Loss of Spatial Coherence by a Single Spontaneous Emission

T. Pfau, S. Spälter, Ch. Kurtsiefer, C. R. Ekstrom, and J. Mlynek
Fakultät für Physik, Universität Konstanz, D-78434 Konstanz, Germany
(Received 9 March 1994)

We have demonstrated the loss of transverse spatial coherence of an atomic wave function after a single spontaneous emission. He^* atoms were both diffracted and excited by a standing light wave with a variable period. After the interaction, the excited atoms decay by a single spontaneously emitted photon. By changing the period of the standing light wave, we have mapped the loss of spatial coherence as a function of the transverse coordinate. By detecting the emitted photon one could "erase" the position information available and recover the transverse coherence in a correlation experiment, or realize a Heisenberg microscope.

PACS numbers: 32.80.–t, 41.85.–p, 42.50.Vk

A measurement apparatus influences a classical object in a deterministic way, such that in principle the disturbance by the measurement can approach zero. In the measurement of a quantum mechanical object, however, there is always a minimum amount of indeterministic disturbance of the object that is connected to the amount of extractable information. This difference was discussed by Heisenberg in 1927 [1] and subsequently by many authors using various gedanken experiments [2]. In this paper, we present a realization of such a gedanken experiment using the diffraction of atoms from a standing light wave.

The scattering of a single photon is a fundamental dissipative process that can be used to measure the position of an object [1]. The scattering process couples the motional degrees of freedom directly to the continuum of radiation modes of the emitted photon. The spread in momentum space via the recoil of the photon on the object is directly coupled to the precision of the localization process. If the localization is not perfect, the spatial coherence of the object is not completely destroyed. In order to describe this partial loss of spatial coherence of an object, we use the transverse one-dimensional coherence function as in classical optics,

$$g^{(1)}(z) = \int \phi(z' - z)\phi^*(z')dz' = \mathcal{F}_z\{|\psi(k^o)|^2\}, \quad (1)$$

where $\mathcal{F}_z$ denotes the Fourier transform with respect to k^o. This is the two-point correlation function of the transverse atomic wave function $\phi(z)$. The corresponding wave function in momentum space is $\psi(k^o) = \mathcal{F}_{k^o}\{\phi(z)\}$, where k^o is the transverse momentum of the object, which in this paper will be an atom, and $\mathcal{F}_{k^o}$ denotes the Fourier transform with respect to z. This concept can be generalized for a statistical mixture of states described by a density matrix ρ to give [3]

$$g^{(1)}(z) = \mathcal{F}_z\{\langle k^o|\rho|k^o\rangle\} \equiv \mathcal{F}_z\{I(k^o)\}, \quad (2)$$

where $I(k^o)$ is the momentum distribution of the object, which is experimentally accessible. A photon with a wave vector of length $k^p = |\mathbf{k}^p|$, that is spontaneously emitted with a given radiation pattern, produces a spread of the transverse momentum distribution of the object k^o via its recoil. The final momentum distribution of the object is then given by [4]

$$I_f(k^o) = \int dk^p I_i(k^o - k_z^p)P(k_z^p) = I_i(k^o) \otimes P(k_z^p), \quad (3)$$

where $\otimes$ denotes a convolution and $P(k_z^p) = P(-k_z^p)$ is the probability of emitting a photon with the transverse component of the momentum k_z^p; i.e., the projection of the radiation pattern on the z axis [see Fig. 1(a)].

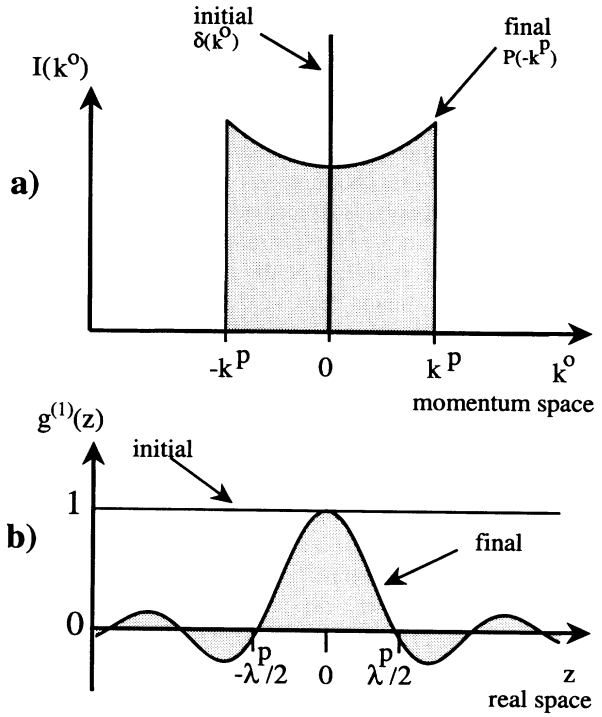

FIG. 1. Influence of a single spontaneously emitted photon on an atom initially in a plane de Broglie wave state without transverse momentum: (a) on the transverse momentum distribution and (b) on the transverse coherence in real space.

