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Production of Ultrabright Slow Atomic Beams Using Laser Cooling*

M. D. Hoogerland, D. Milic, W. Lu, H.-A. Bachor, K. G. H. Baldwin and S. J. Buckman

Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia.

Abstract

We propose to use a three-step transverse and longitudinal cooling scheme, to compress and collimate a strongly diverging flow of metastable rare gas atoms. Simulations show that an atom beam flux of 10^{10} s^{-1} in a small diameter (<1 mm), well-collimated (divergence <10 mrad), slow (50 m s^{-1}) atomic beam could be achieved. This technique can be extremely valuable in many areas of atomic physics, e.g. in (electron) spectroscopy and atomic collision physics where high beam densities are desirable.

1. Introduction

The concept that neutral atoms can be cooled to very low temperatures using (near) resonant laser radiation pressure was first proposed by Wineland and Dehmelt (1975) and Hänsch and Schawlow (1975). With the first experimental results of Chu *et al.* (1985), laser cooling has experienced a rapidly increasing interest over the last decade. Many applications of laser cooling in various other fields are being proposed. One area is ultra-high resolution spectroscopy, where cold atoms can be used for atomic frequency standards (Hall *et al.* 1985) and for atomic interferometers (Kasevich and Chu 1992; see also Special Issue *Journal de Physique* 1994). Other possibilities for application lie, e.g., in the study of extremely cold collisions (Dulieu *et al.* 1994; Bardou *et al.* 1992; Katori and Shimizu 1993; Walhout *et al.* 1995). Laser manipulation allows not only 'real' cooling in three dimensions, but also one- and two-dimensional cooling as well as non-cooling effects like deflection and focussing of thermal atomic beams. Thus, 'optical' elements for neutral atomic beams have been developed (Adams *et al.* 1994 and references therein; Balykin *et al.* 1988; Kasevich *et al.* 1990; Baldwin *et al.* 1990; Stenlake *et al.* 1994). Unlike in traditional optics, due to the dissipative nature of laser cooling the phase space volume of an atomic beam can be reduced. Thus, the control offered of the motion of free atoms is virtually complete, opening the way to even more applications.

In collision physics, very intense and well-collimated atomic beams are required to accurately study, e.g., atomic collision processes with small cross sections or collisions between excited state atoms. In our own laboratory we have an interest in

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low energy electron collisions with long-lived (metastable) excited states of atoms. Recent work on angular distributions for electrons superelastically scattered by He(2^3S) (Jacka *et al.* 1995) highlights the problems involved in such experiments with conventional excited state beam sources. In the present work a scheme is proposed where two-dimensional laser cooling, slowing and compression of an atomic beam are used to produce a very intense, slow and well-collimated atomic beam. This beam can be used as a source for the previously mentioned experiments.

2. Basic Techniques

Radiation pressure arises when a two-level atom is placed in a resonant laser field. The atom absorbs a photon from the laser beam, and thereby the photon momentum in the direction of the laser beam, and re-emits the photon spontaneously in a random direction. Over many of these events, the latter contribution averages out to zero, whereas the former adds up to a force: the radiation force $F = \hbar k \Gamma n_e$. The force is proportional to the spontaneous emission rate Γn_e, with n_e the excited state population and Γ the decay rate of the upper level, and to the photon momentum $\hbar \mathbf{k}$, with $|\mathbf{k}| = 2\pi/\lambda$ the wavenumber of the photon. The upper state population for resonant excitation is given by $n_e = s/2(s+1)$, with the on-resonance saturation parameter $s = I/I_0$, which is proportional to the laser intensity. The saturation intensity I_0 is a characteristic of the atomic transition. The maximum force $F = \hbar k \Gamma/2$ yields an acceleration of the order of $10^5\ \mathrm{m\,s^{-2}}$ for a light atom like helium with a strong transition. For non-resonant excitation, the Lorentzian profile of the transition has to be taken into account. The expression for the radiation pressure force on an atom from a single laser beam then takes the form (Lett *et al.* 1989):

$$F = \frac{\hbar k \Gamma}{2} \frac{s}{1 + s + (2\Delta_L/\Gamma)^2}, \tag{1}$$

with Δ_L the detuning. For a moving atom, the effective detuning is not only determined by the laser frequency, but also includes a contribution $\Delta_D = -\mathbf{k} \cdot \mathbf{v}$ due to the Doppler effect. The Doppler effect thus makes the force strongly dependent on the atomic velocity in the direction of the laser.

