High-Resolution Studies in Ion Beams with Laser-Induced Resonances

M. Dufay, M. Carré, M. L. Gaillard, G. Meunier, H. Winter,* and A. Zgainski
Laboratoire de Spectrométrie Ionique et Moléculaire,† Université de Lyon I, 69621 Villeurbanne, France
(Received 29 July 1976)

In order to observe energy-level splittings in free ions, we used a new technique based upon the superposition of a fixed-frequency c.w. laser beam and of a post-accelerated (or -decelerated) fast ion beam. Narrow spectral features observed in fluorescence under these conditions are easily identified within a simple hole-burning model. Implications of our results for high-resolution spectroscopy of free ions are discussed and an application is given in the case of hyperfine-structure measurements.

Experiments on interaction of laser radiation with a fast ion beam, initiated by Andrä,[1] have been carried out so far in crossed-beam geometry. With such a setup, the very short interaction time between the two beams is a drawback for the study of specific laser excitation effects because of the high laser power requirements. Under those conditions only one successful saturated-absorption experiment has been reported, in a fast neutral Ne beam.[2]

This prompted us to investigate an alternative geometry whereby the accelerated ion beam and the laser beam are superimposed over a long path in vacuum. It is then possible to take advantage of the fact that charged particles can easily be speeded up (or slowed down) along their path by application of external electrical fields. This enables us to switch rapidly on or off the resonant interaction with the laser field by Doppler tuning or detuning the ion beam velocity in a manner which is reminiscent of the Stark switching technique of Brewer and Shoemaker.[3] Of course under proper experimental conditions, this switching can be made to affect only one velocity class within the ion velocity distribution. Under the assumption that the laser beam is able to modify the ion-beam velocity distribution at some point upstream (for example, emptying one velocity class by saturated absorption), we can probe this effect by using the same laser beam again downstream after rapid post-acceleration (or -deceleration) of the ion beam and monitoring the fluorescence at 90° to the beam.

In the superimposed-beam geometry, both beams traveling in the same direction, optical resonance is achieved between a $^{138}Ba^{+}$ ion beam and an argon laser at 4545 Å when the ion velocity reaches $\beta = v/c = 0.001\,978$. The excited $6p\,^2P_{3/2}$ state can then decay along two channels, either back to the ground state or to the metastable $5d\,^2D_{3/2}$, and $5d\,^2D_{5/2}$ levels. Given the short lifetime of the $6p\,^2P_{3/2}$ state (6.312 ± 0.016 ns) the main effect of a steady-state interaction between ion and laser beams would be to pump the ions optically into the ^2D states.

The main component of our experimental setup, as indicated in Fig. 1, is a commercially available 350-keV ion-implantation unit with a hollow-cathode discharge ion source. The extracted ion beam is mass-analyzed by a 90° magnet and accelerated up to a maximum of 320 keV. The laser beam enters the vacuum chamber through a

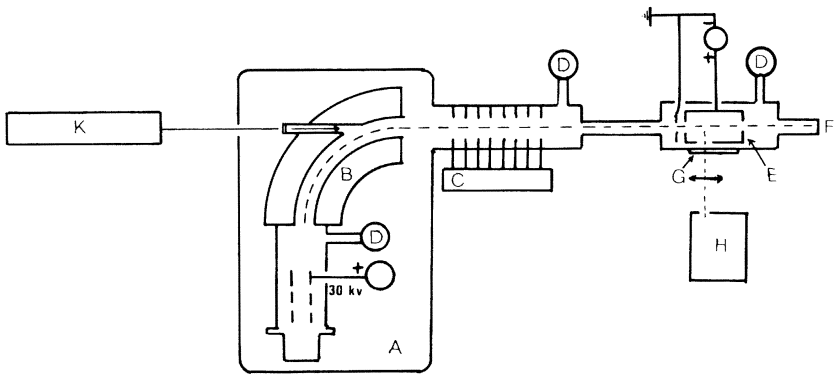

FIG. 1. Experimental setup. A, 350-kV heavy-ion accelerator; B, mass separator; C, high voltage supply; D, vacuum pumps; E, post-acceleration electrodes; F. Faraday cup; G, quartz window and lens system; H, monochromator; K, Ar^{+} c.w. laser.

