INTRA-DOPPLER SPECTRAL LINE STRUCTURE

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The noise spectrum of a photodetector irradiated by the superradiance from a gas discharge in Xe^{129} with a wavelength of 3.508 microns is investigated. In a magnetic field, the noise spectrum is found to possess two peaks corresponding to gyromagnetic ratios 0.96 and 1.27 and attributed to the beats of the magnetic component of two hyperfine transitions. Together with a preceding publication by authors[1], the results of the present paper show that the noise spectrum of coherently amplified radiation contains information regarding the structure of the spectral line of separate atoms; this information is usually masked Doppler broadening.

In an earlier article, the authors[1] reported a new method of revealing the spectral structure of radiation, a structure possessed by individual atoms, regardless of how large the Doppler broadening of the line may be. The method is based on an analysis of the low-frequency power spectrum of the radiation. It is easy to verify[1] that the power spectrum of a classical radiation field of an assembly of statistically moving radiators (atoms) in the "low" frequency region is made up of the spectrum of the frequencies of the beads between the radiation fields of different atoms, and the spectrum of the beads of the components of the radiation of the individual atoms. The former (collective) spectrum has a doubled Doppler width (a typical value is 10^9 Hz) and decreases monotonically with increasing frequency. The second (individual) spectrum has as a rule several maxima, this being connected with the simultaneous emission of a complex frequency spectrum by each atom, as a result of the magnetic of hyperfine structure. The widths of these maxima are determined in the absence of a perturbation by the lifetime of the initial state and are therefore always smaller than 10^8 Hz, making it possible to separate the individual spectrum against the background of the collective spectrum.

Allowance for the quantum character of the radiation field leads to the conclusion that the correlations corresponding to the individual spectrum of the atoms disappear from the photocurrent of the receiver. Such correlations, however, can be observed if the investigated radiation is subjected to coherent amplification, since the operation of amplification brings the radiation field of the atoms close to the classical field.

An experimental verification of these considerations was obtained for the 3.508 μ Xe line (transition $5d[7/2]_3 - 6p[5/2]_2$), since a gas discharge in Xe has a large gain at this line. We registered the photocurrent noise-spectrum structure, which depends on the magnetic field and is connected with the interference of the Zeeman components of the spectrum of the individual atoms. However, the results obtained in[1], which on the whole favor the advanced considerations, were not reliably interpreted, owing to the absence of spectroscopic data on the 3.508 μ line. Namely, two close maxima of the noise spectral density were observed, with a distance between them that depended on the magnetic field. The hypothesis was advanced that this is the result of the complicated isotopic and hyperfine structure of the 3.508 μ Xe line. On the basis of the ratio of the Landé factors established in this experiment, and from indirect considerations regarding the relative intensity of the spectral maxima, the larger maximum was ascribed to the even isotope Xe^{32}, and the smaller to the hyperfine level $F = 7/2$ of Xe^{129}. The latter conclusion called for an additional assumption that the hyperfine component of Xe^{129}, $F = 7/2\, 5d[7/2]_3 \rightarrow F' = 5/2\, 6p[5/2]_2$ coincides over the spectrum with the single 3.508 μ line of Xe^{132}.

A check on these conclusions would be highly desirable both from the point of view of confirming the technique of the spectral analysis of light beams, and for the purpose of justifying the drawn spectroscopic conclusions[1)]. In this connection, we undertook experiments similar to those of[1], but with enriched xenon containing 93% of Xe^{129}.

The experimental technique is described in detail in[1]. We used a tube with effective length 4.4 meters, in which a dc discharge was excited in Xe vapor at 77°K. A slowly varying magnetic field, modulated at audio frequency, was applied to part of the tube. The radiation of the tube first passed through a linear analyzer and was then registered by a low-inertia receiver based on InSb. The photoresponse of the receiver was amplified by a resonant amplifier tuned to 22 MHz with a band width 100 kHz. The output signal was detected, amplified at low frequency, and again detected in phase with the modulation of the magnetic field.

Figure 1 shows typical plots of the noise as a function of the magnetic field. Figure 1a is a control plot obtained with a natural mixture of isotopes, duplicating the results of[1]. Two dispersion-type lines are clearly seen. Figure 1b shows the signal obtained with Xe^{129}. We see that one of the lines remained in place, and the other disappeared and was replaced by a new one. As expected, the line that disappeared was the one interpreted in[1] as the magnetic-splitting line of Xe^{132}. The remaining line was the one ascribed to Xe^{129}, $F = 7/2$. The appearing new line corresponds in position, accu-

[1)]We have learned that an attempt was made in [2] to analyze the hyperfine structure of the 3.508μ line of Xe. The conclusions of this analysis greatly contradict the assumptions made in [1] and confirmed in the present paper (see below).

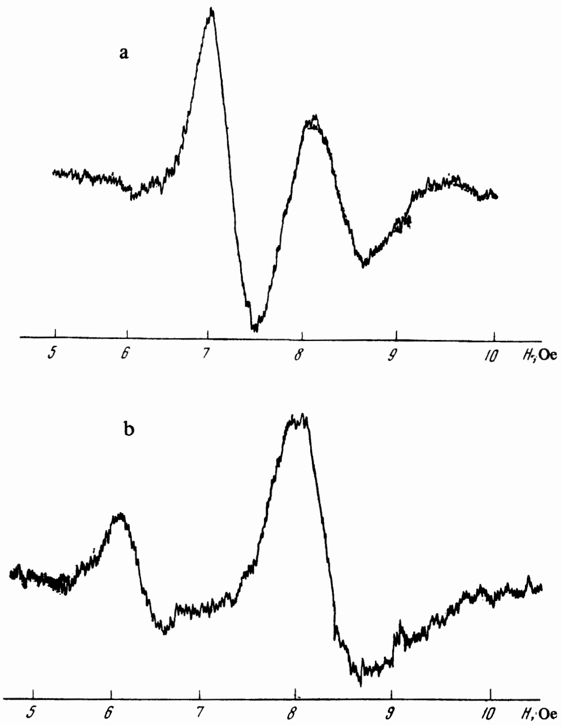

FIG. 1. Comparison of signals of noise beats from a natural mixture of xenon isotopes (a) and from the isotope Xe^{229} (b).

