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Reply to "Comment on 'Saddle-point shifts in ionizing collisions' "

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It is argued that the electron plate-impact contamination reported in the preceding Comment [G. Bernardi and W. Meckbach, Phys. Rev. A **51**, 1709 (1995)] cannot be considered as insignificant.

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In a recent paper [1], we presented experimental evidence that strongly supported the hypothesis of the existence of saddle-point electrons [2,3]. The experimental observations, involving C^+, C^{2+}, and C^{3+} ions incident on He and Ne, not only exhibited maxima in the 10° ejected-electron energy spectra ($d^2\sigma/d\Omega dE$), but also revealed projectile charge-dependent shifts of these maxima in *all* $d^2\sigma/d\Omega dE$, $d^2\sigma/d\Omega dv$, and $d\sigma/d\mathbf{v}$ spaces. We had also mentioned a possible experimental problem that could give an explanation for some of the discrepancies that exist between the experimental work reported in the literature. This experimental problem involves low-energy electron signal contamination due to high-energy electrons impacting the back plate of an analyzer. In typical analyzer measurements, one obtains data by sweeping the voltage across the analyzer plates, thus changing the analyzer pass energy. However, at low analyzer plate voltages, electrons in the high-energy portion of the spectrum can impact the back plate of the analyzer resulting in spurious signal due to electron reflection and secondary electron emission. This spurious signal may give rise to an artificial enhancement in the low-energy portion of the electron energy spectrum. If a maximum did exist in the initial spectrum of interest, the artificial enhancement at low energies could effectively "wash out" this maximum. One may then erroneously conclude that a maximum does not exist in the actual ejected-electron energy spectrum, and subsequently, that saddle-point electrons do not exist.

This electron "plate-impact" problem has been studied previously [4,5]. Earlier measurements, carried out in 1960 by Marmet and Kerwin [4], have shown that, for low-energy electrons, reflection coefficients of most metals are rather high (> 50%). Although sooted metals (deposited from a flame) work relatively well, reflection coefficients are still on the order of 20% [4]. Thus, one *must* take additional steps to alleviate plate-impact contamination, such as replacing deflection plates with transparent grids, or milling a "sawtooth" profile in the outer deflection plate [5]. It is important to point out that the experimental data, reported in Ref. [1], involved a new experimental method in which high-energy electrons were prevented *altogether* from striking the analyzer back plate. (See Ref. [1].)

In regard to this plate-impact problem, the authors of the preceding commentary [6] presented in their Fig. 1, experimental measurements (raw data) of the contamination induced by 300-eV electrons impacting the back plate of their analyzer. This measured contamination, which is on the order of 0.02%, appears, at first glance, to be quite insignificant; and thus, the authors state that high-energy electron plate-impact contamination is not a significant problem in their experimental measurements. In Fig. 2, they present a spectrum (corrected for this plate-impact contamination) of measurements of ejected electrons in collisions of 100-keV H^+ ions incident on He.

Because the authors in Ref. [6] and I disagree on the significance of plate-impact contamination, and on the experimental analysis of this problem, I would like to present what I feel is the correct analysis of contamination due to high-energy electron plate impact. Let us assume that the function $C(E)$ represents an arbitrary incident electron energy distribution that we wish to measure using a typical electrostatic energy analyzer. Because the analyzer has a finite energy acceptance range, ΔE, the measured count rate versus electron energy, $I(E)$, or "raw" data, is given by

$$I(E)=\varepsilon\int_{\Delta E}C(E')dE' , \tag{1}$$

where ε is the analyzer detection efficiency, which we will assume is on the order of unity. In this case, $I(E)$ represents the actual signal one would obtain if plate-impact contaminations were *not* present. The energy acceptance range ΔE depends upon the electron energy E and is given by

$$\Delta E=EA_0 , \tag{2}$$

where A_0 is a constant of the apparatus. The measured uncontaminated signal can be rewritten

$$I(E)=\int_{E-\Delta E/2}^{E+\Delta E/2}C(E')dE' . \tag{3}$$

Using Eq. (2) in Eq. (3) results in

$$I(E)=\int_{E(1-A_0/2)}^{E(1+A_0/2)}C(E')dE' . \tag{4}$$

If we assume that the spectrometer constant $A_0 \ll 1$ (which is the case in most analyzers) and that the incident electron energy distribution $C(E)$ varies slowly over the integration interval, Eq. (4) reduces to

$$I(E)=A_0C(E)E . \tag{5}$$

This explains why one must "correct" the raw data, by dividing by the energy of the electron E to reproduce the actual incident electron energy distribution $C(E)$.