The velocity dependence of the radiation pressure force forms the basis for the 'standard' laser cooling effect known as 'Doppler cooling' or 'optical molasses' (Lett *et al.* 1989). Atoms are placed in a standing wave of slightly red-detuned laser light. An atom moving slowly in the direction of one of the laser beams will see the counterpropagating beam slightly blue-shifted by the Doppler effect, and consequently closer to resonance. The atom will absorb more photons from the counterpropagating laser beam than from the copropagating beam and experiences a stronger radiation pressure force from the counterpropagating beam. The resulting acceleration as a function of the atomic velocity for a typical example of a cooling transition and for the optimal laser detuning $\Delta_L = -\Gamma/2$ is shown in Fig. 1. For small velocities ($v < 1\ \mathrm{m\,s^{-1}}$), the decelerating force is proportional to the velocity, and thus constitutes a pure friction force. The atomic motion is damped and the atoms are cooled. If three orthogonal pairs of laser beams are used, in a so-called optical molasses configuration, three-dimensional cooling results (Lett *et al.* 1989). In two dimensions, an atomic beam can be collimated this way.

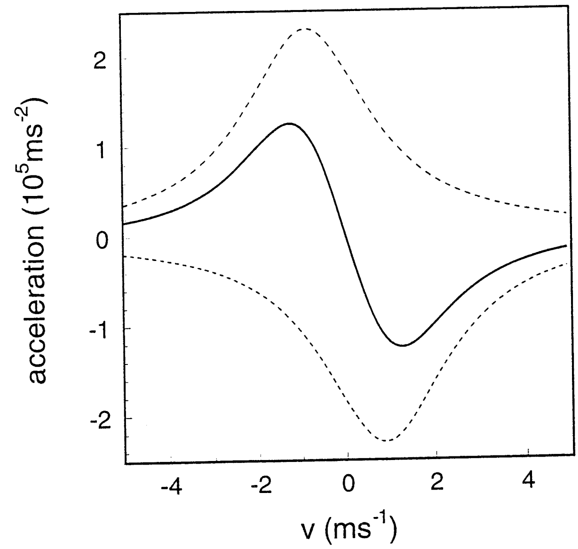

Fig. 1. Acceleration of helium atoms due to the radiation pressure force in a standing laser wave as a function of the atomic velocity for optimal conditions $\Delta_L = -\Gamma/2$. The contributions to the total force of the two laser beams are represented by the dashed curves respectively. The total force is represented by the full curve, showing a linear increase with the velocity for small velocity. The saturation parameter $s = I/I_0 = 1$ for both laser beams.

To obtain a position sensitive force, a magnetic field in combination with σ polarised laser light can be used. In a magnetic field, the atomic energy levels are shifted by an amount $\Delta E = \hbar\mu_B Bmg_j$ with B the magnetic field, g_j the Landé factor, μ_B the Bohr magneton and m the magnetic quantum number for the quantisation axis of the field. Thus $\mu_B m$ is the magnetic moment of the atom in the direction of the magnetic field. Using a magnetic field combined with a σ polarised laser field, an additional detuning $\Delta_{\rm mag} = \mu_B B(g_{j_e}m_e - g_{j_g}m_g)/\hbar$ can be introduced, which for a $J_e = J_g + 1$, $m_g = J_g \rightarrow m_e = J_e$ transition reduces to $\Delta_{\rm mag} = \mu_B B/\hbar$. Using an inhomogeneous magnetic field, the resulting force on an atom can also be made position dependent. This results in the possibility of making, e.g., lenses for neutral atoms. A combination of velocity and position dependent forces is used to obtain efficient trapping and cooling of atoms in a so-called magneto-optical trap (MOT) (Raab *et al.* 1987). In our setup we use a two-dimensional version, in which efficient two-dimensional compression of a slow atomic beam can be obtained (Nellesen *et al.* 1990).