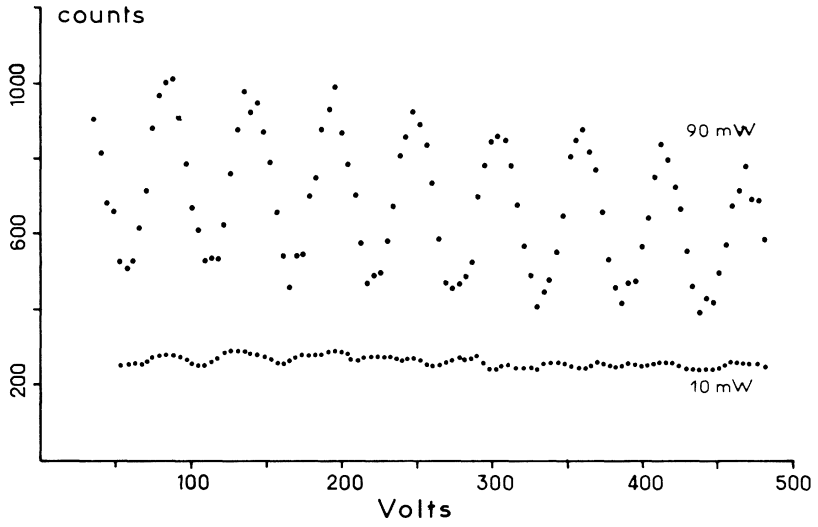

FIG. 2. Fluorescence count rate vs post-acceleration voltage at various laser powers. Laser in multimode operation at 4545 Å. $^{138}Ba^{+}$ beam at 251 KeV.

window located between the pole pieces of the analyzing magnet. The observation chamber was insulated and could be held at a variable potential.

In a first stage of the experiment, the electrodes in the observation chamber were kept grounded and a $^{138}Ba^{+}$ beam was superimposed with a multimode laser beam at 4545 Å. The accelerating voltage being tuned for maximum fluorescence signal at 4554 Å, we then scanned the observation chamber voltage while monitoring the fluorescence. The results obtained for various incident laser powers are displayed in Fig. 2. Interpretation of the phenomena is straightforward in a hole-burning model. Each longitudinal laser mode is assumed to drill a Bennett hole in the ground-state $^{138}Ba^{+}$ velocity profile, as indicated in Fig. 3. Thus downstream, the comb of laser modes tests a comb of shifted Bennett holes. The fluorescence light displays saturated absorption. Its minima and maxima are, respectively, associated with the coincidence and anticoincidence of both modes and shifted holes. Support for this interpretation is provided by the measure of the difference in the applied voltage corresponding to two peaks on the modulated curve of Fig. 2, which corresponds to 145.3± 0.3 MHz, in excellent agreement with the mode spacing of the laser (142.8± 4.1 MHz) specified by the manufacturer.

This first observation prompted us to repeat the same experiment, but this time with a single-mode laser. We observed, as expected from the interpretation above, a single dip centered around the zero value of the applied post-acceleration potential. As shown in Fig. 4, power broadening was clearly observed and the measured width of the dip varies linearly with the applied laser field, within experimental uncertainties. In order to demonstrate that this signal could be used for high-resolution spectroscopy, we tuned the isotope separator to obtain beams of either one of the odd-mass isotopes $^{137}Ba^{+}$ or $^{135}Ba^{+}$ superimposed with the single-mode laser light. Keeping the accelerator voltage fixed at the center of the resonance associated with the excitation from

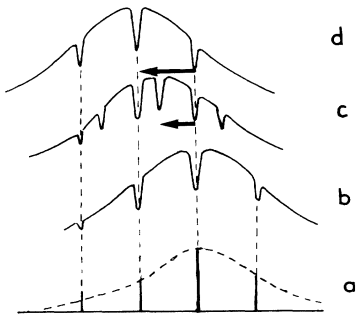

FIG. 3. Hole burning model (schematic). a, profile of the laser line, laser in free-running multimode operation. b, saturation holes in the velocity distribution of the ions in the ground state before entering the post-acceleration region. c, velocity distribution of the ions after post-acceleration; the fluorescence signal which is proportional to the area of the dips is now stronger than is case (b). d, velocity distribution after a post-acceleration corresponding to a laser mode spacing: Saturated absorption is observed.

