Photo ionization of an atom passed through a diffraction grating

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Abstract

We consider photo ionization of an atom which, due to passing through a diffraction grating, is prepared in a multi-site state possessing a periodic space structure with alternating maxima and minima. It has been found that this process qualitatively differs from photo ionization of a ‘normal’ atom. In particular, the spectra of emitted electrons and recoil ions in this process display clear one- and two-particle interference effects. Moreover, there are also striking differences between the momentum distributions of these particles, which no longer mirror each other. The origin of all these features is discussed in detail. It is also shown that the information about the diffraction grating, which is encoded in the multi-site state of the atom, can be fully decoded by exploring the spectra of recoil ions whereas the photo-electron spectra contain this information only partially.

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I. INTRODUCTION

Photo ionization of atomic systems belongs to the most ‘popular’ processes studied by atomic physics. Since the discovery of the photoelectric effect numerous studies on photo ionization of atoms, ions and molecules have not only greatly improved our knowledge of their structure but also substantially contributed to the understanding of the basic laws of quantum physics. Modern experiments on photo ionization of atoms and simple molecules performed using COLTRIMS techniques \textsuperscript{[1]} can provide a complete information on the momenta of all reaction fragments.

Break-up of a hydrogen-like atomic system due to absorption of a photon is the most basic (and simple) photo ionization process. It has been scrutinized in numerous studies and its quantum dynamics has been understood in very great detail.

The process of photo ionization of molecules is more complex and its description and understanding are substantially more complicated. The basic prototype of this process is represented by photo break-up of a system, which consists of a single electron and two nuclei (e.g., H\textsubscript{2}\textsuperscript{+}) forming a bound state due to the interactions between them. One of interesting effects, which can arise in photo ionization of such a system, is interference (observed e.g. in the electron emission pattern).

The origin of this interference can be qualitatively understood by regarding the state of the electron in the molecule, where it simultaneously orbits around two nuclei, as a superposition of two atomic-like electron states centered on the nuclei. Within such a simple picture the electron, by absorbing a photon, is launched simultaneously from the two sites of the molecule. As a result, two undistinguishable reaction pathways arise that leads to interference.

In an atom, where an electron orbits around only one nucleus, multi-site electron states, similar to those in a molecule, of course cannot exist. Therefore, in photo ionization of an atom there are no interference effects, which would be caused by a multi-site structure of the electron state. Indeed, when the wave function of a free atom is represented (as usual) by

\begin{equation}
\Psi(R, r, t) \sim e^{i(P \cdot R - E_0 t)} \times \varphi(r) \exp(-i\epsilon t),
\end{equation}

where the plane-wave refers to the center-of-mass motion of the atom and the rest describes the internal atomic degrees of freedom, such interference effects are naturally absent.

However, even a single atom can be prepared in a state possessing a multi-site structure. This can be done, for instance, by letting an atom to pass through a multi-slit screen (a diffraction grating) as illustrated in Fig.\textsuperscript{[1]}

After the passage, the atomic wave function acquires a periodic space structure with alternating maxima and minima in its absolute value (depicted in the figure by pink fringes). This, to some extend, can be viewed as ‘splitting’ the atom into a set of identical atomic ‘copies’ with equidistant separation between them. Such a multi-site atomic structure (termed in \textsuperscript{[2]} ‘quantum grating’), is organized based on only one ‘real’ nucleus (and, in the simplest case, only one ‘real’ electron). Hence, such a ‘multi-site’ atom qualitatively differs from an object like e.g. H\textsubscript{2}+, where a two-site structure of the electron state is created by the presence of two ‘real’ nuclei.

Therefore, there are all grounds to expect that the process of photo ionization of a ‘multi-site’ atom will strongly differ from photo ionization of not only a ‘normal’ atom but also a molecule. It is thus the goal of the present article to theoretically explore photo ionization of such a ‘multi-site’ atom taking, as its simplest representation, a hydrogen-like atomic system.

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The atomic units are used throughout the text except otherwise stated.

