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Accurate (0.25 mrad) perpendicular alignment of a continuous-wave single-mode dye laser beam and an atomic beam

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Two simple methods are described for an accurate perpendicular alignment of a laser beam and an atomic beam, which is required for a velocity independent, i.e., Doppler-free interaction, of the laser beam with the atomic beam. With the first method a free running single-mode cw dye laser beam and an atomic beam are aligned perpendicular with an accuracy of 0.25 mrad. This alignment takes typically 2 h. The second method needs a laser beam that is absolutely stabilized to the investigated atomic transition. With this method a 0.2-mrad accurate perpendicular alignment is obtained within only 5 min.

INTRODUCTION

Nowadays, many crossed laser beam-atomic beam experiments are performed, e.g. Doppler-free observations of the interactions between atoms and photons,¹ state selection²⁻⁴ or state sensitive detection of the atomic beam,^{2,3} and collision experiments with atoms that are excited by a laser beam.⁵ The linewidths encountered in these experiments are almost Doppler free and range from the natural linewidth up to a few times this natural linewidth. Therefore, a frequency stabilization of the laser beam at the resonance frequency of the transition within a few percent of the natural linewidth is necessary. In most cases the laser frequency is stabilized at the frequency ν'_o where the number of fluorescence photons produced at the interaction center of laser beam and atomic beam reaches its maximum $\dot{N}_{f,\max} = \dot{N}_f(\nu'_o)$. This method guarantees an almost optimal interaction between laser beam and atomic beam. However, a velocity-independent interaction requires an accurate perpendicular alignment of both beams. For a thermal atomic beam with a mean velocity of, e.g., $u = 800$ m/s and an atomic transition at 600 nm with a natural linewidth of 10 MHz (FWHM), the required accuracy is already 2 mrad. This cannot be achieved by a simple mechanical alignment.

We now discuss the influence of a misalignment β with respect to the perpendicular crossing of the beams ($\beta = 0$, see also Fig. 4) on the signal $\dot{N}_{f,\max}$, on the frequency ν'_o where it occurs, and on the width $\Delta\nu$ of this excitation profile. The aim of this discussion is to find a parameter that can easily be measured explicitly and is sensitive for small deviations from zero of the misalignment β .

First, we consider the maximum number of fluorescence photons $\dot{N}_{f,\max}$. Because the misalignment is in first order compensated by the corresponding Doppler shift it shows a very flat maximum as a function of β and its optimization will not result in an accurate perpendicular alignment. Second, we consider the Doppler shift due to β and the mean velocity u of the atomic beam, as given by

$$\nu'_o - \nu_o = \nu_o \beta u / c, \quad (1)$$

with ν_o the resonance frequency of the transition. Although

this is a large effect, it cannot be measured directly by lack of an absolute frequency scale.

Third, we consider the width of the excitation profile, i.e., the number of fluorescence photons as a function of the laser frequency. Both the rms width δu of the velocity distribution of the atomic beam and the total rms divergence $\delta\beta = (\delta\beta_a^2 + \delta\beta_l^2)^{1/2}$ of both beams contribute, with $\delta\beta_a$ and $\delta\beta_l$ the rms divergence of the atomic beam and the laser beam, respectively. The three contributions are

$$\delta\nu_1 = \nu_o \delta\beta u / c, \quad (2)$$

$$\delta\nu_2 = \nu_o \delta\beta \delta u / c, \quad (3)$$

$$\delta\nu_3 = \nu_o \beta \delta u / c, \quad (4)$$

resulting in a total contribution

$$\delta\nu = (\delta\nu_1^2 + \delta\nu_2^2 + \delta\nu_3^2)^{1/2} \quad (5)$$

of the Doppler broadening to the full width at half-maximum of the excitation profile, given by

$$\Delta\nu \approx \Delta\nu_{\text{nat}} + \delta\nu, \quad (6)$$

with $\Delta\nu_{\text{nat}}$ the natural linewidth (FWHM) of the transition. Typical numerical values are $u = 800$ m/s, $\delta u = 100$ m/s, and $\delta\beta_a = 0.5$ mrad, with $\Delta\nu_{\text{nat}} = 10$ MHz for a supersonic beam of metastable neon atoms and $\delta\beta_l = 0.5$ mrad and $\lambda = 600$ nm for the laser beam, resulting in $\delta\nu_1 = 0.9$ MHz, $\delta\nu_2 = 0.12$ MHz, and $\delta\nu_3 = 0.17(\text{MHz/mrad})\beta$. The effective sensitivity now is approximately given by

$$\Delta\nu / \Delta\nu_{\text{nat}} = 1.095 + 0.003 (\text{mrad}^{-2}) \beta^2 \quad (7)$$

and a misalignment $\beta = 6$ mrad results in only 10% broadening of the excitation profile.