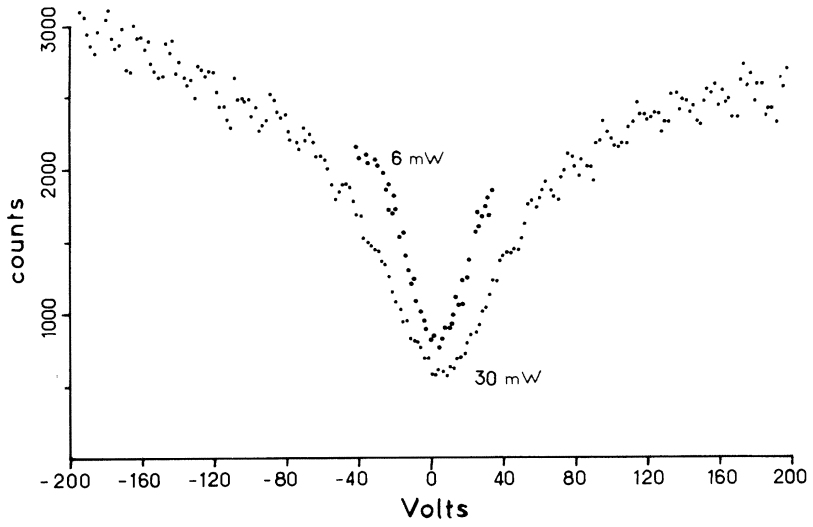

FIG. 4. Fluorescence count rate vs post-acceleration voltage at various laser powers. Laser in monomode operation at 4545 Å. Beam of $^{138}Ba^{+}$ at 251 keV.

the $6s\,^2S_{1/2}$, $F=2$ sublevel (Fig. 5), we scanned the post-acceleration (or -deceleration) voltage. Three dips are observed and their intervals, as indicated in Table I, are in good correspondence with the hyperfine splittings of the upper $6p\,^2P_{3/2}$ state as measured by previous authors.[5,6] The absence, in our measurement, of the dip corresponding to the overlap of the $F=2$ to $F=2$ hole with the $F=2$ to $F=1$ hole is correlated with the lower oscillator strength of those transitions compared with the $F=2$ to $F=3$ transition.

One can already foresee several applications for the arrangement introduced in this first series of experiments. Quite obviously, high-resolution studies of resonant excited states of ions are possible, without any of the sophistication currently associated with tunable narrow-line lasers.

Tunability is obtained continuously over angstroms by simply scanning the accelerator high voltage, and resolution is obtained with only low stability requirements on both the laser and the accelerator. Indeed, it is easy to see that shifts in laser wavelength or accelerator voltage do not affect the position of the center of the observed dips. This position is determined only by the post-acceleration potential which can be measured with high accuracy. A further advantage

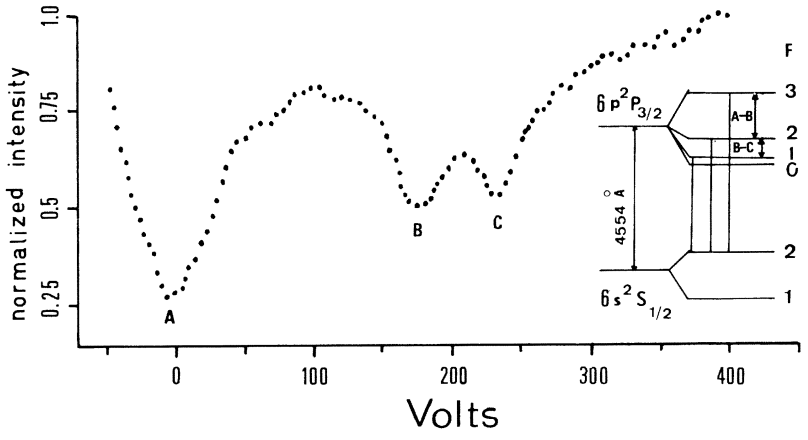

FIG. 5. Normalized intensity of the fluorescence vs post-acceleration voltage. Laser in monomode operation at 4545 Å. Beam of $^{137}Ba^{+}$ at 249.4 keV.