[Diagram of atom and photon interaction]

FIG. 1: A sketch of preparing and photo ionizing a 'multi-site' atom. An atom with a well-defined initial momentum after passing through a diffraction grating (blue screen with slits) finds itself in a multi-site state (purple fringes). In the interaction region the atom is ionized by a light beam (marked with cyan and orange). The momenta of the emitted electron (red sphere) and the recoil ion (green sphere) can then be measured using two dimensional position-sensitive detectors, labeled by (a) and (b), respectively.

II. GENERAL CONSIDERATION

Let an atom (or an atomic ion) with a momentum \( \mathbf{P}_i = (P_{i,x}, P_{i,y}, P_{i,z}) = P_i \) pass through a diffraction grating. We suppose that the grating is located in the \((x,y)\)-plane (i.e., perpendicular to \( \mathbf{P}_i \)) and consists of \( N_0 \) equal-size slits placed along the \( x \)-direction (see Fig. 1). The dimensions of the slit along the \( x \)- and \( y \)-directions are \( a \) and \( b \), respectively. The separation between the neighbor slits along the \( x \)-direction (the grating constant) is \( d \).

After the passage through the grating the wave function of the atom at large distances can be obtained using the Huygens-Fresnel principle (see e.g. [3]) and is very well approximated by

\[
\Psi_i(\mathbf{R}, \mathbf{r}, t) \propto e^{iDP} e^{i(\mathbf{P}, \mathbf{Z} - \mathbf{E}, t)} \times \frac{\sin(\alpha X)}{\alpha X} \frac{\sin(N_0 \gamma X)}{\sin(\gamma X)} \frac{\sin(\beta Y)}{\beta Y} \varphi_i(\mathbf{r}) \tag{2}
\]

Here, \( \mathbf{R} = (X, Y, Z) \) is the position vector of the atomic center-of-mass with respect to the origin, \( \mathbf{r} \) is the electron position vector with respect to the atomic nucleus, \( \varphi_i(\mathbf{r}) \) is the initial internal state of the atom with an energy \( \varepsilon_i \), and \( E_i = \frac{P_i^2}{2M_A} + \varepsilon_i \) is the total energy of the atom with \( M_A \) being its total mass, \( \alpha = \frac{P_a}{2D} \), \( \beta = \frac{P_b}{2D} \) and \( \gamma = \frac{P_c}{2D} \). As the origin of our coordinate system we have taken the center of the interaction region (where the atom and photon beams cross) whose linear dimensions are assumed to be much less than the distance \( D \) between this region and the diffraction grating.

In the interaction region the atom is irradiated by an electromagnetic plane wave with a (central) frequency \( \omega_\kappa \), momentum \( \mathbf{k} \) and polarization vector \( \mathbf{e}_\kappa \) (\( \mathbf{k} \cdot \mathbf{e}_\kappa = 0 \)). Absorption of a photon results in electron emission. Assuming that the momenta of the emitted electron and recoil ion can be measured with high accuracy, we take the final state of the atom as the product of a plane wave, which describes the motion of its center-of-mass, and an internal (continuum) state \( \varphi_{\mathbf{k}_e}(\mathbf{r}) \) with an energy \( \varepsilon_{\mathbf{k}_e} = k_e^2/2 \) where \( \mathbf{k}_e \) is the momentum of the emitted electron with respect to the atomic nucleus.

After a (somewhat lengthy) calculation we obtain that the fully differential cross section for photo ionization is given by

\[
\frac{d\sigma_{fi}}{d^3P_{\text{rec}} d^3\mathbf{p}_e} \propto \frac{1}{\omega_\kappa} \delta(E_f - E_i - \omega_\kappa) \delta(P_i - P_{f,z} + \kappa_z) \times \left| \frac{\langle \varphi_{\mathbf{k}_e} | e^{i\mathbf{k}_e \cdot \mathbf{r}} (\mathbf{e}_\kappa \cdot \mathbf{p}_i) | \varphi_i \rangle \right|^2 \times \left| F_\beta(P_{f,y} - \kappa_y) \sum_n F_n (P_{f,x} - \kappa_x + nP_D/D) \right|^2. \tag{3}
\]