Finally, we consider the Doppler splitting of the excitation profile due to two antiparallel laser beams. In this way we avoid the need for an absolute frequency scale. The practical implementation of such a measuring scheme is discussed in the next section.

I. ALIGNMENT WITH A FREE RUNNING LASER BEAM

To align both beams we use a second antiparallel laser beam (Fig. 1) and measure the excitation signal $\dot{N}_f(\nu)$ during a frequency scan of the laser. Due to the opposite sign of the

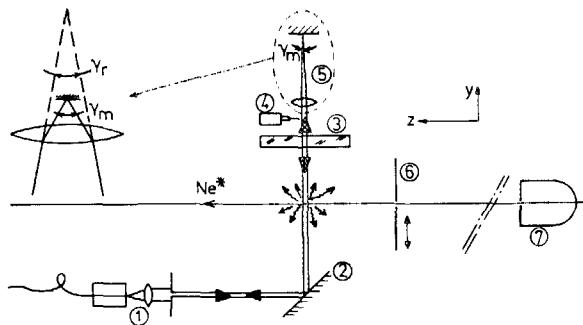


FIG. 1. A schematic view of the auxiliary beam machine with the reflected laser beam. The visible fluorescence photons are detected with a photomultiplier placed along the axis perpendicular to both beams. (1) Fiber holder with focusing lens and laser beam collimator, (2) mirror, (3) vacuum window, (4) computer-controlled beam flag, (5) reflecting optics (flat mirror near the focus of a $f = 300$ -mm lens), (6) stepper motor driven atomic beam collimator, (7) beam source for thermal metastable rare-gas atoms. The insert shows schematically the definition of the angles γ_r and γ_m .

Doppler shift for the two laser beams, the frequency distance between the maxima of the two excitation profiles is equal to

$$\nu'_o - \nu''_o = 2\nu_o \beta u/c. \quad (8)$$

For angles $\beta = 5$ mrad already two maxima can be seen in $\dot{N}_f(\nu)$. The alignment is performed by calculating the frequency distance between the centroids M_1 of the excitation profiles measured with and without reflected laser beam (Fig. 2). The centroid M_1 of an excitation profile is defined by

$$M_1 = \frac{\sum(\nu_i S_i)}{\sum S_i}, \quad (9)$$

with ν_i and S_i the (relative) laser frequency and the excitation signal of the equidistant datapoints, respectively. The misalignment angle β between laser beams and atomic beam is varied by scanning the atomic beam collimator with a step-

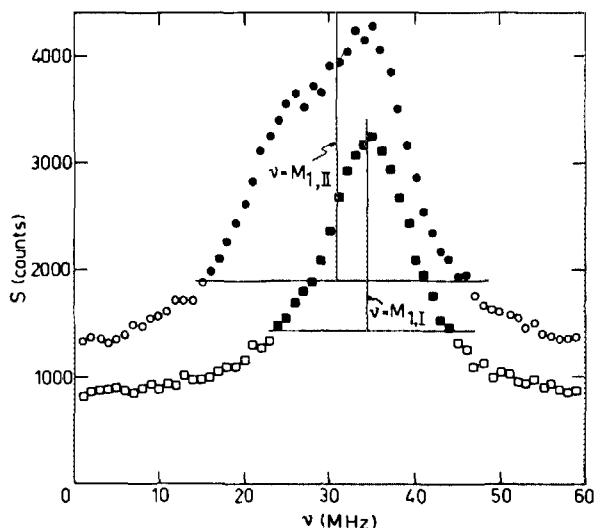


FIG. 2. The excitation profiles with (circles) and without (squares) reflected laser beam. Only the full datapoints (above the horizontal lines) are used for the calculation of the centroids indicated by the full vertical lines. The value of the misalignment $\beta = 6.3$ mrad.