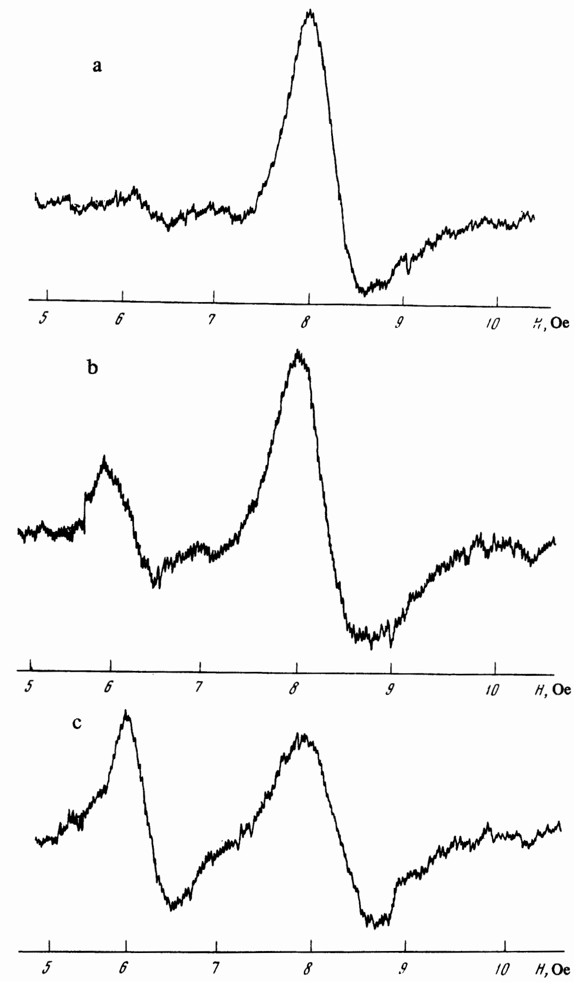

FIG. 2. Example of the dependence of the ratio of the hyperfine components of the signal on the discharge current. a—40 mA, b—50 mA, c—60 mA.

rate to 1%, to the calculated value of the Landé factor for the $F = 5/2$ level of Xe^{129}.

To understand the resultant evolution of the noise spectrum, it must be kept in mind that the position of the noise maximum is determined by the gyromagnetic ratio of the initial state, and the amplitude of the maximum depends on the intensity of the corresponding spectral line. In a natural mixture of isotopes, all the isotope and hyperfine components of the 3.508 μ differ so much from one another in strength, that when the amplifying discharge is sufficiently long the output radiation contains only one spectral component of Xe^{132}, namely $5d[7/2]_3 \to 6p[5/2]_2$. This circumstance, in the presence of two maxima in the noise spectrum (Fig. 1a), forces us to propose that one of the hyperfine components of the 3.508 μ line of Xe^{129} coincides with the single line of Xe^{132} (see[1]). On the other hand, in the case of the discharge in Xe^{129}, the 3.508 μ line has two components with nearly equal strengths, related as 1 : 0.7. These lines start from different hyperfine levels $F = 7/2$ and $F = 5/2$ of the state $5d[7/2]_3$, thus explaining the repeated appearance in the noise spectrum of two maxima corresponding to the Landé factors 1.27 and 0.96. The relative values of these maxima depend strongly on the discharge conditions. Figure 2 shows plots of the signals obtained following a successive increase of the discharge current, which is this region is accompanied by a general increase of the power of the emitted radiation at $\lambda = 3.508\ \mu$. We see that initially there is only the one line $F = 7/2$, and then the line $F = 5/2$ appears, followed by equalization of the intensities of the two lines.

Such a dependence of the signals on the discharge regime can be easily explained as follows: in the case of small discharge currents, the radiation power is relatively small, and consequently the role of the radiative saturation of the transition is also small. Since the total gain reaches nevertheless large values, even a small difference in the line strengths has a great effect: for example, when the gain of the stronger line if of the order of 10^4 [1], the second line has a gain smaller by a factor of 20 and produces no noticeable signal. With increasing discharge current, the intensity of the radiation increases and saturation begins to assume an ever increasing role. The growth of the gain of the stronger line begins to slow down, and the gains of both lines become equalized, leading to the appearance of two signals.

A few words concerning the shapes of the signals. The figure shows that the curves, which should have a dispersion shape, are strongly asymmetrical. This asymmetry is apparently not a fundamental factor, since it depends on the direction of the constant magnetic field: reversal of the field makes the curve almost symmetrical. This is probably connected with the influence of laboratory magnetic fields, which are superimposed on the controlled axial fields.

The results confirmed decisively the validity of the initial assumptions with respect to the possibility of analyzing the spectrum of individual atoms by using the intensity noise. In addition to the spectroscopic data obtained by this method in[1] with respect to the $5d[7/2]_3$ state of Xe, we can now state that the hyperfine component of the $F = 7/2 \rightarrow F' = 5/2$ transition of the Xe^{129} 3.508 μ line coincides within 10 MHz with the single line of Xe^{132}.

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96