0031-9007/94/73(9)/1223(4)$06.00

The subscripts i and f refer to the initial and final distributions. The transverse coherence function after the spontaneous emission is then

$$g_f^{(1)}(z) = g_i^{(1)}(z)\mathcal{F}_z\{P(k_z^p)\}, \quad (4)$$

where the loss of coherence is described by $\mathcal{F}_z\{P(k_z^p)\}$. As the transverse radiation pattern $P(k_z^p)$ is usually a discontinous function at $k_z^p = \pm k^p$, the coherence function after the scattering of the photon shows oscillations, indicating the quantum nature of the scattering process. Consider, for example, a spherically symmetric radiation pattern; because the transverse projection is a square function, the initial spatial coherence function is multiplied by $\mathrm{sinc}(k^p z)$. In Fig. 1 we show this behavior for the radiation pattern appropriate to our experiment [see Eq. (5)] and for an initial plane atomic de Broglie wave.

In order to measure this change in the transverse coherence, experiments have been proposed diffracting excited atoms from a Young's double slit with a variable distance between the two slits [5,6]. In these experiments, the visibility of the atomic interference pattern after a single spontaneous emission is a direct mapping of the loss of the transverse coherence $\mathcal{F}_z\{P(k_z^p)\}$.

In the experiment described here, a standing light wave with variable period is used as a diffracting phase grating for an atomic wave function. The diffraction of atoms from such a light-induced periodic phase object has been studied previously [7]. The diffraction leads to discrete diffraction orders in momentum space, which are observed in the far field as a spatial distribution. If a spontaneous emission occurs immediately after the diffraction region, the momentum distribution has to be convolved with the transverse radiation pattern $P(k_z^p)$. The influence of the spontaneous emission in standing wave diffraction theory is described in detail in [8]. This convolution leads to a reduction and sometimes also to a sign change of the visibility of the diffraction pattern [9]. In real space, this means that we diffract atoms first with the initial and then with the reduced transverse coherence function from a phase grating with a variable period. By taking the Fourier transform of the diffraction pattern with and without the spontaneous emission, we obtain the loss of the spatial coherence $\mathcal{F}_z\{P(k_z^p)\}$ experimentally.

To briefly descibe the diffraction from a standing light wave, we consider a two-level atom with a transition frequency ω_0. The atom-laser interaction energy in the electric dipole approximation is given by $-\boldsymbol{d}\cdot\boldsymbol{E}(\boldsymbol{r},t)$, where $\boldsymbol{d}$ is the electric dipole operator and $\boldsymbol{E}(\boldsymbol{r},t) = E_0(x,y)\hat{\boldsymbol{\epsilon}}_y\cos(k_\alpha z)\cos(\omega t + k_x x)$. The laser field is produced in our experiment by reflecting a linearly polarized laser beam through the angle α from a mirror in the x-y plane (see inset of Fig. 2). This field describes a standing wave with variable wave vector $k_\alpha = k^p\cos\alpha$ in the z direction, transverse to the atomic beam, and a running wave in the x direction. In the experiment, the angle α was varied between 0° and 70° varying the standing wave

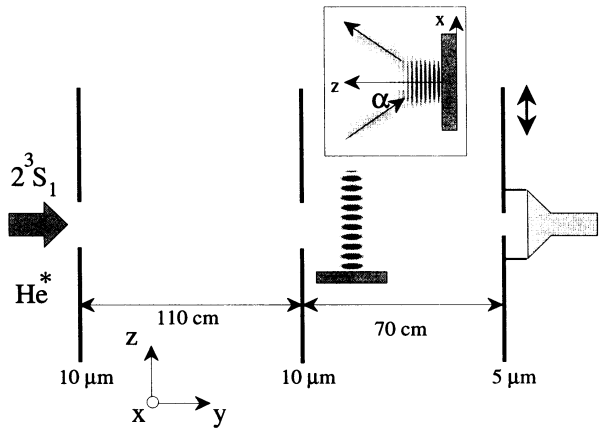

FIG. 2. The experimental setup: A metastable triplet helium beam is diffracted by a standing light wave with variable period. Inset: view along the atomic beam axes; the period of the standing wave can be varied continuously by varying α between 0° and 70°.

