Observation of a Čerenkov-type radiation during the propagation of picosecond light pulses in sodium vapor

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A conical emission which is excited in sodium vapor by laser light tuned over the short-wave region of the $3S$–$3P_{3/2}$ transition ($\lambda_l = 589$–576 nm) has been studied. The experimental results can be used to interpret the observed scattering in a model of Čerenkov radiation.

Studies of the interaction of an atomic medium with quasiresonant laser light with a frequency $\omega_l \gtrsim \omega_{ab}$ (ω_{ab} is the frequency of the absorption line) which is propagating in the medium have revealed the appearance of a forward emission with a frequency $\omega_k \lesssim \omega_{ab}$ and a clearly expressed conical structure.[1–4] Various theoretical models based on four-wave mixing and scattering under conditions of self-focusing of the laser light have been offered in attempts to explain the observed effect.[2–4] However, these models fail to give a satisfactory explanation for the nature of this effect, since the spatial-frequency spectrum of the scattered light lacks the high-frequency component which is symmetric with respect to the low-frequency component and which is unavoidable in a four-wave mixing. The only case in which the model of four-wave mixing has been found to correspond to the experimental results has been in a study of the conical emission which arises during the resonant excitation of a two-photon-allowed transition.[5,6] Golub *et al.*[7] have interpreted the conical emission which arises during near-resonance excitation of sodium vapor in a model of Čerenkov radiation from the surface of a filament of a self-focused pump beam. The theoretical groundwork for the possible appearance of a radiation of this type had been laid earlier by Askar'yan.[8] In the present letter we report experiments which confirm both qualitatively and quantitatively that the scattering that occurs is of a Čerenkov nature.

In sodium vapor we observe a broad-band conical scattering which is induced by a laser pump tunable over the short-wave vicinity of the $3S$–$3P_{3/2}$ transition (Fig. 1). As the pump we use the second harmonic of a single-pulse picosecond light source, amplified in a dye (rhodamine 6G). The energy of the pump light is ~ 0.5 mJ at a pulse length of 25 ps and a spectral width ~ 60 cm^{-1}. The pump light, focused by lenses with $f = 25$–150 cm (or without focusing), is directed into a cell holding sodium vapor at a density of $(1$–$50) \times 10^{15}$ cm^{-3}. The power density at the focus ranges up to 10 GW/cm^2. The exciting light is tuned over the wavelength interval 589–576 nm, which includes a two-photon resonance with a $3S$–$4D$ transition. By way of comparison we note that in all of the previous studies the medium has been excited by nanosecond-range pulses ($\tau_l = 2$–7 ns, $I \sim 0.1$–1 MW/cm^2) with a wavelength tunable over an interval < 1 nm.

We studied the behavior of the characteristics of the conical radiation as we varied the tuning of the exciting light $\Delta\omega_l = \omega_l - \omega_{3S-3P_{3/2}}$, the extent of focusing of

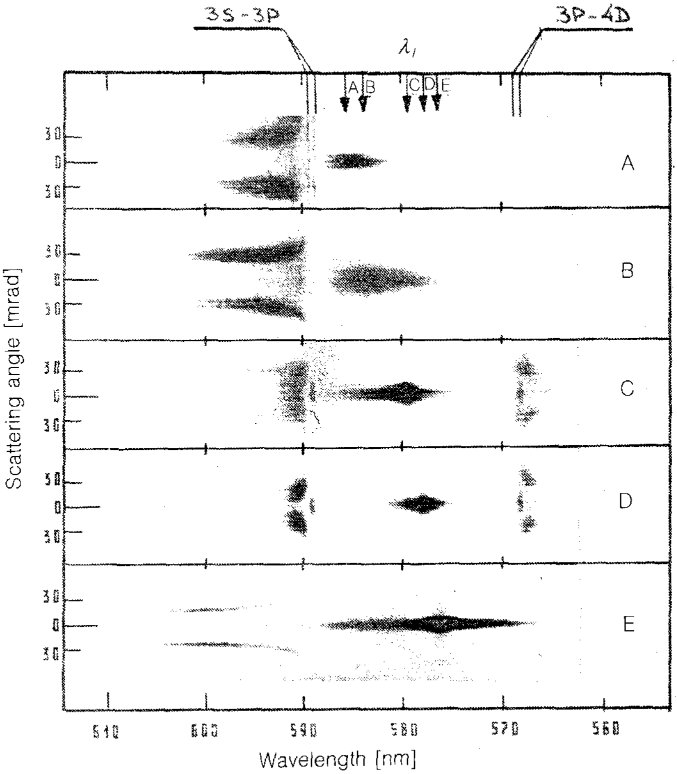

FIG. 1. Spatial-frequency spectra of the scattered light as the pump frequency is tuned over the high-frequency region of the $3S$–$3P_{3/4}$ transition. a—95 cm^{-1}; b—140 cm^{-1}; c—260 cm^{-1}; d—305 cm^{-1}; e—360 cm^{-1} ($N = 1.4 \times 10^{16}$ cm^{-3}).

