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Abstract

Full Text

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On the Broadening of Hydrogen Lines in the Plasma of an Arc and a Shock Tube

(Presented by Academician L. A. Artsimovich, December 15, 1960)

Until recently, the determination of the concentration of charged particles in plasma from hydrogen lines was carried out by comparing the experimental contours of these lines with theoretical ones calculated according to Holtsmark's theory (¹⁻⁴). However, the reliability of the results obtained has always been open to doubt, since Holtsmark's theory takes into account only the statistical action of ions and neglects the effect of impact electron broadening; moreover, the action of ions is taken into account while neglecting the influence of the mutual correlation of the positions of charged particles and the thermal motion of ions.

Grim, Kolb, and Shen (⁵) (G. K. Sh.) calculated the contours of hydrogen lines under the combined broadening action of ions and electrons. They considered the system: a hydrogen atom situated in a static field E , causing Stark splitting of the levels of the hydrogen atom, and an electron moving with velocity v at an impact parameter ρ from the radiating atom. G. K. Sh. solved the time-dependent Schrödinger equation for the time-evolution operator in the impact approximation. This solution made it possible to take into account the transitions between the Stark components of an individual level induced by electron impacts and thereby to determine, after averaging over the flight parameter ρ and the electron velocity v , the contour of the line of a hydrogen atom situated in the static field E and perturbed by passing electrons.

The second part of the problem—the allowance for the broadening action of the microfield of ions—is solved by integration over all values of the field E . As the distribution function $W(E)$, the Ecker function was used, taking into account ionic correlations and the effect of electron screening.

In considering the problem of the joint broadening by ions and electrons, G. K. Sh. introduced a number of approximations: solution of the Schrödinger equation in the quasi-classical approximation (the electron is regarded as a point charge moving along a rectilinear trajectory); truncation of the integrals in averaging over ρ from below at the Weisskopf radius and from above at the Debye radius; use as the distribution function $W(E)$ of the Ecker function, which is insufficiently justified and is hardly valid at high ion densities ($N_i > 10^{17} \text{ cm}^{-3}$, $T = 10\,000^\circ\text{K}$), and so on. G. K. Sh. analyzed all the approximations made and substantiated their admissibility; nevertheless, it is necessary

Figure 1

Figure 1: Figure 1

to compare the theory of G. K. Sh. with experiment, since the adequacy of the theory is of interest both from the standpoint of the physics of the process and from the practical standpoint—plasma diagnostics.

The present communication is devoted to a comparison of the experimental contours of the H_α and H_β lines with theoretical ones calculated according to the theory of G. K. Sh.

Figure 1 shows the experimental contours of the H_α and H_β lines emitted by a carbon direct-current arc burning in an argon atmosphere with an admixture of 5% hydrogen, at a current $i = 200$ A ⁽⁶⁾. The lines were recorded with a DFS-4 spectrograph. The half-width of the instrumental function was 0.3 Å.

Figure 2 shows the contours of the H_α and H_β lines obtained in the gas behind a shock wave ⁽⁷⁾: in Fig. 2a, the contour of the H_α line in krypton with an admixture of $\sim 1\%$ hydrogen behind the passing shock wave; in Fig. 2b, the contour...

line H_β in argon with an admixture of $\sim 2\%$ hydrogen behind the reflected shock wave. The H_β line was recorded with an ISP-51 spectrograph with a medium camera ($f = 270$ mm, half-width of the instrumental function ~ 0.8 Å), and the H_α line with an ISP-51 spectrograph with a long camera ($f = 840$ mm, half-width of the instrumental function ~ 1 Å).

Experimental contours of the H_α and H_β lines were compared with theoretical ones calculated according to the theory of G. K. Sh. From Figs. 1 and 2 it is evident that the experimental contours agree quite satisfactorily with the theoretical ones. It should be noted, however, that such agreement holds only as long as the instrumental function and the Doppler effect can be neglected (the Doppler effect is not taken into account in the theory of G. K. Sh.; the instrumental function is not taken into account in our experimental contours). When the influence of the instrumental function became appreciable in our investigations, the agreement between theory and experiment became worse. The experimental contour of the H_β line agrees well with the theoretical one whose half-width is equal to the experimental half-width.

Fig. 1. Contours of the H_α (a) and H_β (b) lines in the arc. Solid line—experimental contour; points—theoretical contour calculated according to the theory of G. K. Sh. ($a-N = 4 \cdot 10^{16}$ cm⁻³, $b-N = 3.9 \cdot 10^{16}$ cm⁻³)

Satisfactory agreement between theory and experiment in the arc investigation for the H_α line (with the exception of the line center) was observed when the half-width of the theoretical contour was $\sim 20\%$ smaller than the half-width of the experimental one (see Fig. 1a). Agreement of the experimental and theoretical contours of the H_α line with equal half-widths was observed in the

Figure 2

Figure 2: Figure 2

Figure 3

Figure 3: Figure 3

shock-tube investigations, when the half-width of the experimental contour of the H_α line was greater than 8 \AA .

Fig. 2. Contours of the H_α (a) and H_β (b) lines in the gas behind the shock wave. Solid line—experimental contour; points—theoretical contour calculated according to the theory of G. K. Sh. (a — $N = 9.5 \cdot 10^{16} \text{ cm}^{-3}$, b — $N = 1 \cdot 10^{17} \text{ cm}^{-3}$)

From comparison of the experimental and theoretical contours of the H_α and H_β lines, concentrations of charged particles were obtained both in the gas behind the shock wave and in the arc plasma. The concentrations obtained for one regime from the contour of the H_α line and from the half-width of the H_β line agree within the accuracy of the experiment ($\sim 10\%$). Quite satisfactory agreement is also found between the concentrations determined from the contours of the H_α and H_β lines and the concentrations of charged particles calculated from the Saha formula.

