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ABSTRACT

The time-resolved Stark broadened spectrum of the H_β line of hydrogen has been observed in a pulsed microwave field of 20nsec duration, a frequency of 4.6GHz, and a field strength of ~100kV/cm, generated by a relativistic electron beam magnetron. The resulting line broadening can be used to determine the electric field strength and its spatial mode structure.

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Novel microwave sources[1-5] capable of delivering up to 4GW of power, generate rf electric fields of several hundred kV/cm in associated microwave guiding structures. In this note we explore the feasibility of observing these fields through the Stark broadening of atomic spectral lines. Such measurements have a two-fold purpose. First, they provide a means of checking the predictions of Stark broadening theory in time-dependent, sinusoidal rf fields. And secondly, once these checks have proved satisfactory, the resulting line broadening can be used in the determination of the absolute electric field strength and of its spatial mode structure in the waveguide system in question. To date all experiments of this type have been performed at electric field strengths at least an order of magnitude lower than those reported here. The accompanying theory and numerical calculations of spectral line shapes[6-10] are likewise known in a regime that may not be fully applicable to the present experiments. For example, an important quantity in the theory is the ratio[11,12] of the frequency of precession of the atomic dipole moment about the direction of the electric field, to the frequency of the rf oscillations. This ratio written out in full

$$R \equiv (3nh\varepsilon_o/me)(E/\omega) \qquad (1)$$

is then a statement concerning the degree of adiabaticity of the motion. [Here e and m are the charge and mass of the electron, respectively, n is the principal quantum number of the upper state of the transition, E is the electric field strength, and ω is the angular frequency of the rf perturbation.] In experiments reported hitherto[6,7,8] the parameter $R \lesssim 5$; in our measurements $R \simeq 170$. Furthurmore, in the earlier experiments, the electric field was either a continuous wave or, if pulsed, there were several thousand rf periods per pulse. In the present experiment the pulse is comprised of only ~75 periods of the rf oscillation, a fact that may have to be incorporated in a comprehensive analysis.

The experimental arrangement is illustrated in Fig. 1. The power from the magnetron is extracted from one of the six resonators (which form its slow wave structure[1,2]) and is guided by means of a section of evacuated S-band waveguide towards the transmitting horn. The 17nsec long wave pulse of frequency 4.6GHz travels down the guide in the principal TE_{10} mode. A quartz capillary Geissler tube (0.75mmID), filled with 4Torr of spectroscopically pure hydrogen passes down the middle of the rectangular waveguide, with the tube axis oriented parallel to the rf electric field. The discharge tube is provided with stainless steel electrodes situated outside the waveguide, so that a weak plasma can be struck with a dc field typically equal 200V/cm and at a dc current of ~10mA. The light from the dc discharge is used to align the optics. But, more importantly, it is employed as a "keep-alive" during the actual experiments. By maintaining the discharge tube lit one is assured of having copious electrons to initiate the rf breakdown, with the result that fairly good shot-to-shot reproducibility is achieved. The diameter of the discharge tube is purposely chosen to be small (0.75mmID) so as to cause a minimal perturbation to the wave. We checked this by measuring the power flowing from the magnetron to the horn with and without the discharge tube, but found no noticeable change.

The light from the discharge is focused onto the 100μm wide entrance slit of a half meter Jarrell-Ash monochromator. The light from the exist slit enters the photomultiplier tube shielded both electrically, and against the x-ray flux emitted by the magnetron when the ~0.4MeV electrons strike the anode block. The photomultiplier dynodes are gated off except for a ~1μsec wide time interval spanning the microwave pulse. In this way we prevent saturation of the photomultiplier by the light from the steady keep-alive discharge. The output from the photomultiplier is displayed on a fast oscilloscope triggered by the discharging of the Marx generator, which is the source of energy for the magnetron.[1,13]

