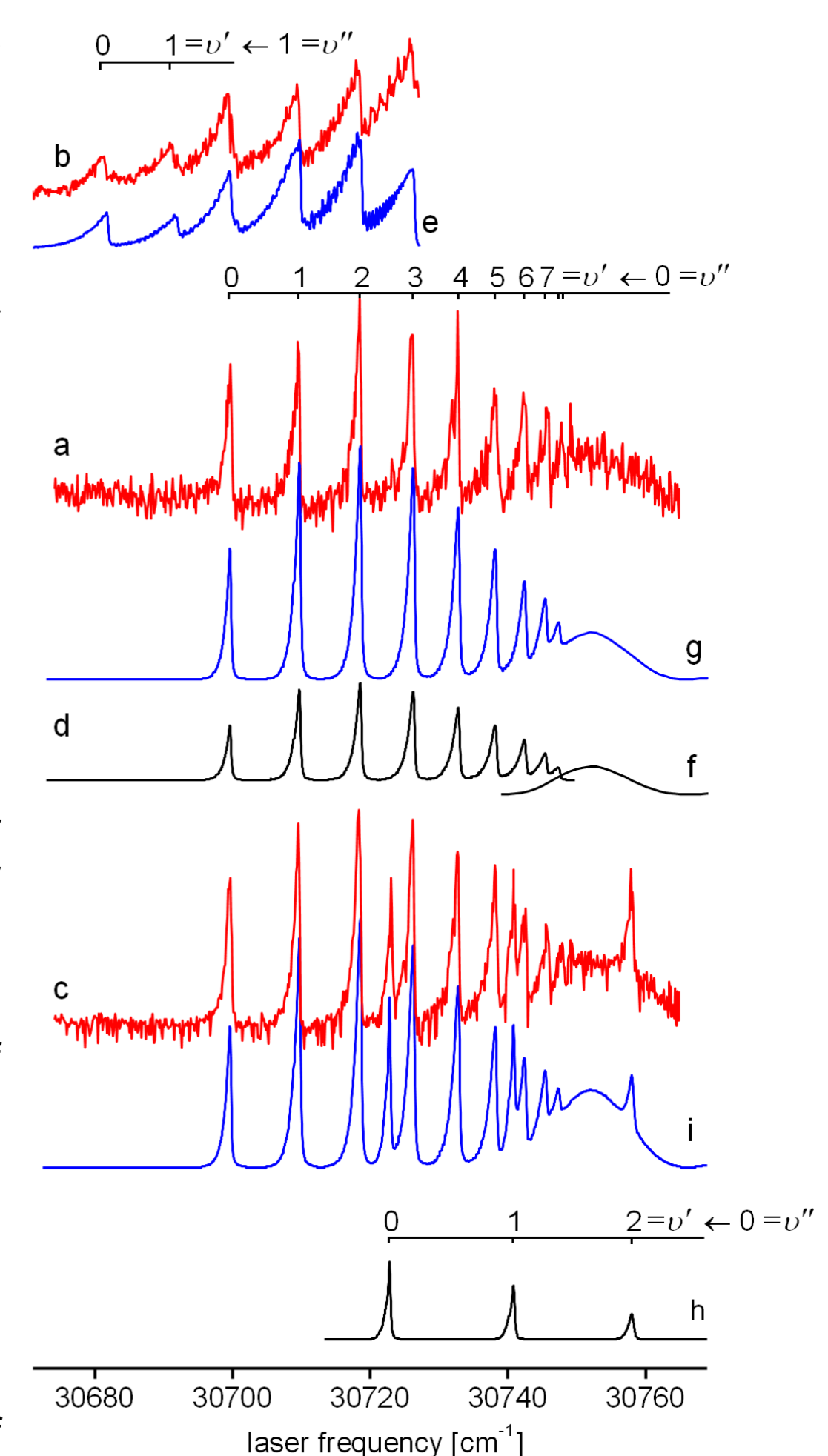

Fig. 6

References

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[2] E.S. Fry, Th. Walther, S. Li, *Phys. Rev.* **A 52** (1995) 4381.
[3] T. Urbańczyk, M. Strojecki, M. Krośnicki, J. Koperski, *Opt. Appl.* (2012), submitted.
[4] T. Urbańczyk, J. Koperski, *Rev. Sci. Instrum.* (2012), submitted.