Reply to "Comment on 'Photodetachment in a strong laser field: An experimental test of Keldysh-like theories' "

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(Received 4 April 2008; published 11 June 2008)

The Comment by Reiss [preceding Comment, H. R. Reiss, Phys. Rev. A **77**, 067401 (2008)] is negated. His analysis [H. R. Reiss, Phys. Rev. A **76**, 033404 (2007)] of our experimental data on strong-field photodetachment in a circularly polarized laser field [B. Bergues *et al.*, Phys. Rev. Lett. **95**, 263002 (2005)] is contested.

DOI: 10.1103/PhysRevA.77.067402 PACS number(s): 32.80.Gc

In his Comment [1] on our recent work [2], Reiss rejects our conclusion that the length-gauge version of the strong-field approximation (SFA) should be used in the description of electron detachment in a strong laser field. Despite the fact that he is commenting upon Ref. [2], neither a discussion nor an objection concerning the analysis of experimental data presented therein are provided by Reiss. This analysis, however, led us to our conclusion. Instead, Reiss refers to two other experiments, trying to give "counterexamples" in order to refute our results in Ref. [2]. In one example he refers to our experiment on photodetachment of F^- in a circularly polarized laser field [3]. Following his discussion of this experiment in Ref. [4], Reiss claims that the maximum of the measured photoelectron spectrum should lie at the kinetic energy that equals the ponderomotive energy at the peak intensity in the laser focus. Based on this consideration, Reiss concludes that the length-gauge SFA fails to reproduce the experimental data. In the second example he refers to an experiment on photoionization of He [5] and to the analysis of this experiment in the velocity-gauge SFA [6]. Reiss' objection is that photoelectron spectra of He are well described by his velocity-gauge SFA. Both Reiss' points are addressed in the present reply.

First it should be noted that the exact solution of the problem of strong-field ionization is gauge invariant, as it has been confirmed many times in numerical solutions of the time-dependent Schrödinger equation. However, if an approximation is made, predictions are not necessarily gauge invariant. The SFA, where the interaction of the ejected electron with the core is neglected and the final electron state is approximated by a Volkov state, represents such a case. The main discrepancy between SFA predictions in the velocity and the length gauge consists in their different (ℓ,m) dependency of the detachment rate and arises for initial states with $\ell \neq 0$ [2,7]. Here (ℓ,m) denote the angular momentum quantum numbers of the initial state. For electron detachment from an initial *s* state, in contrast, the two SFA approaches give similar results. Due to the inevitable experimental uncertainty in the determination of the focal intensity distribution, it is rather difficult to test experimentally which SFA theory gives the correct result in the latter case. Ionization from the ground state of the He atom represents such an example. Indeed, with the code that we used in simulations of the F^- spectrum [3], we obtained in the length gauge the same good agreement with experimental results by Mohideen *et al.* [5] as reported for the velocity gauge in [6]. This answers the second objection made by Reiss: The good agreement of the velocity-gauge SFA with the experiment [5] does not invalidate the length-gauge SFA.

In order to decide experimentally which SFA approach gives the correct result, electron detachment from initial states with $\ell \neq 0$ need to be considered. Therefore, in Refs. [2,3] we focused on electron detachment from an initial *p* state, where the discrepancy between predictions in the two gauges is essential. For electron detachment in a linearly polarized laser field, which was the subject of our work [2], the positions of maxima in photoelectron spectrum predicted in one gauge correspond to positions of minima predicted in the other gauge. The direct comparison of our measurements with predictions by the velocity-gauge SFA [8] and the length-gauge SFA [9] clearly reveals that only the length-gauge SFA correctly reproduces the experimental data. The result of this comparison is, however, disregarded by Reiss in his Comment.

