PHYSICAL REVIEW E **69**, 028402 (2004)

Reply to "Comment on 'Highly nonlinear, sign-varying shift of hydrogen spectral lines in dense plasmas'"

Eugene Oks
Physics Department, 206 Allison Laboratory, Auburn University, Auburn, Alabama 36849, USA

(Received 11 April 2003; revised manuscript received 3 September 2003; published 27 February 2004)

We show that the difference between Halenka's model simulations and our analytical results is most probably due to some assumptions and inherent restrictions of his model.

DOI: 10.1103/PhysRevE.69.028402 PACS number(s): 52.70.Kz, 32.70.Jz, 52.25.Os

Halenka compares his *model simulations* with our *analytical* results. His model assumptions are listed, e.g., on p. 19 of the paper by Halenka and Olchawa [1] (his Ref. 7). Below we will show that the difference between his and our results is most probably due to some of assumptions and inherent restrictions of his model.

It is well known that statistical fluctuations of the simulated distribution should very strongly affect numerical calculations of the Stark shift, which is a much more subtle effect than the Stark width and might actually prevent a "catching" of the Stark shift. This fact has been explicitly confirmed in the recent paper by Wujec *et al.* [2], where in Sec. II A they wrote, "Unfortunately, even after averaging of 10,000 initial perturber configurations, the resulting statistical noise of the imaginary part of the autocorrelation function, Im $C(t)$, did not allow to determine reliable asymmetries and shifts of the profile." No wonder that by averaging over only 3000 initial perturber configurations, Halenka was much further away from obtaining a reliable shift than in the work [2].

We note that a uniform shift of the entire profile, used by Halenka as a "test," is not adequate to the real situation. Indeed, in reality, different parts of the profile are shifted differently—in magnitude and, sometimes, even in sign. The resulting *shift of the center of gravity* is much harder to catch in simulations (burdened by the high statistical noise) than the uniform shift of the entire profile. However, it is precisely the *shift of the center of gravity* that is identified by us analytically as the dipole ionic-electronic shift (DIES).

Halenka's simulations seem to be ill suited when a plasma approaches nonideality, thus putting a physical restriction on the effective number of perturbers. But this is precisely the range of plasma parameters where the DIES becomes significant. For plasmas far from being nonideal, where his simulation technique should work well, our analytical results show that the DIES becomes "nearly zero" or, physically speaking, insignificant compared to other sources of the shift—in agreement with the outcome of Halenka's simulations (the DIES dramatically decreases with increasing T and/or decreasing N_e).

In addition, Halenka's simulation technique (first presented in the paper by Halenka and Olchawa [1]) requires the introduction of some *arbitrary* minimal cutoff parameter $R_{\min}$ (minimal impact parameter), as was emphasized especially clear (several times) in recent papers by Olchawa [3] and by Wujec *et al.* [2]. The cutoff chosen by Halenka coincides by an order of magnitude with the electron Weisskopf radius R_W.

In distinction, our analytical theory does not require a cutoff at impact parameters comparable to R_W. Moreover, it is important to realize that the DIES accrues a significant part of its value at impact parameters within R_W. Therefore, the truncation of the simulation volume by an inner sphere of the radius $R_{\min}$ might be another probable reason that prevented Halenka from "catching" the DIES.

Figure 2 from Halenka's Comment actually illustrates this point. From his Fig. 2 it is seen that his Im $C(t)$, simulated with $R_{\min}=5a_0$ (a_0 is the Bohr radius), differs from zero much more significantly than his Im $C(t)$, simulated with $R_{\min}=13.5a_0$.

In the latest paper on this simulation technique [3] Olchawa, while emphasizing that the line shift in this model *strongly depends* on the choice of $R_{\min}$, wrote that achieving a good fit of calculated H_α shifts to the experimental ones requires even a higher value of $R_{\min}$: namely, $R_{\min}=22a_0$. This means that already at $R_{\min}=13.5a_0$ and even more so at $R_{\min}=5a_0$ Halenka would be at odds with experiments and this discrepancy would increase if he would try to diminish $R_{\min}$.

Halenka wrote that as the electron density grows and causes the increase of the linewidth, it becomes more favorable for his simulations that work better at short times while computing $C(t)$. However, while this might be sufficient for determining the width, we note that $C(t)$ calculated accurately only at short times would not be able to adequately describe the central part of the profile and would result in a significant loss of accuracy in determining the shift.

Halenka wrote that the leading point of the DIES was the dipole electron shift d_n originally introduced by Sholin, Demura, and Lisitsa [4]. However, within the framework of [4], for each and every pair of Stark components having the same absolute value of $n(n_1-n_2)-n'(n'_1-n'_2)$, the center of gravity shift is zero (here n_1 and n_2 are parabolic quantum numbers of the upper Stark state; those with the prime refer to the lower Stark state). Therefore, within the framework of [4], the center of gravity shift of the entire line is zero. In reality, the leading point of the DIES was the allowance for the *indirect coupling* between the electron and ion microfields, carried out via the radiator as the intermediary. It is the allowance for this indirect coupling, made within the framework of the generalized theory (GT) [5–7], that resulted in the nonzero shift of the center of gravity of the line, which we called the DIES [8].