In this expression \( \mathbf{P}_f = (P_{f,x}, P_{f,y}, P_{f,z}) \) and \( E_f = P_f^2/2M_A + k_e^2/2 \) are the final total momentum and energy, respectively, of the atomic system (the electron + residual ion), and \( P_{\text{rec}} \) and \( \mathbf{p}_e \simeq \mathbf{k}_e + \mathbf{v} \), where
\( \mathbf{v} = \mathbf{P}_r/M_A \), are the momenta of the recoil ion and the emitted electron, respectively, \( (P_{rec} + \mathbf{p}_e = \mathbf{P}_I) \); all these momenta and the energy refer to the laboratory frame. \( \mathbf{p}_r \) is the momentum operator acting on the internal states. The sum in (3) arises due to the periodic structure of the state \( |2\rangle \) running over the number of the 'localization sites' of the state (this number is equal to the number of slits of the diffraction grating).

The two delta-functions in (3) ensure the momentum conservation along the \( z \)-axis, given by \( p_{rec,z} = P_t + \kappa_z - p_{e,z} \), and the energy conservation, which reads \( (p_e - \mathbf{v})^2/2 = \omega_\kappa - \mathbf{v} \cdot \kappa + \varepsilon_i \), where the term \( \mathbf{v} \cdot \kappa \) accounts for the (non-relativistic) Doppler shift of the photon frequency in the rest frame of the atom (note that it is quite small and can normally be neglected).

Had we considered photo ionization of a 'normal' atom, the corresponding fully differential cross section would involve two more delta-functions expressing momentum conservation along the \( x \)- and \( y \)-directions. In the case of a 'multi-site' atom, however, they are replaced by the terms in the last line of Exp. (3), where the functions \( F_\eta (\eta = \alpha, \beta) \) are given by

\[
F_\eta (\zeta) = \int_{-L/2}^{L/2} dl \ e^{i\zeta l} \frac{\sin(\eta l)}{\eta l}.
\]

Here, \( L \) is the length of the interaction region (for simplicity we assume that it is the same for both \( x \)- and \( y \)-directions). If \( L \gg 4 \pi \eta \), the function \( F_\eta (\zeta) \) takes on very simple form: \( F_\eta (\zeta) = \pi/\eta \) at \( |\zeta| < \eta \), \( F_\eta (\zeta) = \pi/(2\eta) \) at \( |\zeta| = \eta \), and \( F_\eta (\zeta) = 0 \) at \( |\zeta| > \eta \).

The conditions \( L \gg 4 \pi \alpha (L \frac{P_{rec}}{D} \gg 2\pi) \) and \( L \gg 4 \pi \beta (L \frac{P_{rec}}{D} \gg 2\pi) \) hold for a very broad parameter range and in what follows we shall assume that they are fulfilled. In such a case Exp. (3) predicts that the momenta of the reaction fragments must fall into the momentum bands defined by \( |P_{rec,x} + p_{e,x} - \kappa_x + n P_t + \pi| \leq P_t |\eta| \) and \( |P_{rec,y} + p_{e,y} - \kappa_y| \leq P_t |\eta| \). These requirements, together with the momentum conservation along the \( z \)-axis and the energy conservation, determine the photo ionization kinematics.

Note that the absence of the delta-functions for the momentum balance in the \( (x,y) \)-plane is a direct consequence of regarding the diffraction grating as an external field acting on the atom. The total momentum of the system consisting of the atom, the grating and the photon is conserved leading to a strong (momentum) entanglement between the first two (since the photon momentum can normally be neglected). However, since the grating's degrees of freedom are not included in the consideration, the momentum conservation is sacrificed. In contrast, the energy conservation remains since the macroscopic grating (which was initially at rest), due to its enormous mass, does not participate in the energy exchange with the atom.

