Production of a “natural” metastable nozzle beam: Van der Waals - Zeeman atomic levels near a metal surface

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Abstract. A method for obtaining a metastable atom beam with properties near to those of a ground state supersonic beam is demonstrated. Calculations on m sublevels of metastable argon near a metal surface are then presented.

1. Production of a natural metastable atom beam
Because of their low translational temperature (a few K), Campargue-type [1] nozzle beams are characterized by a narrow velocity distribution, both in direction and modulus, and an effective source diameter significantly smaller than the nozzle diameter. Unfortunately when excited species are produced by electronic bombardment within such ground-state atom beams, these characteristics are strongly deteriorated. Within region where metastable atoms are produced, the “primary” metastable atom beam and the ground-state atom nozzle beam, which is almost unaffected by the electron bombardment, overlap. In this region, low-energy exchange collisions (down to 1 meV or less) occur between metastable and ground-state atoms. The velocity distribution of “secondary” metastable atoms generated by exchange is almost identical to that of the ground-state atom nozzle beam. This has been demonstrated in Ref. [2], by means of a time-of-flight analysis.

Fig. 1a shows the profile of a Ar beam obtained when a single circular diaphragm (80µm in diameter) is set downstream, at 116 mm from the nozzle. Wide primary metastable (angular aperture $\delta \theta_1 = 9$ mrad) shifted by 4 mrad with respect to the initial beam axis and narrow secondary metastable (angular aperture $\delta \theta_2 = 0.78$ mrad) centered on the ground-state atom nozzle beam axis are easily identified. As shown in fig. 2, the secondary metastable atoms fraction grows linearly as a function of the supersonic beam input gas pressure.

From the value of $\delta \theta_1$, it is possible to estimate the effective source diameter at about $20 \pm 5$ µm, a value smaller than the nozzle diameter (50µm), as usually observed. For Ar* atoms of velocity 580 m/s, i.e. a longitudinal de Broglie wavelength of 0.018 nm, corresponding to a transverse coherence length of $720 \pm 200$ nm at a distance of 1 m from the nozzle. When a second diaphragm (diameter 100µm) is set at 395 mm from the nozzle, a singly peaked profile is isolated (Fig. 1b). Its angular width (FWHM) is 0.35 mrad, which corresponds to a rms transverse velocity of 0.2 m/s, i.e. a mean
transverse de Broglie wavelength of 51.4 nm. This method of generating a “natural” nozzle beam of metastable atoms works as well, even sometimes better, for other rare-gas atoms such as helium and neon atoms. These beams have been used to observe atom beam diffraction by silicon nitrid grating with a 100 nm period [3].

Fig.1. Transverse profile of a metastable Ar* beam:
(a) collimation by a single 80µm-diameter diaphragm; primary and secondary contributions are easily identified; (b) collimation by two diaphragms (80 and 100µm)

Fig.2. Ratio of the secondary peak intensity on the primary peak intensity as a function of the input gas pressure of the supersonic beam.

2. Van der Waals - Zeeman atomic levels near a metal surface
The van der Waals (vdW) interaction between an atom and an ideal planar metallic perfect conductor - when a static magnetic field B is present is given by: \( V = (16 \frac{z}{r}^3 (D^2 + D_z^2) - g \mu_B J \) where \( z \) is the distance to the surface and \( D_z = D \cdot \hat{z}, \hat{z} \) being the normal to the surface, \( e \) is the electrostatic
permittivity of the medium, $g$ being the Landé factor and $\mu_B$ the Bohr magneton. Actually $V$ is not a purely scalar operator and it can be expanded into scalar and quadrupolar parts. It is this latter part that is responsible for inelastic surface induced transitions such as fine-structure transitions ($^3P_0 \leftrightarrow ^3P_2$) already observed in Ar* and Kr* [4].