Further, Halenka reiterated Griem's comment [9] that presumably allowance for the Debye shielding would radically diminish d_n and the DIES. We had already rebutted Griem's comment and refer readers to our rebuttal [10].

Halenka also brought up a hypothesis that the discrepancy between his model simulations and our analytical results might be due to approximations we made. The approximations we made for electrons were based on the fact that for the conditions of the experiment [8] the number of electrons $\nu = 4\pi N_e R_W^3/3$ in the sphere of the electron Weisskopf radius is much smaller than unity. For example, for the most intense lateral components of the H_α line we find $\nu \cong 0.01 \ll 1$ for the conditions of the experiment [8]. It is commonly accepted that for $\nu \ll 1$, the binary and impact approximations (as well as the perturbation theory used for the minor part of the microfield) should be adequate. As for the quasistatic approximation for ions, it was eliminated by us in Ref. [11] (Halenka's Ref. [16]) without a significant effect on the results.

Halenka mentioned that an additional source of the shift arises when the inhomogeneity of the electric microfield is taken into account. He referred this discovery to the paper by his collaborator Olchawa [3] published in 2002 (Halenka's Ref. 13). However, in reality this was discovered by us as early as 1997 and published in Ref. [12] (Halenka's Ref. 14). We called this source of shift the quadrupole ionic-electronic shift (QIES)—to acknowledge the role of the inhomogeneity of the electric microfield represented by the quadrupole interaction with the radiator.

Below Halenka's Eq. (1), he wrote that in his simulations ‘‘the electron-ion coupling was taken into account in a natural way.’’ However, from his Eq. (1) it is clear that in reality he did not take into account the direct interaction of the electrons and ions, represented by the acceleration of electrons by the ion field (AEIF) [13,10].

Halenka's model calculations of the plasma state and his ‘‘second guessing’’ of the diagnostics in the experiment [8] are based on questionable assumptions. By now, the experimental results from [8] have been independently confirmed in other experiments at the same range of plasma parameters as in [8], but performed at a different plasma source by Flih *et al.* and published recently in Ref. [11]. The plasma source is a flash tube: it produces a plasma of $N_e \sim 10^{18}$ cm^{-3} and higher in the range of the temperature $T \approx (1-2)$ eV, N_e and T being measured independent of the H_α line shape, width, and shift [11]. These are practically the same ranges of N_e and of T as in the laser-induced underwater plasma [8]. Flih *et al.* [11] found that their experimental results are consistent with the H_α widths and shifts measured in the laser-induced underwater discharge [8,14]. Flih *et al.* [11] also found that their experimental widths and shifts of the H_α line were in good agreement with Oks's theory of Stark widths and shifts [5–7,10–13,15], while comparison with the corresponding Griem's theory [16–18] yielded significant discrepancies: up to a factor of 2 for the shifts—just as in the experiment [8].

---

[1] J. Halenka and W. Olchawa, J. Quant. Spectrosc. Radiat. Transf. **56**, 17 (1996).

[2] T. Wujec, W. Olchawa, J. Halenka, and J. Musielok, Phys. Rev. E **66**, 066403 (2002).

[3] W. Olchawa, J. Quant. Spectrosc. Radiat. Transf. **74**, 417 (2002).

[4] G. V. Sholin, A. V. Demura, and V. S. Lisitsa, Sov. Phys. JETP **37**, 1057 (1973).

[5] Ya. Ispolatov and E. Oks, J. Quant. Spectrosc. Radiat. Transf. **51**, 129 (1994).

[6] E. Oks, E. A. Derevianko, and Ya. Ispolatov, J. Quant. Spectrosc. Radiat. Transf. **54**, 307 (1995).

[7] J. E. Touma, E. Oks, S. Alexiou, and A. Derevianko, J. Quant. Spectrosc. Radiat. Transf. **65**, 543 (2000).

[8] A. Escarguel, E. Oks, J. Richou, and D. Volodko, Phys. Rev. E **62**, 2667 (2000).

[9] H. R. Griem, Phys. Rev. E **64**, 058401 (2001).

[10] E. Oks, J. Phys. B **35**, 2251 (2002).

[11] S. A. Flih, E. Oks, and Y. Vitel, J. Phys. B **36**, 283 (2003).

[12] E. Oks, J. Quant. Spectrosc. Radiat. Transf. **58**, 821 (1997).

[13] E. Oks, J. Quant. Spectrosc. Radiat. Transf. **65**, 405 (2000).

[14] A. Escarguel, B. Ferhat, A. Lesage, and J. Richou, J. Quant. Spectrosc. Radiat. Transf. **64**, 353 (2000).

[15] E. Oks, in *Spectral Line Shapes*, edited by J. Seidel, AIP Conf. Proc. No. 559 (AIP, Melville NY, 2001), Vol. 11, p. 54.

[16] H.R. Griem, *Principles of Plasma Spectroscopy* (Cambridge University Press, Cambridge, England, 1997); *Spectral Line Broadening by Plasmas* (Academic, New York, 1974).

[17] H. R. Griem, Phys. Rev. A **28**, 1596 (1983).

[18] H. R. Griem, Phys. Rev. A **38**, 2943 (1988).