### III. RESULTS AND DISCUSSION

#### A. Spectra of electrons and recoil ions

![FIG. 2: The cross section \( \frac{d\sigma}{dp_e dp_{rec,x}} \) for photo breakup of He\(^+\)(1s) by a linearly plane wave with central frequency \( \omega_\kappa = 120 \text{ eV} \) and bandwidth \( \Delta\omega_\kappa = 1 \text{ eV} \). The multi-site state of He\(^+\)(1s) is formed by passing with initial momentum \( P_t = 8 \times 10^2 \) a.u. (\( v \approx 0.1 \) a.u.) through a diffraction grating with \( a = d/2 = 100 \mu \text{m} \). The distance \( D \) between the grating and the interaction region is 18 cm. The cross section is plotted as a function of \( p_{e,x} \) and \( p_{e,y} \) at fixed \( p_{e,z} = v \approx 0.1 \) a.u. and \( P_{rec,x} = 0 \). The upper and lower panels correspond to polarization along the \( x \)- and \( y \)-axis, respectively, the number of slits is marked in the upper-right corner of each panel.](image-url)

Fig. 2 shows spectra of electrons emitted from multi-site He\(^+\)(1s) ions due to absorption of photons from a linearly polarized radiation with a central frequency \( \omega_\kappa = 120 \text{ eV} \) and a bandwidth \( \Delta\omega_\kappa = 1 \text{ eV} \). The multi-site state of He\(^+\)(1s) is formed by passing with initial momentum \( P_t = 800 \) a.u. through a diffraction grating (\( a = b/2 = 100 \mu \text{m} \)). The distance \( D \) between the grating and the interaction region is 18 cm and \( L = 1 \) mm, respectively. The spectra are represented by the cross section \( \frac{d\sigma}{dp_e dp_{rec,x}} \) and are given as a function of the electron momentum components \( p_{e,x} \) and \( p_{e,y} \) at \( p_{e,z} = v \approx 0.1 \) a.u. and \( P_{rec,x} = 0 \). The upper and lower panels of Fig. 2 display results for the absorption of photons polarized along the \( x \)- and the \( y \)-axis, respectively.

Had we considered photo breakup of the 'normal' He\(^+\)(1s) (assuming that \( a \to \infty \) and \( b \to \infty \) and keeping the other parameters as they are given in Fig. 2) the corresponding cross section \( \frac{d\sigma}{dp_e dp_{rec,x}} \) would be represented by just two short lines of infinitesimally small width along the \( x \)-axis (their size along the \( y \)-axis is proportional to \( \Delta\omega_\kappa \)), which are located at \( (p_{e,x}, p_{e,y}) = (0; \pm \sqrt{2(\omega_\kappa - |\varepsilon_i|)} \) (\( \pm \)). Moreover, a similar result would also hold for ionization of a molecule.
In contrast, the electron spectra in Fig. 2 possess a clear interference structure originating in the coherent contributions of different sites of the state (2) to the photo breakup process. The main features of this structure can be qualitatively understood by noting the following points. First, because of the energy conservation the photo electron spectra in the \((p_{e,x}, p_{e,y})\)-plane can only be located on a ring with the (mean) radius \(p_0^1 = \sqrt{2(\omega - |\varepsilon_i|)} - (p_{e,z} - v^2) = \sqrt{2(\omega - |\varepsilon_i|)}\); due to a finite radiation bandwidth \(\Delta \omega_\nu\), the ring has a width \(\Delta p_0^1 \approx \Delta \omega_\nu/p_0^1\). Second, the dipole selection rules (the dipole approximation is valid since the photon momentum is negligible) encourage the emitted electron to move along the photon polarization axis. Third, and what makes the crucial difference compared to the standard photo ionization, is that in the momentum balance along the \(x\)-axis, which is determined by the function \(F_\alpha\) (see the discussion after Exp. 1), the strict unambiguous relation \(p_{e,x} = -P_{rec,x}\) \((= 0\) a.u.) is now replaced by the much milder condition of prohibiting the emitted electron to fall outside the momentum bands \([p_{e,x} + n P_0^1/2] \leq P_{\perp} \leq P_{\perp}/2\) \((n = 0, \pm 1, \pm 2, \ldots)\).