Figure 2 shows a set of oscilloscope traces of a single shot: that is, the light intensity from the hydrogen-filled tube, the microwave power emanating from the horn antenna, the magnetron current, and the magnetron voltage. We see that the microwave burst is accompanied by a pronounced signal from the photomultiplier (of approximately 2V peak) indicating the occurrence of rf ionization. We note that the keep-alive discharge produces a photomultiplier signal of only 20mV. Thus, the microwave field increases the light intensity by two orders in magnitude, which is in part due to production of additional electrons and in part due to electron heating by the microwaves. We point out that there is no measurable delay between the onset of the microwave pulse and the onset of rf breakdown. Measurements made in other gases[14] indicate that at the level of rf field strengths with which we are dealing here (≃100kV/cm), the "breakdown lag" is less than 2nsec.

Figure 2a gives the relative light intensity for a given setting of the monochromator wavelength. To obtain the line shape of the H_β line, the monochromator is advanced to a new wavelength setting and all measurements like those shown in Fig. 2 are repeated. Some thirty successive shots lead to the line profile illustrated in Fig. 3a. Despite notable shot-to-shot variations, a clearly defined broadened line profile emerges. We cannot establish the level of the continuum with precision and therefore we can only estimate the value of the line width. We find that the full width at half power (FWHP) is approximately 6Å. This is to be compared with the instrumental profile shown in Fig. 3c whose full width is 1.0Å.

We see from Fig. 2a that the intense burst of light during the microwave pulse is followed by long lasting "afterglow" light radiated by the plasma as it slowly decays by diffusion and recombination processes. Figure 3b shows the line shape at the peak of this afterglow, that is, some 150nsec after the microwave burst has ceased. It is seen that the line width had decreased dramatically and equals, within the accuracy of this determination, to the instrumental line width. This is most gratifying: it demonstrates that the line broadening shown in Fig. 3a is indeed predominantly due to the rf electric field, and that Stark broadening by the plasma ions (and electrons) is not an important contribution. [An independent estimate suggests that the upper limit on the charged particle density is $\sim 10^{14} cm^{-3}$ which results[15] in a line-broadening contribution of no more than 0.4Å.]

We do not have at this time a detailed line shape calculation corresponding to the parameters of our experiment. In lieu of this we take the quasi-static theory as a first approximation in our attempt to relate the half power width $\Delta\lambda_{1/2}$ to the peak electric field amplitude E_o of the microwave signal. The appropriate expression is[12]

$$\Delta\lambda_{1/2} = [3\lambda_o^2\varepsilon_o h(n_1^2-n_2^2)/2\pi^2 mec]E_o \qquad (2)$$

where λ_o is the wavelength of the transition whose upper and lower states are n_1 and n_2. For the H_β line one finds that

$$\Delta\lambda_{1/2} = 0.0579\ E_o \qquad (3)$$

where now $\Delta\lambda_{1/2}$ is given in Å and E_o is in kV/cm. Using the measured value, $\Delta\lambda_{1/2} \simeq 6$Å, yields E_o=104kV/cm. This is to be compared with the value of 102kV/cm obtained from measuring the microwave power output from the horn antenna (Fig. 2b), and then integrating Poynting's flux over the waveguide cross section.

In conclusion then, we have reported preliminary observations of Stark broadening in sinusodal rf fields where the intensity greatly exceeds that employed by earlier workers. Detailed line shape measurements and detailed line shape calculations are yet to be done. Nonetheless, the technique may prove useful as a diagnostic of the strength of such microwave fields. By focusing different sections of the discharge tube onto the spectrometer slits, and by properly orienting the tube relative to the direction of the electric field, one may be able to map out the entire spatial distribution of the field. This may be advantageous in more complex situations where the mode structure may not be well-known.

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FIGURE CAPTIONS

Fig. 1. Schematic of the experiment.

Fig. 2. Oscilloscope traces of (a) the relative light intensity from the hydrogen discharge; (b) the peak microwave power emitted by the horn; (c) the current drawn between the magnetron cathode and anode; and (d) the voltage applied across the magnetron electrodes. In (a) note the short light pulse followed by a long afterglow.