period between $\lambda^p/2$ and $3\lambda^p/2$. We define the atom-field coupling $\omega_R(x,y) = \boldsymbol{d}\cdot\boldsymbol{\epsilon}_y E_0(x,y)/\hbar$ as the Rabi frequency.

If the detuning $\Delta = \omega - \omega_0$ is much larger than the inverse interaction time, the internal state of the atom adiabatically follows one energy eigenvector. The transverse standing wave leaves a periodic phase modulation $\theta(z)$ on the transverse atomic wave function. The momentum distribution is then given by $I(k^o) \propto |\mathcal{F}_{k^o}[e^{i\theta(z)}]|^2$. If the laser is far off resonance, only even diffraction orders with an even number of transferred recoil momenta $\hbar k^p\cos\alpha$ are populated. The atom leaves the interaction zone in the ground state. On resonance (i.e., for $\Delta = 0$), however, the adiabatic assumption is no longer valid, and half of the atoms leave the interaction zone in the excited state and in the odd diffraction orders. In this paper, we investigate these excited state components, which decay after the diffraction zone by spontaneously emitting a photon.

The experiment was performed with an atomic beam machine designed for use with metastable rare gas atoms. A discharge source at room temperature produced a beam of metastable He atoms, more than 90% of which were in the $2\,^3S_1$ state. The source yielded 10^{14} counts/(s sr). They had an average velocity of $v_y \simeq 2150$ m/s and a velocity distribution with $v/\Delta v = 4.3$ (FWHM).

The beam was collimated by two slits of width 10 μm placed 110 cm and 1 cm upstream from the interaction region (see Fig. 2). The transverse beam profile was measured 69 cm downsteam from the interaction region, using a 5 μm scanning slit in front of a channeltron detector. The spatial resolution in the detector plane corresponded to a momentum resolution of $0.5\hbar k^p$. All slits were 3 mm high and aligned parallel to each other using an optical diffraction technique. The triplet He^* atoms interacted with a light field of wavelength

1.083 μm, tuned to the closed $2\,^3S_1$ to $2\,^3P_2$ transition. The light was obtained from a diode-pumped LNA laser [10] in a standing wave configuration. The laser was frequency stabilized to the atomic transition using saturation spectroscopy in a dc helium discharge.

The laser beam was brought into the vacuum chamber using a single mode optical fiber. The light was s polarized with respect to the mirror surface and expanded by a telescope to produce a parallel Gaussian beam with a waist of $w_x = 850$ μm. The light was then focused in the y direction by a cylindrical lens to a waist $w_y = 19$ μm in the plane of the atomic beam. A mirror was placed into the focal plane of the cylindrical lens in order to produce a standing light wave. The distance from the atomic beam to the mirror was 50 μm. The light-atom interaction time was $2w_y/v_y \simeq 18$ ns, significantly shorter than the $2\,^3P_2$ state natural lifetime of 99.5 ns. The probability of spontaneous emission during the interaction with the resonant light was therefore less than 10%.

The $J = 1$ to $J = 2$ transition behaves like an effective two-level system in the excitation, because for π-polarized light, the coupling strengths of the magnetic sublevels to the respective excited state sublevels differ by only 15%. The projection of the emission probability on the z axis for an excitation of this transition by light with linear polarization along the y axis is given by

$$P(k_z^{\mathrm{p}}) = \begin{cases} [11 + 3(k_z^{\mathrm{p}}/k^{\mathrm{p}})^2]/24k^{\mathrm{p}}, & \text{for } |k_z^{\mathrm{p}}| < k^{\mathrm{p}}, \\ 0, & \text{elsewhere.} \end{cases} \quad (5)$$

The laser power at the atomic beam was stabilized to a corresponding maximum Rabi frequency of about $\omega_R/2\pi = 300$ MHz on resonance and $\omega_R/2\pi = 500$ MHz for the off-resonant diffraction, where the detuning was $\Delta/2\pi = 160$ MHz. These ratios were chosen such that the envelope functions of the on- and off-resonant diffraction patterns were equal. As the height of the atomic beam is much larger than the vertical waist of the laser field, the vertical distribution of Rabi frequencies leads to equal envelopes for the ground and excited state components of the on-resonant diffraction pattern, due to the central limit theorem.