Using the above three points one can qualitatively (and even quantitatively) explain: i) the positions of the maxima in the spectra (including the double-splitting of the single maximum in the upper-left panel of Fig. 2), ii) how the spectrum change with the number of slits and also iii) the single maximum in the upper-left panel of Fig. 2), i) how the maxima in the spectra change with the number of slits and also iii) how the maxima in the spectra change with the number of slits and also iii) how the maxima in the spectra change with the number of slits and also iii) how the maxima in the spectra change with the number of slits and also iii) how the maxima in the spectra change with the number of slits.

This choice of the cross section for the recoil ions (and of the latter two momentum components) was made in order to 'mirror' the conditions for the electron emission spectra in Fig. 2. However, when the radiation is polarized along the \(x\)-axis there is no 'mirroring' between the electron and recoil ion spectra at all (since the latter simply vanishes at \(p_{e,z} = 0\)). If the radiation is polarized along the \(y\)-axis, there is indeed a certain correspondence between these spectra. Yet, in contrast to photo ionization of a 'normal' atom (or molecule) in which the momentum spectra of electrons and recoil ions would be very strongly correlated exactly mirroring each other, this correspondence does not imply such a strong correlation even in the single-slit case \((N_0 = 1)\) and further rapidly diminishes when the number of slits increases.

The positions of the maxima in Fig. 3 are determined by the conditions \(|P_{rec,x} + n P_{\perp}/2| \leq P_{\perp} a D\) and \(|P_{rec,y} + P_0^1| \leq P_{\perp} b D\). The value of \(p_{0,y}^1\) is determined by the energy conservation, \(\varepsilon = (p_{e,x}^2 + (p_{e,y}^2 + (p_{e,z} - v^2)/2 = \omega - |\varepsilon_i|\), where now \(p_{e,z} = 0\), \(p_{e,z} = p_{i} - P_{rec,z} = v\) and, hence, \(p_{0,y}^1 = \pm \sqrt{2(\omega - |\varepsilon_i|)} \approx \pm 2.2\) a.u. Due to the radiation bandwidth \(\Delta \omega_\nu\), there is a momentum uncertainty \(\Delta p_{0,y}^1 \approx \pm \Delta \omega_\nu/(2P_0^1) \approx \pm 0.01\) a.u. (note that \(P_{\perp} a D = P_{\perp} b D \approx 0.22\) a.u.).

These conditions, in particular, show that the number of the maxima in the recoil ion spectra is simply equal to the number of slits \(N_0\) and, unlike the electron spectra, no 'saturation' in the pattern of the recoil cross section occurs when this number grows. The reason for this is that – because of the huge difference between the electron and nucleon masses – the recoil ion momenta \(P_{rec,x}\) and \(P_{rec,y}\) do not enter the expression for the energy conservation in photoeffect, \((p_{e} - v)^2/2 = \omega - |\varepsilon_i|\), and the possible values of \(p_{rec,x}\) are unrestricted by the energy constraints.

Let us, as the last examples, consider the cross sections \(d\sigma/dP_{rec,x}\) and \(d\sigma/dp_{rec,x}\). A simple analysis of the fully differential cross section (4) shows that after its integration over all possible states of the recoil ion the resulting electron momentum spectrum acquires exactly the same shape as in the case of photo breakup of a 'normal' atom (or ion). Namely, the electron momenta in the three dimensions are located on a sphere with the (mean) radius \(\sqrt{2(\omega - |\varepsilon_i|)}\) centered at \((0; 0; v)\); the sphere is broadened due to the radiation bandwidth and the intensity distribution on it depends on the polarization of the radiation. Fixing a value of \(p_{e,z}\) we obtain that in the \((x-y)\)-plane the electron momenta are located on a corresponding ring.