Electrons entering the analyzer with energies E greater than

$$E > eV_p/\sin^2\theta \ , \tag{6}$$

where e is the charge of an electron, V_p is the analyzer plate voltage, and θ is the analyzer entrance angle, will strike the back plate of the analyzer and may result in a spurious signal. Using the characteristics of the Bernardi *et al.* analyzer [7], the minimum energy $E_{\min}$ required to strike the back plate is

$$E_{\min} = 1.44 E_p \ , \tag{7}$$

where E_p is the analyzer pass energy.

Let us define the plate-impact contamination signal $I_c(E_p,E)$ measured at an analyzer pass energy E_p, as

$$I_c(E_p,E) = g(E_p,E) I(E) \ , \tag{8}$$

where $g(E_p,E)$ is the fractional "contamination" factor and is assumed to be much less than one. This contamination is caused by electrons of energy E impacting the analyzer back plate, with the requirement that $E > E_{\min} = 1.44E_p$. The contamination factor $g(E_p,E)$ corresponds, roughly, to the actual measurements obtained by the above authors [6], utilizing an electron gun, and is shown in their Fig. 1 for $E = 300$ eV. To obtain the "total" plate-impact contamination at E_p for a *broad* electron energy spectrum, one must integrate $I_c(E_p,E)$ over all electron energies E. (This is because all electrons with $E > E_{\min}$ contribute to the total contamination of the signal at E_p.) The total contamination signal I_T, at E_p, is then obtained by using $I(E)$ as defined in Eq. (5),

$$I_T(E_p) = A_0 \int_{E_{\min}=1.44E_p}^{E_{\max}} g(E_p,E') C(E') E' dE' \ , \tag{9}$$

where $E_{\max}$ is the maximum energy of the electrons under study. Since the uncontaminated signal at E_p can be obtained from Eq. (5), the ratio $R_c(E_p)$ of the contamination to the uncontaminated signal is therefore given by

$$\begin{aligned} R_c(E_p) &= I_T(E_p)/I(E_p) \\ &= [C(E_p)E_p]^{-1} \int_{1.44E_p}^{E_{\max}} g(E_p,E') C(E') E' dE' \ . \end{aligned} \tag{10}$$

In order to understand how small amounts of electron plate-impact contamination can significantly effect measurements of electron energy spectra, let us examine the case when the incident electron energy distribution $C(E)$ is constant for energies ranging from 0 to 100 eV. If we make the additional approximation that $g(E_p,E)$ is essentially constant, that is $g(E_p,E) \approx g_0$, then Eq. (10) results in

$$R_c(E_p) = (g_0/2E_p)[E_{\max}^2 - (1.44E_p)^2] \ . \tag{11}$$

Using Eq. (11), one can then estimate the required value of g_0 for 50% plate-impact contamination at an electron energy $E_p = 1$ eV, for $E_{\max} = 100$ eV. This results in $g_0 = 0.0001$, or 0.01%. If we examine the case in which $C(E)$ is constant out to 300 eV, (or in other words $E_{\max} = 300$ eV), a value of $g_0 = 0.00001$ will result in 45% contamination at 1 eV. Thus, what at first glance may appear to be an "insignificant" contamination at E_p, due to plate impact of electrons at a particular energy E, yields "significant" contamination when the proper integration over electron energy is performed.