this light, and the density of the sodium vapor. From an analysis of the results we drew the following conclusions: 1) The structure of the scattered light remains constant over the entire range over which the pump frequency is tuned, except near the two-photon resonance with the $3S$–$4D$ transition (Fig. 1). The spectral width of the scattered light reaches ~ 780 cm^{-1}, which is significantly greater than that observed previously[1–4] (~ 5–10 cm^{-1}). 2) The spatial-frequency distribution of the conical radiation corresponds well to a radiation of a Čerenkov type (Fig. 2), with scattering angles determined by the expression

$$\theta_C = \arccos \frac{n_l}{n(\omega)} \left[1 + \frac{\omega_l}{n_l} \frac{dn}{d\omega} \bigg|_{\omega = \omega_l} \right] \approx \sqrt{2[n(\omega) - n_l]} \bigg|_{\theta_C \ll 1}, \qquad (1)$$

where $n(\omega)$ is the refractive index. 3) There is some discrepancy between the measured scattering angles and those calculated from (1), which we attribute to changes in the conditions of the self-focusing of the exciting light (in accordance with Ref. 9)

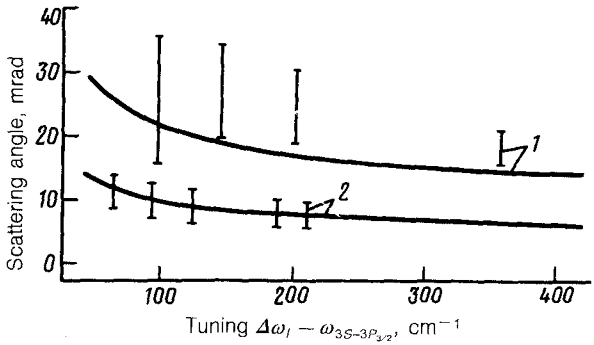

FIG. 2. Vertex half-angle of the Čerenkov radiation cone, $\theta_C = \sqrt{2(n_{\lambda=600} - n_l)}$ at the wavelength $\lambda = 600$ nm versus the tuning of the exciting light. The vertical bars correspond to the scattering angles detected experimentally. 1—$N = 1.4 \times 10^{16}$ cm^{-3}, $f = 30$ cm; 2—$N = 2.9 \times 10^{15}$ cm^{-3}, $f = 100$ cm.

as the sodium or the extent of focusing of the pump are varied. Focusing the pump light also increases the scattering angles (Fig. 3). Increasing the sodium vapor density weakens the dependence of the scattering angle on the focusing. 4) As the frequency of the exciting light approaches that of the $3S$–$4D$ two-photon resonance, the nature of the conical emission is determined by two processes, which can be distinguished quite well on the spectrogram (Fig. 1c): a radiation of a Čerenkov type, with $\omega_4 < \omega_{3S-3P_{3/2}}$, and a radiation resulting from a four-wave parametric scattering with complete phase matching of the interacting waves, $\omega_{4WM}^{(1)} < \omega_{3S-3P_{3/4}}$ and $\omega_{4WM}^{(2)} > \omega_{3P_{3/2}-4D}$, analogous to that studied in Refs. 5 and 6. (5) Exactly at the $3S$–$4D$ two-photon resonance (Fig. 1d), we observe complete suppression of the Čerenkov radiation. Here the nature of the conical radiation is determined exclusively by the four-wave parametric scattering. As the deviation from the resonant frequency is increased, the light corresponding to the four-wave parametric scattering disappears, and the broad-band Čerenkov radiation reappears (Fig. 1e). We interpret the latter behavior as a strong argument that the observed scattering can be explained by the model of Čerenkov radiation. The disappearance of the Čerenkov scattering at the two-photon resonance is attributed to the elimination of the source of this radiation because of the resonant two-photon absorption of the pump.[10]

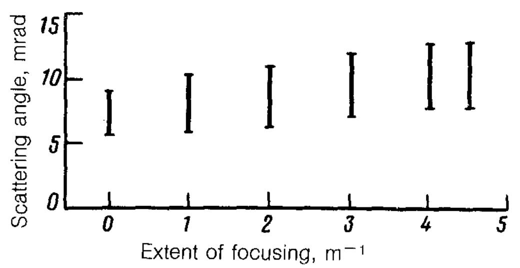

FIG. 3. Scattering angles detected experimentally at the wavelength $\lambda = 600$ nm versus the extent of focusing of the exciting light, with $\lambda_l = 582$ nm at $N = 3.1 \times 10^{15}$ cm^{-3}.

In summary, experimental results obtained in a study of conical scattering in sodium vapor excited by picosecond light pulses make it possible to link this scattering to a Čerenkov radiation which occurs at the surface of self-focusing filaments of the laser pump beam.

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