The agreement of the theoretical and experimental contours, as well as the agreement between the concentrations determined from the contours of H_α and H_β and calculated from the Saha formula, makes it possible to conclude that the theory of G. K. Sh. as a whole satisfactorily represents the broadening of hydrogen lines in a plasma and can be used to determine the concentrations of charged particles in the plasma. To determine this concentration, it is not necessary each time to study in detail the contour of the H_β line. The good agreement of the experimental and theoretical contours makes it possible to recommend determining the concentration of charged particles from the half-width of the H_β line, using a graph of the theoretical dependence of the half-width on the concentration.

Fig. 3. Graphs of the dependence of the half-width of the H_β line on the concentration of charged particles. 1, 2, and 3—according to the data of G. K. Sh.: 1— $T = 10\,000^\circ\text{K}$; 2— $20\,000^\circ\text{K}$; 3— $40\,000^\circ\text{K}$; 4—according to Holtsmark.

Figure 3 gives graphs of the dependence of $\delta\lambda_{H_\beta}$ on N_i for temperatures $10\,000$, $20\,000$, and $40\,000^\circ\text{K}$, constructed on the basis of the data of G. K. Sh. In the same figure, for comparison, a graph is given of the dependence of $\delta\lambda_{H_\beta}$ on N_i corresponding to Holtsmark's theory. For one and the same half-width of the H_β line, Holtsmark's theory gives larger concentrations than the theory of G. K. Sh. (For $\delta\lambda_{H_\beta} = 40 \text{ \AA}$, N_i according to Holtsmark is $\sim 18\%$ greater than N_i according to G. K. Sh. for $T = 10\,000^\circ\text{K}$.)

Fig. 4. Graph of the dependence of the distance Δ_{H_β} between the violet and red maxima of the H_β line on the half-width of the line $\delta\lambda_{H_\beta}$. Solid line—according to the G.K.Sh. theory; points—experiment

Figure 4: Fig. 4. Graph of the dependence of the distance Δ_{H_β} between the violet and red maxima of the H_β line on the half-width of the line $\delta\lambda_{H_\beta}$. Solid line—according to the G.K.Sh. theory; points—experiment

It is interesting to note that the dependence of N_i on T (for a given value of $\delta\lambda_{H_\beta}$) at $N_i > 10^{15} \text{ cm}^{-3}$ is nonmonotonic: as T increases from 10 000 to 20 000°K, N_i increases; with a further increase in temperature, N_i begins to decrease, passes through the value corresponding to $T = 10\,000^\circ\text{K}$, and at $T = 40\,000^\circ\text{K}$ has a value smaller than at $T = 10\,000^\circ\text{K}$.

Summarizing the results of our studies, it should be recommended that, for determining the concentration of charged particles in the range $N_i = 2 \cdot 10^{15} \div 10^{17}$, the H_β line be used (the concentration can be determined from the half-width of this line), and for $N_i > 3 \cdot 10^{16}$, the H_α line. Extending the range of applicability of the method for determining the concentration of charged particles from hydrogen lines toward lower concentrations is possible through the use, for this purpose, of lines with higher quantum numbers, and also by taking into account the Doppler effect in the theory of G. K. Sh.

A detailed analysis of the results of comparing the experimental and theoretical contours of the H_α and H_β lines shows that the experimental contours are, on the whole, satisfactorily described by the theory of G. K. Sh.; however, according to the theory of G. K. Sh., the H_β contour should be symmetric, whereas the experimental contours of the H_β line are asymmetric ⁽⁷⁾: the violet and red maxima of the H_β line are not symmetric either in position relative to the line center or in intensity. Griem ⁽⁸⁾ explains the asymmetry in the H_β line by the influence of the quadratic Stark effect, which is not taken into account in the theory of G. K. Sh. In addition, the magnitude of the intensity dip at the center of the experimental H_β contour for broad lines ($\delta\lambda_{H_\beta} > 40 \text{ \AA}$) is greater than the theoretical one, while for narrower lines it is smaller than the theoretical one.

The theoretical dependence of the distance Δ_{H_β} between the violet and red maxima of the line on the half-width $\delta\lambda_{H_\beta}$ of the H_β line (see Fig. 4) also differs from the experimental one: for $\delta\lambda_{H_\beta} > 40 \text{ \AA}$ the experimentally measured value Δ_{H_β} increases with increasing $\delta\lambda_{H_\beta}$ faster than the theoretical one. The deepening of the dip at large $\delta\lambda_{H_\beta}$, in comparison with the G.K.Sh. theory, as well as the more rapid increase, than predicted by the theory, of

Fig. 4. Graph of the dependence of the distance Δ_{H_β} between the violet and red maxima of the H_β line on the half-width of the line $\delta\lambda_{H_\beta}$. Solid line—according

to the G.K.Sh. theory; points—experiment

$\Delta_{H\beta}$ with $\delta\lambda_{H\beta}$ may apparently indicate the necessity of taking into account in the theory the role of distant electrons, i.e., that the truncation of the integrals should be carried out at a radius larger than the Debye radius.

The smoothing of the depth of the dip for small $\delta\lambda_{H\beta}$ can be understood if one takes into account the Doppler effect and the insufficient resolving power of the apparatus.

Thus, the experiment indicates that the G.K.Sh. theory of the broadening of hydrogen lines must be refined for the center of the line. In this refinement it is necessary once again to analyze the admissibility of truncating the integrals at the Debye radius, and also to take into account the role of the Doppler effect.

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