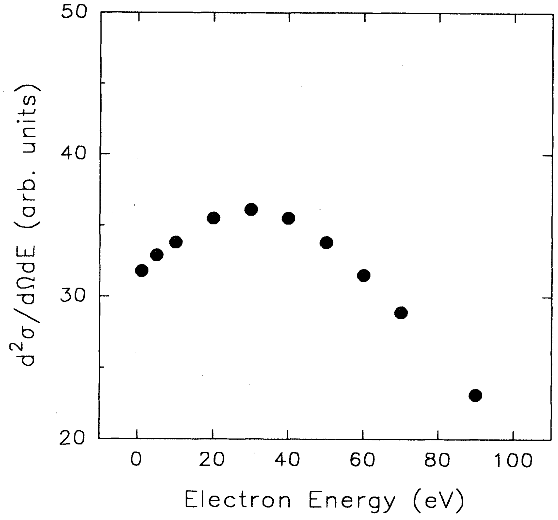

FIG. 1. Initial electron energy distribution $C(E)$. (See text.)

Equation (10) can also be applied to the experimental data presented by Bernardi and Meckbach [6] in their Fig. 2. In this case, one may replace $C(E)$ with $d^2\sigma/d\Omega dE$. The contamination function $g(E_p,E')$ is taken, in a similar manner as the above authors, as the shape of the hump presented in their Fig. 1. More specifically, $g(E_p,E')$ is taken as a Lorentzian distribution function with a maximum value of 2×10^{-4} centered at $0.62E$. Integrating over the data in their Fig. 2, from 1.6 to 100 eV, results in 11.5% contamination at an electron energy of 1 eV. Although there does exist disagreement on how to properly weigh the contamination function $g(E_p,E')$, [see Eq. (9) above and Eq. (2) of Ref. [6]] this is in agreement with Bernardi and Meckbach's value of 10% as illustrated in their Fig. 2.

However, I would like to point out that in order to obtain the "actual" contamination induced by electron plate impact, one must have prior knowledge of the actual incident electron energy distribution, $C(E) = d^2\sigma/d\Omega dE$, which confounds the situation because $C(E)$ is *precisely* what we are trying to measure. Because the actual contamination depends not only on $g(E_p,E')$, but $C(E)$ as well, the above analysis is not adequate enough to determine the actual extent of plate-impact contamination. To illustrate this point, let us assume that a maximum *does* exist in the initial electron energy distribution. We then wish to determine if the contamination function $g(E_p,E')$, as measured by the above authors, is sufficient enough to "wash out" or obscure this maximum. Figure 1 illustrates an initial spectrum $C(E)$, which exhibits a broad maximum near 30 eV. This spec-

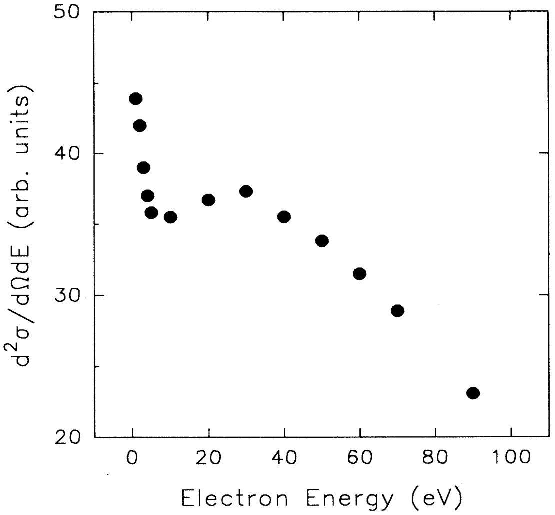

FIG. 2. Final electron energy distribution obtained by integrating $g(E_p,E)$ over the initial energy distribution in Fig. 1. (See text.)

trum was generated using a Gaussian distribution function and is based on the experimental data reported in Figs. 5 and 7 of Ref. [1], which exhibit maxima at electron energies between 30 and 40 eV. Integrating over $C(E)$ in Fig. 1, with $g(E_p,E')$ defined as before, results in the final "contaminated" spectrum, as would be measured with the Bernardi *et al.* analyzer [7] used in Ref. [6], in Fig. 2. For comparison, the experimental data presented in Fig. 2 of Ref. [6], is plotted on a *linear* scale in Fig. 3. One can readily see the similarities between Figs. 2 and 3.

Although this analysis is by no means conclusive, it does indicate that a maximum could possibly exist in the 10° ejected-electron energy spectrum for 100-keV H^+ ions incident on He, and that this maximum is being obscured due to electron plate-impact contamination. I would like to emphasize again that such maxima were observed in the experimental data reported in Ref. [1], and that these data were taken in such a way that electrons were prevented altogether from striking the analyzer back plate.