The velocity and position selective forces described above provide us with a powerful means to manipulate atoms. Application of these forces to create a bright thermal beam has recently been demonstrated by Hoogerland *et al.* (1993, 1995) and for a slow, cold and bright beam by Scholz *et al.* (1994). In this paper, we propose to use these forces in a similar scheme to obtain a slow, ultrabright atom beam. First, two-dimensional laser cooling is used to collimate the thermal atomic beam. Then, the beam is slowed as well as velocity bunched using the Zeeman slowing technique. As the full beam flux is maintained during the slowing process, a large increase in density is obtained. Finally, the slow beam is compressed using a two-dimensional magneto-optical trap. The resulting 'bright' beam contains the full atom flux captured in the first section.

3. Proposed Setup: Slow Bright Atom Beams

(3a) Collimation

In Fig. 2 the proposed setup to brighten and slow a metastable (2^3S) helium atomic beam is shown. All laser beams are produced by diode lasers (SDL 6702-HI) tuned to the 2^3S_1 to 2^3P_2 transition at 1083 nm. The natural linewidth of the transition is $\Gamma = 1{\cdot}022 \times 10^7\ \mathrm{s}^{-1}$. One photon recoil corresponds to a velocity change of $0{\cdot}09\ \mathrm{m\,s}^{-1}$. As all laser cooling interaction lengths scale with the source temperature, the metastable helium source will be liquid nitrogen cooled.

The first step in the brightening process is to capture as many atoms as possible in a well collimated beam. The capture range of the Doppler cooling process, however, is limited by the natural linewidth Γ of the atoms. In the case of helium, this capture range for $\Delta = -\Gamma/2$ is $\Delta v = \Gamma/2k = 0{\cdot}9\ \mathrm{m\,s}^{-1}$. At an axial velocity $v_{ax} = 1000\ \mathrm{m\,s}^{-1}$, this means a capture angle of 1 mrad. The capture angle can be dramatically increased, while at the same time increasing the interaction length at a small price in laser power by using effectively curved wavefronts, as illustrated in Fig. 3.

A laser beam is injected at the upstream end of a set of almost parallel mirrors at an angle β_0. The Doppler shift of an atom with transverse velocity $v_\perp$ and axial velocity v_{ax} is now $\Delta_D = -kv_\perp \cos\beta - kv_{ax} \sin\beta$. Each mirror is placed at a small angle $\alpha/2$ with the atomic beam axis ($\alpha \sim 1$ mrad). As the laser beam undergoes multiple reflections between the mirrors, each time intersecting the atom beam, with each reflection the angle β between the laser beam and the atomic beam axis is changed by an amount α. For small β, this means that the 'effective detuning' $\Delta_E = \Delta_L + \Delta_D$ of the laser changes with each reflection. Atoms with a large $v_\perp$ (up to $80\ \mathrm{m\,s}^{-1}$ in our proposed setup for helium) are resonant with the counterpropagating laser beam at the upstream end of the mirrors. As $v_\perp$ is reduced, the change in $v_\perp$ in the first term of the Doppler shift is compensated by a change in β in the second term. In this configuration β as a function of the axial position z can be approximated as $\beta(z) = \sqrt{\beta_0^2 - 2\alpha z/d}$, with d the distance between the mirrors. By careful choice of the angles α and β_0, and the laser detuning Δ_L, $v_\perp$ can be 'locked' to Δ_E and thus reduced to zero during the interaction.

By using slightly curved mirrors, β can be made linear in the axial position, achieving an optimal constant deceleration of the atoms. The curvature required is very small, and can be achieved by slightly stressing a flat mirror.

These techniques are easily applicable in two dimensions, yielding a collimated beam in two dimensions. The large capture range ensures a large beam flux. As the diameter of the resulting collimated atomic beam is about 40 mm, additional focussing or compression of the atomic beam is necessary to obtain a large density.

(3b) Slowing

For slowing the design requirement is that the collimated atomic beam, with a high average v_{ax} ($900\ \mathrm{m\,s}^{-1}$ in the case of helium) and a thermal velocity spread, is slowed to 10–100 m s in a relatively short interaction time. To obtain maximum