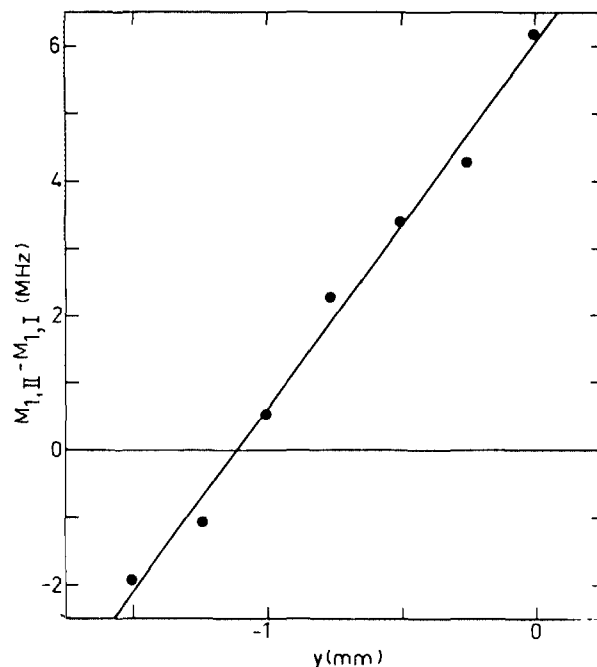


FIG. 3. The frequency distance $M_{1,II} - M_{1,I}$ between the centroids of the excitation signals of one photon beam (I) and two photon beams (II) as a function of the position y of the atomic beam collimator. A displacement of 1.0 mm corresponds to an angle $\beta = 2.44$ mrad. The accuracy of the alignment from the least-squares analysis is typically 0.15 mrad.

per motor in the y direction (parallel to the laser beams, perpendicular to the atomic beam). The position of the collimator where the difference between the centroids is zero now corresponds to $\beta = 0$ mrad (Fig. 3).

We use a combination of a lens and a flat mirror near the focus of the lens as reflecting optics, such that the waists of both laser beams coincide. The greatest advantage, however, is that the angle between the original and the reflected laser beam γ_r is a factor of 7 to 10 smaller than the misalignment angle γ_m of the flat mirror, which is defined as the angle at the mirror between the incoming and reflected laser beams (Fig. 1). The mirror is aligned to let the laser beams coincide at the laser beam collimator with an accuracy of typically 1.0 mm, from which we conclude that the deviation at the lens is also 1.0 mm. Together with the focal length of $f = 300$ mm this results in $\gamma_m < 3.3$ mrad and $\gamma_r < 0.4$ mrad, which means that after alignment of β at $\nu'_o - \nu''_o = 0$, the angle between the original laser beam and the atomic beam is smaller than $\frac{1}{2}\gamma_r = 0.20$ mrad, which is the main contribution to the accuracy of this method.

To eliminate the drift of the laser frequency both excitation profiles are measured during the same frequency scan. At each frequency the excitation signal with the reflected laser beam on is measured with a full sampling time, sandwiched between two measurements with half sampling time of the excitation signal without the reflected laser beam. The alignment procedure can be performed in a short time, because only 60 datapoints are sufficient to calculate an accurate value for the centroid of each excitation profile. In this way the whole alignment, i.e., the collection of all data, the adjustment of the angle, and a control measurement, typical-

ly takes 2 h. We apply this method in our auxiliary atomic beam experiment, which we use for the absolute frequency stabilization at an atomic transition by monitoring the total excitation signal.⁶

This method now results in a very accurate alignment within 0.25 mrad (Fig. 3) but takes 2 h. One should avoid using the direct laser beam, because each readjustment of the laser cavity will change the alignment of the atomic beam experiment. By using an optical fiber to transport the laser beam the adjustment of the laser cavity and the alignment of the atomic beam experiment are fully decoupled,⁶ resulting in an excellent long-term fixation of β .

II. ALIGNMENT WITH AN ABSOLUTELY FREQUENCY STABILIZED LASER BEAM

In our main experiment we perform measurements with a beam of fast (2000 – 10 000 m/s) metastable neon atoms. We use a flat mirror (Fig. 4) for the alignment. The angle φ_m between the mirror surface and the y axis can be adjusted with a stepper motor driven micrometer (step: 0.1 mrad). With the z axis parallel to the atomic beam axis the misalignment angle β now is given by $\beta = 2(\varphi_m - \pi/4)$. An adjustment of φ_m will also result in a displacement of the interaction center C along the atomic beam axis. We have decoupled the angular alignment of the two beams and the alignment of the position of the interaction center along the atomic beam axis, e.g., in the focus of the photon collection optics. This is done by a second stepper motor driven micrometer that adjusts the position z_m of the mirror (step: 0.01 mm). By coupling z_m to φ_m under computer control according to $z_m = d \tan \beta = 2d\Delta\varphi_m$ the remaining independent variables are z_c and β , which allows us to vary β at z_c fixed.