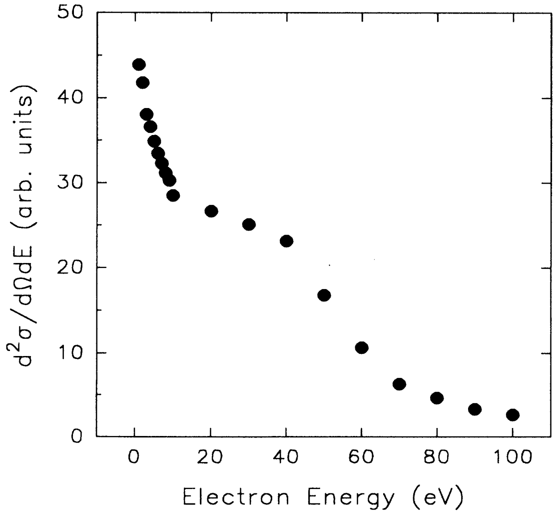

FIG. 3. Experimental data, presented in Fig. 2 of Ref. [6], is plotted on a linear scale.

There still remains the question of the origin of the peaks observed in Ref. [1]. Bernardi and Meckbach have suggested that Irby *et al.* [1] "observed a remnant of convoy-cusp electrons, which subsists at an emission angle of 10°". Obviously, the only way to resolve this issue is by further *careful* experimental measurements of the projectile-charge dependence of ejected electrons taken at an emission angle of 0°. Unfortunately, design characteristics of the spectrometer used in Ref. [1] prohibit measurements at angles below 10°. However, earlier experimental work of Gibson and Reid [8] suggest that these maxima are *not* remnants of convoy-cusp electrons. Their experimental data, obtained from 50-keV H^+ ions incident on He, cover electron ejection angles from 0°–100°. At 0° emission angle, their data exhibits a broad maximum, centered at 15 eV, with 27-eV convoy-cusp electrons superimposed on top of this broad maximum. As the emission angle is increased, the cusp electrons rapidly fall off while the broad maximum (still centered at 15 eV) remains. (See Ref. [8] and Fig. 4 in Ref. [9].) It is important to emphasize that the electron spectrometer used in the work of Gibson and Reid utilized a "wire-mesh" screen for the analyzer back plate [10]. (See also Fig. 16 [11].)

Lastly, Bernardi and Mechbach have pointed out that the peaks observed in Figs. 8–10 of Ref. [1] occur at electron energies that are higher than the emission energies predicted by the saddle-point mechanism for equal target and projectile charges ($Q_t = Q_p = 1$). However, it was stated in Ref. [1] that "This discrepancy may be attributed to the effective charge on the He target as seen by the electron. Initially, the electron sees an effective charge of 1.7. Thus, the initial saddle-point and electron velocity is $0.566v_p$. As the electron travels away from the target atom, the charge seen on the target by the electron rapidly decreases to $Q_t = 1$. The decrease in target charge subsequently causes the velocity and position of the saddle point to decrease. Since the electron no longer finds itself traveling on the saddle point, it experiences an acceleration toward the projectile and eventually emerges with a higher velocity than the saddle point. In order to account for this effect, one must have detailed knowledge of the time dependence of the effective charge on the target as seen by the electron."

In conclusion, the analysis presented here indicates that high-energy electron plate impact *can* produce significant low-energy spectral distortions in experimental measurements involving ejected electrons in ion-atom collisions. In contrast to the opinion of Bernardi and Meckbach, the experimental data presented in Fig. 1 of Ref. [6], indicate, in my opinion, that plate-impact contamination *cannot* be considered as insignificant.

I want to make it clear that it is not my wish to "single out" the experimental measurements of Bernardi and Meckbach in regard to this electron plate-impact problem. I feel that this experimental problem has unknowingly occurred in other research reported in the literature including earlier work in which I was involved [12]. Nonetheless, it is imperative that subsequent research involving low-energy ejected electrons in ion-atom collisions properly addresses this problem. Until further experimental investigations are carried out, with proper care taken to minimize or eliminate electron plate-impact distortions, the validity of the saddle-point ionization hypothesis will remain an open question.

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