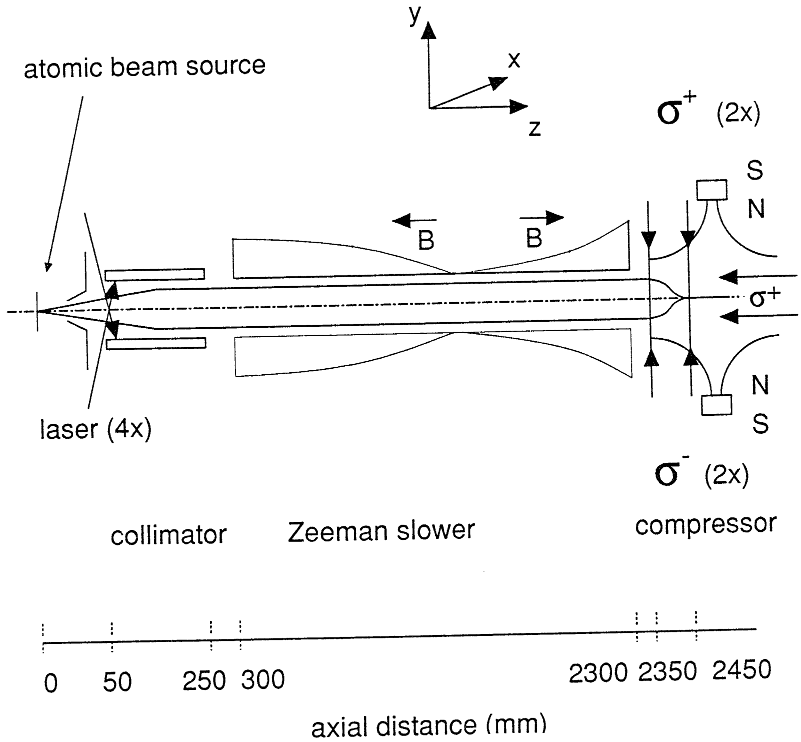

Fig. 2. Proposed setup to produce an intense slow atomic beam of metastable helium. In the first step, the initially diverging atomic beam is collimated. In the second step, the beam is slowed using Zeeman tuning to compensate for the changing Doppler shift. Finally, the slowed atomic beam is compressed to a high density, small cross section and well collimated beam.

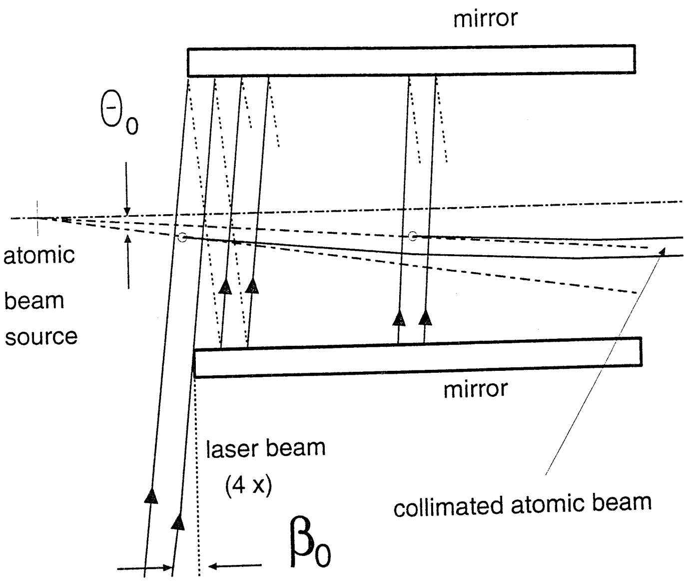

Fig. 3. Schematic view of the mirror section used for collimation of the atomic beam in the first stage. A laser beam is injected between two nearly parallel mirrors at an angle β_0. With each reflection the angle between the laser beam and the plane perpendicular to the atomic beam is reduced by an amount α, resulting in effectively curved wave fronts. The trajectory of the atom is captured at resonance and then follows the wavefront.

deceleration in the slowing process we compensate for the changing Doppler shift kv_{ax} by tuning the atomic transition frequency using the Zeeman shift $\Delta_{\rm mag} = \mu_B B/\hbar$ in a tapered magnetic field coil (Ertmer *et al.* 1985). As the atoms decelerate, the tapering of the magnetic field can be increased. The changing magnetic field $B_z = B_0 + B_1\sqrt{z_{\rm magnet} - z}$, with $z_{\rm magnet}$ the interaction length in the magnet, compensates for the changing Doppler shift of the decelerated atoms. Again, as soon as the atom comes into resonance with the slowing laser, the atomic velocity (and thus the Doppler shift) is 'locked' to the Zeeman shift as long as the maximum deceleration $a_{\rm max}$ is not exceeded. As this process is also dissipative, the longitudinal velocity distribution is bunched while the beam is being slowed. The resulting slow atom beam has a velocity spread of less than $1\,{\rm m\,s^{-1}}$, while the average velocity can be tuned to anywhere between 0 and $100\,{\rm m\,s^{-1}}$. As the slowing process is 100% effective, the full beam flux is maintained.