We turn now to the first "counterexample" given by Reiss. His argumentation presented in Ref. [4] is valid for electron detachment at a fixed laser intensity. However, taking the spatiotemporal distribution of the laser intensity into account represents a crucial part of any comparison between experiment and theory [2,3]. The number of atoms exposed to a given intensity I is defined by the laser focus geometry and can be described by a function $N(I)$. Assuming a Gaussian shape of the spatiotemporal intensity distribution and disregarding the saturation effect, an analytical expression for $N(I)$ is [10]

$$N(I) = \frac{C}{I}\left(\ln\frac{I_0}{I}\right)^{1/2}, \quad 0 < I < I_0, \tag{1}$$

where I_0 denotes the peak intensity of the laser pulse and C is a coefficient that depends on the focus parameters and the target density. The total yield N of photoelectrons produced in a laser pulse is described by the integral

$$N = \int_0^{I_0} N(I)w(I)dI, \tag{2}$$

where $w(I)$ is the photodetachment rate predicted by theory and $w(I)N(I)dI$ represents the number of electrons emitted at

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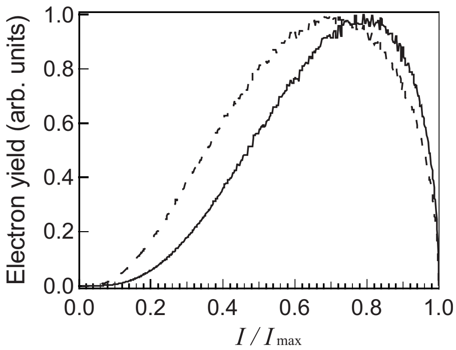

FIG. 1. The intensity distribution of the photoelectron yield calculated in the velocity gauge (solid curve) and in the length gauge (dashed curve) for the experimental parameters of Ref. [3]. The intensity scale is normalized to the measured peak intensity $I_{max} = 2.6\times 10^{13}$ W/cm^2.

intensities in the interval $[I, I+dI]$. Consequently, the measured spectrum of photoelectrons is defined not by the peak intensity, but rather by the dominant intensity I_{eff} that corresponds to the position of the maximum of the product $w(I)N(I)$. The relative contribution of photodetachment at the peak intensity is, in fact, zero because $N(I_0)$ is zero according to Eq. (1).

For the sake of illustration, we plot in Fig. 1 the intensity distribution of the photoelectron yield, $w(I)N(I)$, calculated in velocity and length gauge for the experimental parameters of Ref. [3], that is for photodetachment of F^- in a circularly polarized field of 1500 nm wavelength and 2.6×10^{13} W/cm^2 peak intensity. In these calculations the rate $w(I)$ is evaluated with the use of Eq. (32) of Ref. [8] and Eq. (5) of Ref. [11], respectively. One can see that in both cases the dominant intensity is substantially lower than the peak intensity. Thus, the maximum position of the experimental electron distribution cannot be used as a "direct" measure of the peak intensity. Hence, the Reiss statement in Ref. [4], "There are two independent experimental measurements of the peak intensity: one direct and the other through a measurement of the momentum distribution of the photodetached electron" is incorrect.

Figure 1 demonstrates that the measured peak intensity should be corrected to a higher value, if the maximum of the experimental electron distribution is to match the value of the ponderomotive energy at the dominant intensity. This was properly done in Ref. [3]. The agreement between experiment and the length-gauge SFA theory was found to be perfect. We emphasize here again that the measured intensity value has a statistical error bar of 15% and, in addition to that, it has an uncertainty due to systematic errors. As it is discussed in Ref. [3], a small pointing instability of the laser beam can result in the underestimation of the peak intensity by 45%. These uncertainties are much smaller than in other experiments [5], where Reiss had to correct the measured intensity values by a factor of 1.9 for linear polarization and by a factor of 4.7 for circular polarization [6], in order to fit his velocity-gauge SFA predictions to the experimental data.

Summarizing, there are no "counterexamples" showing the failure of the length-gauge SFA in the description of strong-field electron detachment. In contrast, the velocity-gauge SFA is shown to be unsuccessful in the description of electron detachment from initial p states. This holds for both circular [3] and especially for linear [2] polarization. Therefore, we maintain our statement, based on experimental facts, that the length gauge should be used in the frame of the SFA.

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