The total interaction implicitly contains two different reference axes, namely $\mathbf{u}_z$ and $\mathbf{B}$. So the combined effect of the surface and $\mathbf{B}$ critically depends on the relative orientation of $\hat{z}$ and $\mathbf{B}$. The restriction to the $^3P_2$ level of $V$ can be written:

$$V_e = g \mu_B \mathbf{J} \cdot \mathbf{B} - \left[ C_3 + \left( \frac{\eta}{16} \right) \left( \mathbf{J} \cdot \mathbf{u}_z \right)^2 - \mathbf{J}^2 / 3 \right] / d^3,$$

where $g = 1.5$ is the Landé factor, $\mu_B$ the Bohr magneton; $C_3$ is the scalar vdW constant and $\eta$ is a constant characteristic of the quadrupolar part of the vdW interaction, estimated to $\eta = 0.2$ atomic units [4]. It is useful to introduce the dimensionless reduced variable $\beta$ defined by:

$$\beta = - \frac{\eta}{16 g \mu_B B^2 d^3} \left( \frac{1}{16 g \mu_B B^2 d^3} \right)^{-1}.$$

It is the ratio of the quadrupolar part of the vdW interaction relatively to the Zeeman energy) and the angle $\theta = \mathbf{B} \cdot \mathbf{u}_z$. Numerically $\beta \approx [7.6/d(\text{nm})] B(\text{G})^{-1}$.

Interaction (1) can be rewritten as $V = - C_3 d^{-3} + g \mu_B B V_r(\beta, \theta)$ where:

$$V_r(\beta, \theta) = \mathbf{J} \cdot \mathbf{u}_B + \beta \left( \mathbf{J} \cdot \mathbf{u}_n \right)^2 - \mathbf{J}^2 / 3 = J_z' + \beta \left[ (J_z' \cos \theta + J_x' \sin \theta)^2 - 2 \right].$$

The 5 eigenvalues of $V_r(\beta, \theta)$ then provide us with 5 potential energy surfaces (to which the common scalar energy $- C_3 d^{-3}$ should be added). As expected, for $\beta = 0$, i.e. $d$ infinite, the Zeeman energies, are recovered, at any value of $\theta$. On another hand, for $\theta = 0$, quantization axes $\mathbf{u}_B$ and $\mathbf{u}_n$ coincide and $V_r$ is diagonal in the Zeeman state basis. Energy cus $\theta = 0$, are then straight lines exhibiting a series of crossings, at $\beta = 1/3$ ($m_z = -2, m_x = -1$), $\beta = 1/2$ ($m_z = 0, m_x = -2$), $\beta = 1$ ($m_z = 0, m_x = -1$ and $m_z = +1, m_x = -2$), as shown in fig. 4a.

Fig. 4 : Eigenvalues of $V_r$ (a) for $\theta = 0$ (b) for $\theta = 10^\circ$

As soon as $\theta \neq 0$ these crossings become avoided crossings, which shows that the potential energy surfaces present a series of conical intersection points aligned along the axis $\theta = 0$ (see fig.4b). A priori such intersection points are quite accessible experimentally since for instance the value $\beta = 1$ is obtained at $B = 1\text{G}$ and $d = 7.5$ nm.
Conclusion
One expects that these avoided crossings may lead, in a near adiabatic following regime, to Zeeman transitions in scattering of an atom beam by a metal surface. This may lead to a deflection of the inelastic scattered atoms of the order of magnitude of \((\Delta E/E_0)^{1/2}\) where \(\Delta E = g \mu_B B \left| \Delta M \right|\) is the kinetic energy gain in the transition and \(E_0\) the incident kinetic energy. For a thermal velocity beam, \(E_0\) is typically 60-65 meV whereas, for \(B \approx 20\) G and \(\Delta M = -1\), \(\Delta E \sim 6 \times 10^{-5}\) eV, leading to deflection angles of about 1 mrad. A metastable atom beam obtained by metastability exchange collision would be a convenient and suitable source for the observation of such deflections. We also expect this kind of metastable atom source to reveal extremely efficient in atom optics and interferometry.

References
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