Fig. 3. (a) The Stark-broadened profile of the H_β line of hydrogen observed during the microwave pulse; (b) the line profile of H_β in the afterglow, ~150nsec after the microwave pulse; (c) the instrumental line profile. In (b) note that the H_β line sits atop a pronounced continuum.

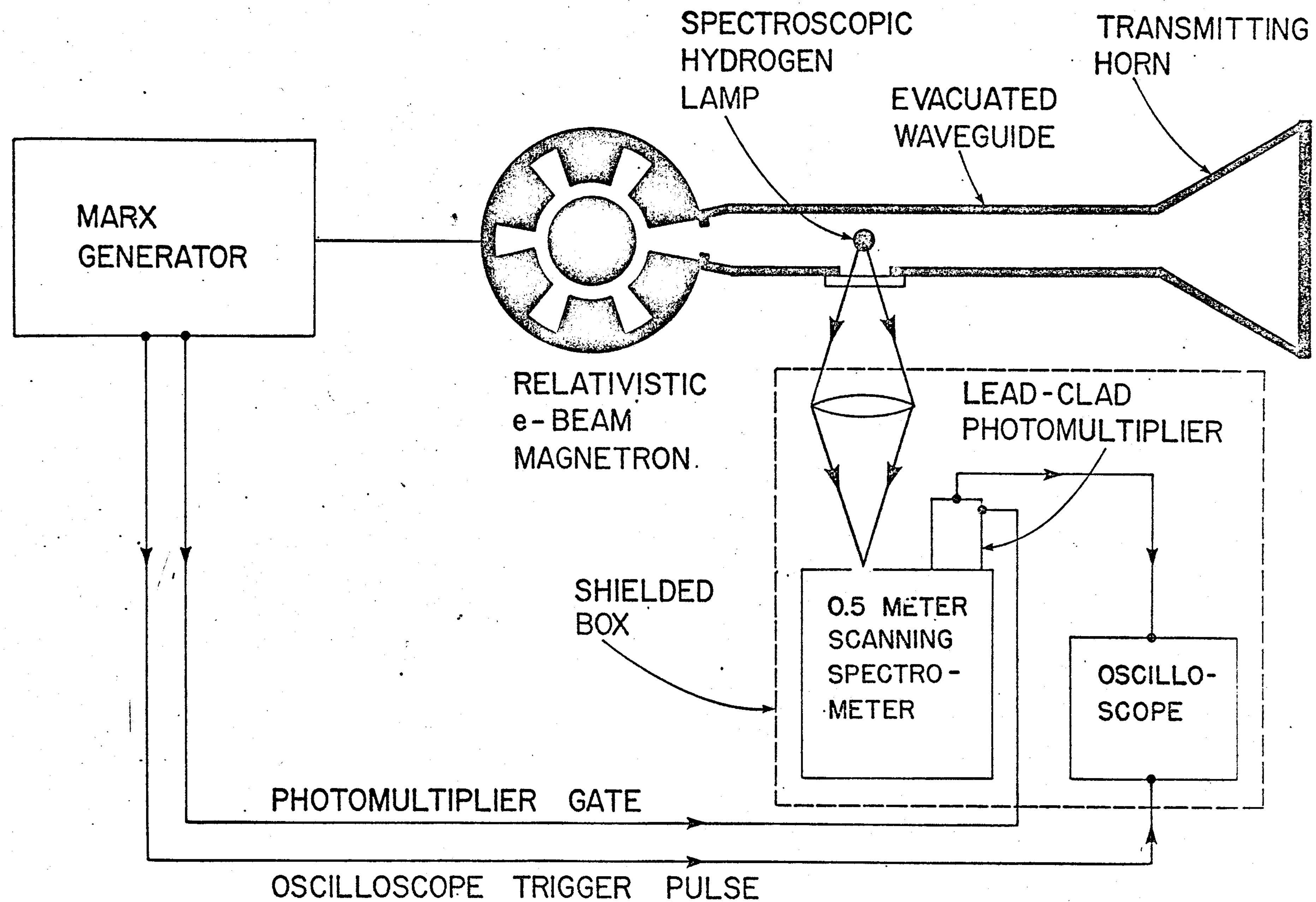

Fig. 1
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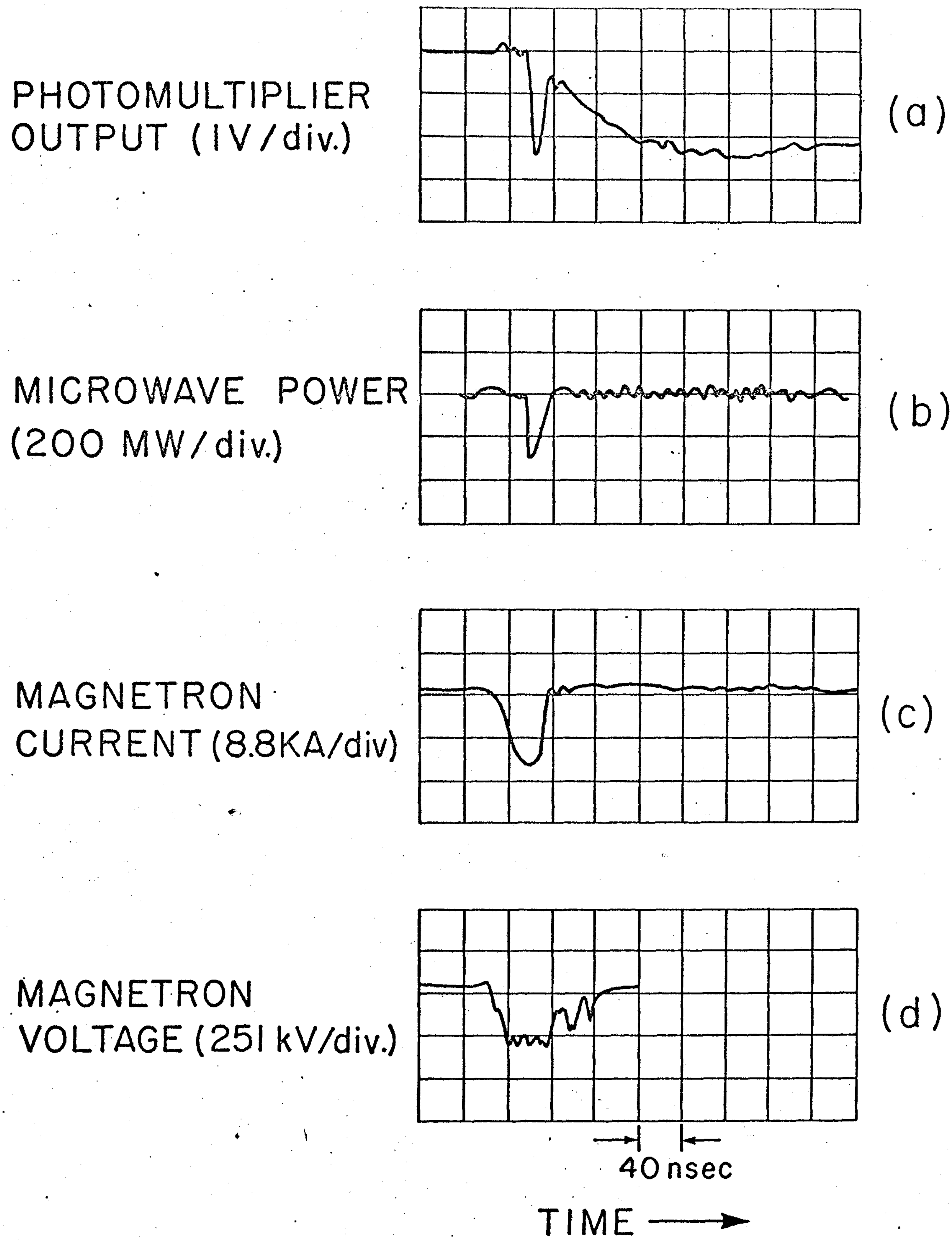