In Fig. 3, the diffraction pattern in the detector plane for the angles $\alpha = 20^\circ$ and $\alpha = 60^\circ$ are displayed for on- and off-resonant diffraction. Because of the nonzero velocity spread, the higher order diffraction peaks are broadened in real space. The zeroth order diffraction peak also contains residual UV photons and singlet atoms.

In the off-resonant case, several diffraction orders are well resolved. Their separation corresponds to the recoil $\hbar k_\alpha$. What we have measured is $I_{\mathrm{off}}(k^{\mathrm{o}})$.

On resonance the visibility of the diffraction pattern is decreased by the additional odd diffraction orders that emerge from the diffraction zone in the excited state. As these diffraction orders are broadened by the recoil of the atom from a single spontaneously emitted photon, what we have measured is

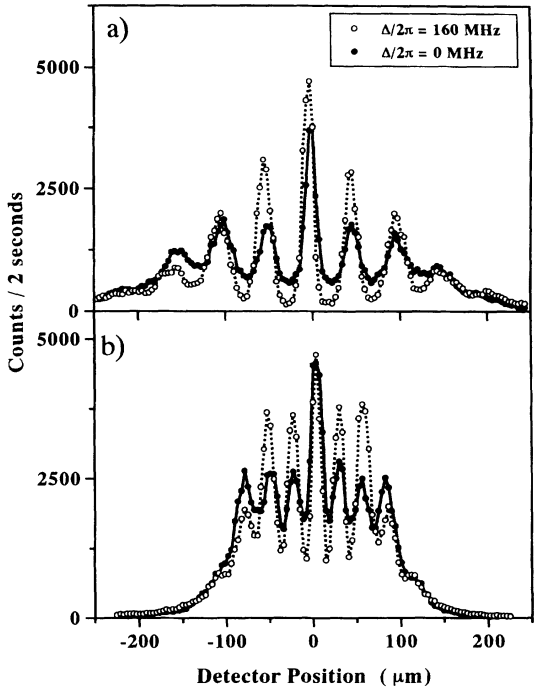

FIG. 3. Atomic diffraction pattern in the far field at the detector plane for (a) $\alpha = 20^\circ$ and (b) $\alpha = 60^\circ$ for both on- (closed circles) and off-resonant (open circles) light.

$$I_{\mathrm{on}}(k^{\mathrm{o}}) = \tfrac{1}{2}(I_{\mathrm{on}}^{g}(k^{\mathrm{o}}) + I_{\mathrm{on}}^{e}(k^{\mathrm{o}}) \otimes P(k_z^{\mathrm{p}})), \quad (6)$$

where the distributions before the spontaneous emission $I_{\mathrm{on}}^{g}(k^{\mathrm{o}})$ and $I_{\mathrm{on}}^{e}(k^{\mathrm{o}})$ both have the same weight. As $I_{\mathrm{on}}^{g}(k^{\mathrm{o}})$ and $I_{\mathrm{off}}(k^{\mathrm{o}})$ have the same envelope, we can obtain the excited state component of the on-resonant diffraction by the subtraction

$$I_{\mathrm{on}}^{e}(k^{\mathrm{o}}) \otimes P(k_z^{\mathrm{p}}) = 2I_{\mathrm{on}}(k^{\mathrm{o}}) - I_{\mathrm{off}}(k^{\mathrm{o}}). \quad (7)$$

In order to obtain the loss of transverse coherence, we exploit the identity

$$\mathcal{F}_z\{P(k_z^{\mathrm{p}})\} = \frac{\mathcal{F}_z\{I_{\mathrm{on}}^{e}(k^{\mathrm{o}}) \otimes P(k_z^{\mathrm{p}})\}}{\mathcal{F}_z\{I_{\mathrm{on}}^{e}(k^{\mathrm{o}})\}}, \quad (8)$$

and take the Fourier transform of the data obtained by Eq. (7) and divide it by the Fourier transform of the momentum distribution in the excited state before the spontaneous emission occurred. For the Fourier component of the diffraction pattern at $z = \lambda_\alpha/2$, $\mathcal{F}_z\{I_{\mathrm{on}}^{e}(k^{\mathrm{o}})\}$ can be replaced by $-\mathcal{F}_z\{I_{\mathrm{off}}(k^{\mathrm{o}})\}$, as the envelope functions for the ground and excited state components are equal. By comparing on- and off-resonant diffraction patterns for a given standing wave period $\lambda_\alpha/2$, we obtain the loss of transverse coherence at $z = \lambda_\alpha/2$ by