In our proposed setup, we choose $B_1 = 0{\cdot}06$ T and $B_0 = -0{\cdot}03$ T, and the length of the magnet $z_{\rm magnet} = 2{\cdot}0$ m. This configuration yields the lowest overall magnetic fields, and also allows for additional transverse collimation of the beam in the region of the magnetic field zero (Joffe *et al.* 1993). For the slowing stage, a liquid nitrogen cooled atom source is of paramount importance, as the required interaction length is linear in the source temperature. For a room temperature (300 K) source, the slowing length would thus go up to 8 m.

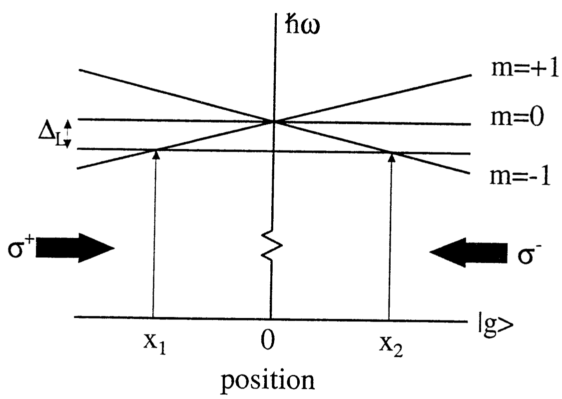

Fig. 4. Operation of a magneto-optical trap in one dimension for a $J = 0 \rightarrow J = 1$ transition. The upper state is split in the quadrupole magnetic field, resulting in a linear dependence of the transition frequency on the distance from the axis. The laser is detuned by an amount Δ_L. A stationary atom at position x_1 will be more resonant with the σ^+ laser beam, pushing it towards the centre. The reverse is true for an atom at position x_2. This principle is easily generalised to two dimensions and a system with more magnetic sublevels.

(3c) *Compression*

To compress the atomic beam we use a two-dimensional magneto-optical trap. In Fig. 4 the basic operation of a MOT is illustrated for a one-dimensional trap for an atom with a $J = 0 \rightarrow J = 1$ transition. However, the scheme can easily

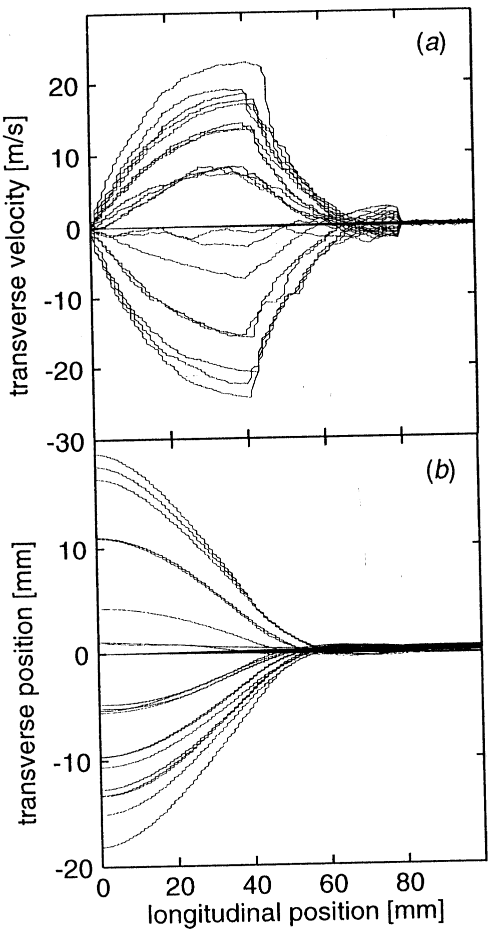

Fig. 5. Simulated atom trajectories in the compression stage. In (*b*), the transverse position is displayed, showing the compression of the initially large atom beam. In (*a*), we see that the transverse velocity distribution is also compressed. In the final 20 mm, optical molasses using linearly polarised light is applied, further reducing the width of the transverse velocity distribution.