Fig. 2
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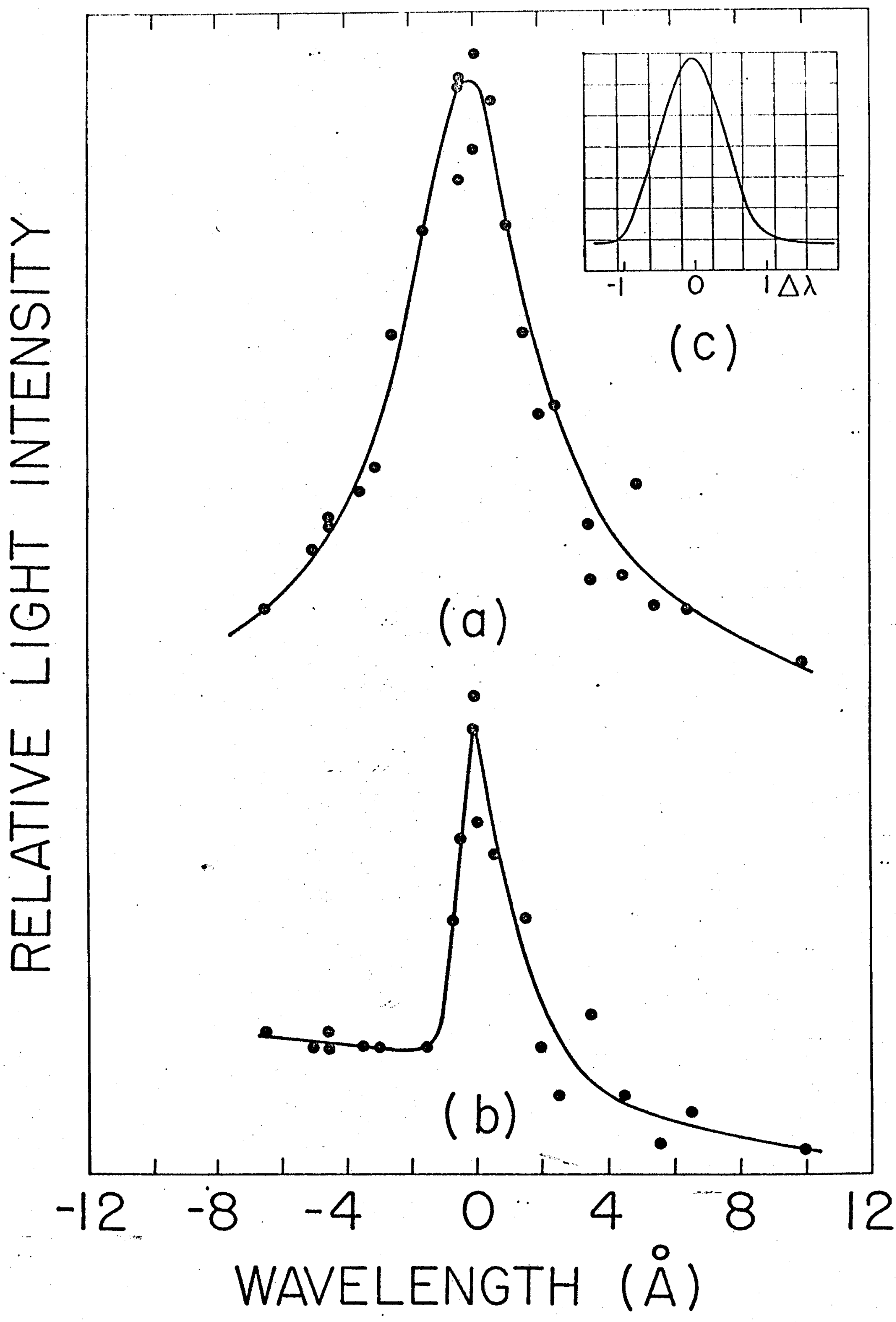

Fig. 3
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