$$\mathcal{F}_z\{P(k_z^{\mathrm{p}})\}_{(z=\lambda_\alpha/2)} = -\frac{\mathcal{F}_z\{2I_{\mathrm{on}}(k^{\mathrm{o}}) - I_{\mathrm{off}}(k^{\mathrm{o}})\}_{(z=\lambda_\alpha/2)}}{\mathcal{F}_z\{I_{\mathrm{off}}(k^{\mathrm{o}})\}_{(z=\lambda_\alpha/2)}}. \quad (9)$$

The result of this measurement is shown in Fig. 4. The underlying solid line shows the theoretical expectation for the loss of transverse coherence for our emission pattern [Eq. (5)], $\mathcal{F}_z\{P(k_z^p)\}(z)$. This theoretical curve has no free parameters. The negative Fourier components and the oscillatory behavior give clear evidence for the emission of a single photon. At $\alpha = 0°$, residual stray light can give rise to more than one scattering process, and therefore leads to a positive value. The scatter of the measurement points is mainly due to the systematic scatter in the widths of the envelope functions. As a consequence of this measured scatter, we obtained a systematic error bar at one angle by measuring the standard deviation of the width of the envelopes. This error increases for increasing angles α, because the magnitude of the measured Fourier component of the diffraction patterns decreases.

In this experiment we did not detect the emitted photon, but information on both the momentum change and the position of the atom is encoded in that photon. Measuring the emitted photon in a given mode yields information about one component in phase space, but not about the complementary one. If, for example, the photon state is projected on a plane wave mode, information about the recoil of the object but no position information is obtained. An experiment measuring the atoms in correlation with the direction of the emitted photon would display the transverse coherence before the emission process up to a phase factor. If, on the other hand, the photon state is projected on a spherical mode, for example, by using a lens, information about the origin of that mode and therefore on the position of the object can be obtained, whereas the recoil on the object is undetermined. This latter version is called a Heisenberg microscope and could be realized by measuring the momentum distribution of the atomic correlation with the origin of the photon. Both of these behaviors are due to the entanglement of the object state with the scattered photon.

To our knowledge, we have measured for the first time the influence of a single spontaneous emission on the transverse coherence function of an atom. We use the comparison between the diffraction of atoms from an on- and off-resonant standing wave to map the loss of coherence as a function of the spatial coordinate. The measured loss of coherence agrees with the theoretical prediction. In future experiments, we plan to show the entanglement of the atomic and the photon state explicitly in correlation measurements that reestablish the transverse coherence or realize a Heisenberg microscope.

This work was supported by the Deutsche Forschungsgemeinschaft. C. R. E. acknowledges support from the Alexander von Humboldt Foundation. The authors would like to point out that the idea for this experiment was initiated by M. Sigel. Finally, we thank T. Sleator, P. Knight, and M. Wilkens for stimulating discussions and S. Hahn for technical assistance.

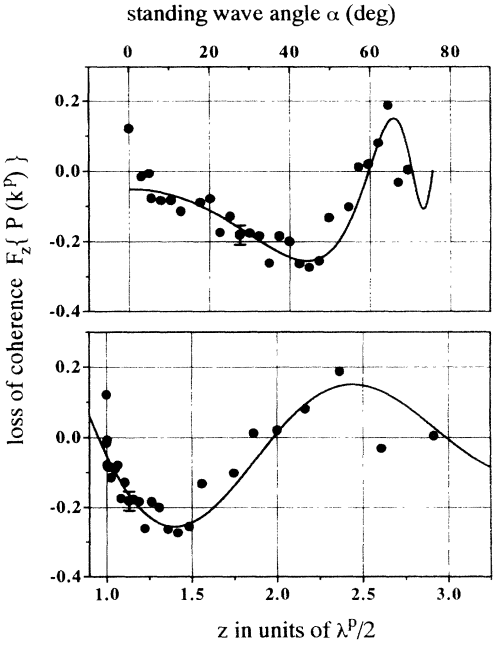

FIG. 4. The measured loss of spatial coherence $\mathcal{F}_z\{P(k_z^p)\}$ as a function of the angle α of the standing wave and the corresponding spatial coordinate z.