be generalised to two and three dimensions and larger angular momenta of the atom. In a quadrupole magnetic field, which is zero on the atomic beam axis and linearly increasing with gradient G away from the axis, the atomic beam interacts with two laser beams with opposite circular polarisation. The laser beams are tuned below resonance. Atoms at position x_1 are more resonant with the σ^+ laser beam, coming from the left, and will thus be pushed towards the beam axis by radiation pressure. As atoms at position x_2 are more resonant with the σ^- laser beam, these will also be pushed towards the atom beam axis. This mechanism is also velocity dependent, and in a long interaction time all atoms will carry out a damped oscillatory motion around and towards the beam axis.

In a beam with a finite axial velocity, the interaction time is limited. Therefore, we increase the magnetic field gradient as the atoms move through the interaction region. The initial gradient is determined by the condition that the Zeeman shift for the outermost atoms should equal the laser detuning. A gradually increasing gradient $G(z)$ initially compensates for the Doppler shift introduced by the atoms starting to move away from the laser beam. Further downstream, the larger gradient yields a tight confinement of the atoms to the beam axis.

The atomic beam is compressed to a needle beam on the axis of the magnetic quadrupole, as shown in the simulation results in Fig. 5. At the upstream end of the compression stage, the atoms are accelerated towards the beam axis. As the magnetic field gradient increases, the (transverse) atomic velocity is locked to the Zeeman shift, and the atom undergoes continuous acceleration towards the axis. Crossing the magnetic field zero on the axis, the force reverses sign and the atoms are confined to the beam axis in a two-dimensional MOT. The radius of the compressed beam is less than a millimetre, and thus a very large density is obtained. In the simulation, we used the parameters for metastable helium atoms with an 80 mm long interaction region and an axial velocity of the atoms of $70\ \mathrm{m\,s^{-1}}$.

The transverse velocity spread entering the compression stage, caused by transverse heating during the slowing process, is 10 m s. The transverse velocity spread of the atoms exiting the compression stage is $\approx 1\ \mathrm{m\,s^{-1}}$. This can be further reduced by polarisation gradient cooling with linearly polarised light in the lin-perp-lin configuration. The last 20 mm of the simulation (Fig. 5) shows the reduction in divergence by Doppler cooling with linearly polarised light.

The atom density in the compressed beam is expected to be limited by intra-beam collisions. Ignoring these, the density in the compressed beam can be estimated by assuming a source flux of $10^{14}\ \mathrm{sr^{-1}\,s^{-1}}$ (Kawanaka *et al.* 1993), an initial capture range of $0\cdot01$ sr, a compressed beam diameter of 1 mm and a beam velocity of $50\ \mathrm{m\,s^{-1}}$. The estimated density is $2\times10^{10}\ \mathrm{cm^{-3}}$, at a beam flux of $10^{10}\ \mathrm{s^{-1}}$. By adjusting the quadrupole magnetic field in the compression stage, the setup can be optimised for either a large beam flux or a small beam diameter.

4. Summary

Summarising, we propose a scheme to collimate, slow and compress a beam of metastable helium atoms. The density in the slow atomic beam will be limited by intra-beam collision processes. As the divergence of the slow beam is low (<10 mrad), the atomic beam can easily be transported to an experiment region removed from the strong magnetic fields that are needed for the slowing and compression stages.

A range of atomic scattering experiments, many of which are marginal prospects with conventional excited beam sources, will be facilitated by such an apparatus. These include low energy (0–5 eV) inelastic electron scattering from metastable helium where differential scattering cross sections for excitation to higher lying excited states can be measured, electron impact ionisation studies, and Penning and associative ionisation studies at ultralow relative velocities.

The apparatus will also provide for an ideal atom source for atom optics experiments. Future applications include experiments on atomic lithography (Timp *et al.* 1992), atom interferometry (see Special Issue *Journal de Physique* 1994) and hollow optical fibres (Marksteiner *et al.* 1994).

All techniques are easily portable to different atomic systems, and can be applied in different areas of atomic physics. Presently, a number of slow atomic beam brighteners are under construction for different atoms for different purposes, ranging from electron physics and atom optics with metastable helium (at ANU Canberra), to atomic collision physics with all metastable rare gases and quantum optics with slow helium atoms (at the Technical University in Eindhoven).

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