For alignment the intensity of the beam of metastable neon atoms downstream of the laser beam is measured by secondary electron emission from an untreated stainless-steel surface, followed by an electron multiplier and an am-

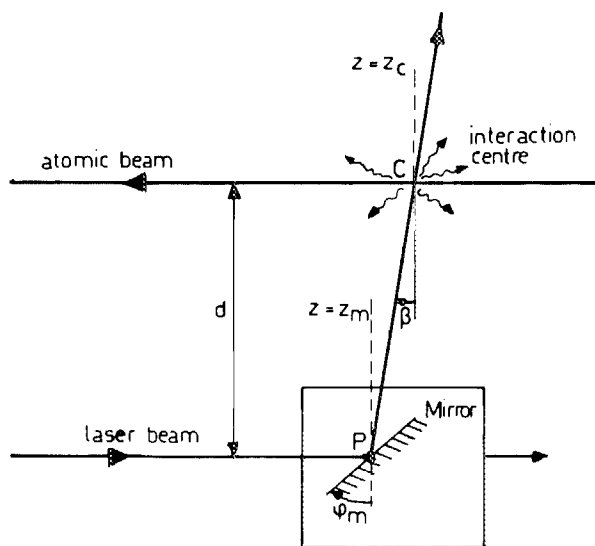


FIG. 4. A schematic view of the main experiment with the atomic beam that intersects the laser beam at C. The mirror can be rotated around the axis through P and translated along the z axis with two stepper motor driven micrometers.

plifier/discriminator combination. The laser beam pumps the metastable neon atoms to the short-lived Ne(3p) states, which cascade (partially) to the ground state.⁴ These ground state atoms are not detected and the signal at the atomic beam detector will be attenuated. The alignment procedure, which optimizes this attenuation as a function of the angle β , is fully under computer control and only takes 5 min elapsed time. Different runs give the same alignment within error bounds of 0.2 mrad.

A time-of-flight analysis on the optically pumped atomic beam and the original atomic beam⁴ results in the velocity dependence of the beam attenuation. This gives an extra check on the alignment of the beams. A slight misalignment will occur when the frequency of the laser beam has an offset $\nu'_0 - \nu_0$ with respect to the atomic transition. This misalignment results in a readily observable maximum in the attenuation at frequency ν'_0 , which coincides with the maximum in the velocity distribution of the atomic beam. Atoms in the tails of the velocity distribution will be pumped less effectively, because they have an extra Doppler shift equal to $\beta \delta u/c$.

This alignment procedure can also be used when the excitation signal \dot{N}_f is registered by counting the fluorescence photons. Generally, the check on the velocity independence of the interaction can be performed by a state selective detection of the atomic beam. This is always possible by splitting the laser beam, using the second beam (at a fixed angle β) downstream of the first beam, and detecting the fluorescence photons. The only exception is a two-level system, where the optical pumping does not result in an attenuation.

This method is only applicable if the frequency of the laser beam is already stabilized to the absolute frequency of the Doppler-free atomic transition. It is very fast and can be performed very accurately. The only requirement is a mechanical support for the mirror with a good reproducibility.

III. APPLICATIONS

We have used the first method to measure accurate lifetimes of the Ne(3p) states with our auxiliary atomic beam experiment.¹ We use the combination of the two methods, the first one for our auxiliary beam which provides the absolute frequency stabilization and the second at our main experiment, for all our measurements that require the interaction of the atomic beam and the laser beam. For example, we have performed Penning ionization cross-section measurement with a beam of state-selected metastable neon atoms,^{7,8} we have probed the plasma of the beam source which produces the fast metastable atoms,⁹ and we have measured the Rabi oscillations in the velocity dependence of the attenuation of the beam of fast metastable atoms.¹⁰ The application of these alignment techniques is very general for all laser beam-atomic beam experiments and becomes even more important for beam experiments with the very fast (above 10 eV) metastable atoms that are produced by charge exchange of an ion beam in an alkali vapor.¹¹

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