[1] W. Heisenberg, Z. Phys. **43**, 172 (1927).
[2] For a recent overview, see V. B. Braginski and F. Y. Khalili, *Quantum Measurement*, edited by K. S. Thorne (Cambridge University Press, Cambridge, 1992).
[3] This statement is analogous to the van Cittert-Zernike theorem in classical optics under the assumption of a statistical mixture of atomic plane waves. This assumption holds in a well-collimated atomic beam.
[4] L. Mandel, J. Opt. **10**, 51 (1979).
[5] T. Sleator, O. Carnal, T. Pfau, A. Faulstich, H. Takuma, and J. Mlynek, in *Proceedings of the Tenth International Conference on Laser Spectroscopy*, edited byM. Ducloy *et al.* (World Scientific, Singapore, 1992), p. 264.
[6] S. M. Tan and D. F. Walls, Phys. Rev. A **47**, 4663 (1993).
[7] See, e.g., P. E. Moskowitz, P. L. Gould, S. R. Atlas, and D. E. Pritchard, Phys. Rev. Lett. **51**, 370 (1983); P. L. Gould, G. A. Ruff, and D. E. Prichard, Phys. Rev. Lett. **56**, 827 (1986).
[8] C. Tanguy, S. Reynaud, and C. Cohen-Tannoudji, J. Phys. B **17**, 4623 (1984).
[9] We define a sign change of the visibility as an exchange of minima and maxima positions in the diffraction pattern.
[10] C. S. Adams, J. Vorberg, and J. Mlynek, Opt. Lett. **18**, 420 (1993).

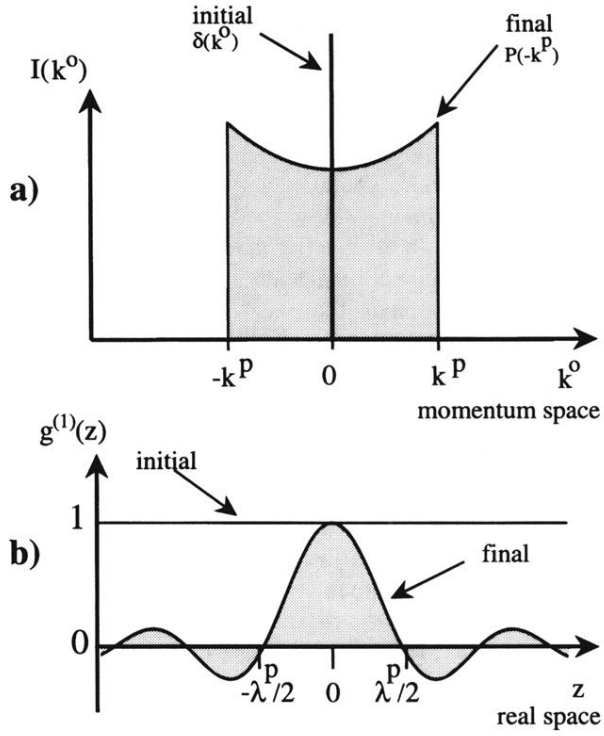

FIG. 1. Influence of a single spontaneously emitted photon on an atom initially in a plane de Broglie wave state without transverse momentum: (a) on the transverse momentum distribution and (b) on the transverse coherence in real space.

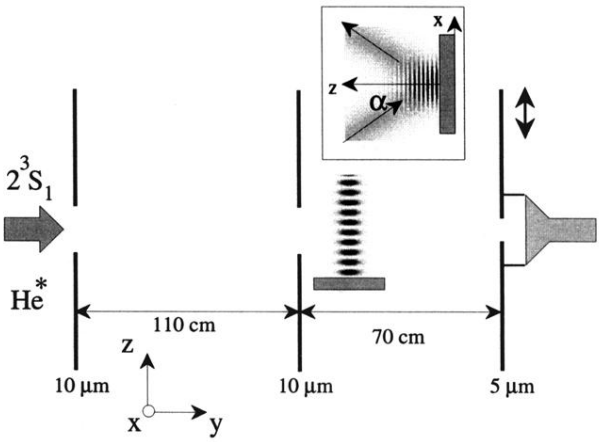

FIG. 2. The experimental setup: A metastable triplet helium beam is diffracted by a standing light wave with variable period. Inset: view along the atomic beam axes; the period of the standing wave can be varied continuously by varying α between 0° and 70°.