TABLE I. Comparison of the intervals between dips A, B, and C in Fig. 5 with previous measurements of $^{137}Ba^+$ and $^{135}Ba^+$. The error on our measurement has been taken arbitrarily equal to a tenth of the observed linewdith, given the preliminary state of the analysis. The ultimate accuracy achievable by this technique will be considerably higher and should compete favorably with previous measurements (Ref. 4).

		$^{135}Ba^+$	$^{137}Ba^+$
Becker[a]	$6\,^2P_{3/2}$ $F=1,2$	163.0 ± 13.2	155.7 ± 18.5
	$6\,^2P_{3/2}$ $F=2,3$	402.0 ± 15.3	476.3 ± 20.8
Kraus[b]	$6\,^2P_{3/2}$ $F=1,2$	164.99 ± 0.99	159.37 ± 0.84
	$6\,^2P_{3/2}$ $F=2,3$	398.61 ± 1.31	470.38 ± 1.06
This work	$B-C$	167 ± 10	155 ± 10
	$A-B$	385 ± 10	484 ± 10

[a]Ref. 5 [b]Ref. 6.

of the technique is that reasonable signal-to-noise ratios are obtained even with low laser power (a few milliwatts per square millimeter) and low beam intensity (10^{11} particles per second). This should make it possible to use c.w. frequency-doubled gas or dye lasers and to widen the field of application of fast-beam laser spectroscopy to beams of less abundant species, such as ions in metastable states or even unstable isotopes. Extension to ionic molecules is also possible, as exemplified by the paper of Wing *et al.*[4]

*Permanent address: Institut für Experimentalphysik III, Ruhr Universität, Bochum, Germany.

†Associé au Centre National de la Recherche Scientifique.

[1]H. J. Andrä, in *Beam-Foil Spectroscopy*, edited by I. A. Sellin and D. J. Pegg (Plenum, New York, 1976), Vol. 2, p. 835.

[2]J. J. Snyder and J. L. Hall, in *Proceedings of the Second International Conference on Laser Spectroscopy*, edited by S. Haroche, J. C. Pebay-Peyroula, T. W. Hänsch, and S. E. Harris (Springer-Verlag, Berlin, 1975), p. 6.

[3]R. G. Brewer and R. L. Shoemaker, Phys. Rev. Lett. 27, 631 (1971).

[4]W. H. Wing, G. A. Ruff, W. E. Lamb, and J. J. Spezeski, Phys. Rev. Lett. 36, 1488 (1976).

[5]W. Becker, W. Fischer, and H. Hühnermann, Z. Phys. Phys. 216, 142 (1968).

[6]M. Kraus, Diplomarbeit, Berlin, 1976, (unpublished).

CO_2-Laser–Excited Langmuir Turbulence in a Dense-Plasma Focus

M. J. Forrest, P. D. Morgan, N. J. Peacock, and K. Kuriki*
EURATOM–United Kingdom Atomic Energy Authority Association for Fusion Research, Culham Laboratory, Abingdon, Oxon OX 143 DB United Kingdom

and

M. V. Goldman† and T. Rudolph†
Department of Astro-Geophysics, University of Colorado, Boulder, Colorado 80309

(Received 29 June 1976)

We report on ruby-laser scattering measurements of Langmuir turbulence excited in a high-density plasma by a CO_2 laser pump. The observations are reasonably consistent with a new theoretical treatment of the convective electron-ion decay instability at equal electron and ion temperatures.

Recently, there has been a great deal of experimental activity[1,2] devoted to plasma properties in the vicinity of the critical surface of laser-irradiated high-density plasmas. Among the diagnostics that have been employed are single-laser reflection[1] and harmonic-light emissions.[2] In this Letter we report direct observations of Langmuir wave turbulence driven by a transverse-excitation-atmosphere CO_2 laser pump near the critical surface of a separately created high-density plasma. The principal diagnostic is incoherent scattering performed with a second (ruby) laser. We believe that incoherent scattering can offer added flexibility and control in comparison with other diagnostic methods for measuring Langmuir turbulence of laser origin in high-density plasmas.

It is significant that almost total absorption of CO_2 laser intensity is observed throughout the 80-nsec time interval when the plasma is overdense. Measurements of CO_2-beam transmission, back-reflection, and refraction at selected angles show intensity levels at least 2 orders of magnitude lower than the level (0.1 kW) which would be associated with uniform refraction into 4π sr. Classical inverse bremsstrahlung would seem to account for no more than 50% of the absorption.