The shape of the cross section \(d\sigma/dp_{rec,x}\) is more interesting, qualitatively differing from that for photo ionization of a 'normal' atom (the latter just exactly mirrors the corresponding electron spectrum). This cross section is shown in Fig. 4 where it is plotted as a function of \(P_{rec,x}\) and \(P_{rec,y}\) at a fixed \(P_{rec,z} = p_{i} - v\). According to this figure the momenta of the recoil ions in

![Fig. 3](image-url)
FIG. 4: The cross section \( \frac{d\sigma}{d^3p_e} \) given as a function of \( P_{\text{rec,x}} \) and \( P_{\text{rec,y}} \) at a fixed \( P_{\text{rec,z}} = P_l - v \). The parameters \( P_l, a, b, D, L, \omega_\kappa \) and \( \Delta \omega_\kappa \) are the same as in Figs. 2–3. The upper and lower panels show results for the radiation linearly polarized along the \( x \)- and \( y \)-axis, respectively. The number of slits is marked in the upper-right corner of each panel.

the \( (x,y) \)-plane are located on (multiple) rings with the mean radius of \( \sqrt{2(\omega_\kappa - |\epsilon_z|)} \approx 2.2 \) a.u. centered at the points \((P_{\text{rec,x}} = n P_l \frac{d}{D}; P_{\text{rec,y}} = 0) \approx (0.89 n; 0)\) with \( n = 0, \pm 1, ... \). The rings have a width due to a finite radiation bandwidth \( \Delta \omega_\kappa \) (this contributes \( \approx 0.02 \) a.u. to the width of the rings) and the momentum bandwidths in the \( x \)- and \( y \)-directions given by \( \Delta P_x = P_l \frac{d}{D} \approx 0.44 \) a.u. and \( \Delta P_y = P_l \frac{b}{D} \approx 0.44 \) a.u., respectively. Thus, at \( N_0 > 1 \) striking qualitative differences arise between the 'individual' momentum distributions of the emitted electrons and recoil ions.

The only fundamental parameter making a drastic difference between the electron and the nucleus of the \( \text{He}^+ \) is their huge mass difference. Therefore, it is obvious that it is exactly this point where the lack of symmetry between the momentum spectra of the photo reaction fragments originates. Even so this point is of course present also for a 'normal' atom (where nevertheless the symmetry between the momentum spectra is present), here its effect is qualitatively different due to a specific state of the atom. Indeed, the atom initially incident along the \( z \)-direction, due to scattering on the diffraction grating, falls into the allowed momentum bands \((n P_l \frac{d}{D} - P_l \frac{b}{D} \leq P_x \leq n P_l \frac{d}{D} + P_l \frac{b}{D}; -P_l \frac{b}{D} \leq P_y \leq P_l \frac{b}{D})\) and, because the electron is much lighter than the nucleus, it is mainly the latter which participates in the momentum exchange with the grating.

B. Photo ionization of a 'multi-site' atom as one- and two-particle interference phenomena

As we have seen, if the diffraction grating contains more than one slit all the above considered cross sections (except \( \frac{d\sigma}{d^3p_e} \)) display pronounced interference patterns. The interference effects are caused by a periodic multi-site space structure of the state of an atom passed through a diffraction grating. Because of that the atom (atomic ion) in the process of photo ionization effectively behaves as a set of equidistant coherent absorbers of radiation that – according to the superposition principle – gives rise to interference.

However, the interference structures in the electron emission spectrum disappear if it is obtained by integrating over all final states of the recoil ion. In other words, interference is absent for the electron taken individually and appears only if the detection of the electron is accompanied by a coincidence measurement of the recoil ion. Thus, the emission pattern in Fig. 2 represents in fact two-particle interference phenomena arising provided the superposition principle and quantum entanglement of the electron and recoil ion 'act' together (two-particle interference phenomena are considered e.g. in [4]-[5]).

In contrast, in the recoil ion spectra the interference structures are present, no matter whether the emitted electron is detected or not. Thus, in this case interference remains even if the recoil ion is taken individually belonging thus to the class of one-particle interference phenomena.

C. Photo ionization of a 'multi-site' atom as the process of extracting information

The process of photo ionization (breakup) can also be viewed from a somewhat different perspective: namely, from the perspective of storing and extracting information.

Unlike the wave function of a 'normal' atom, which carries the information just about its momentum, internal state and its binding energy, the wave function of a 'multi-site' atom contains in addition also the information about the parameters \((a, b, d, N_0)\) of the diffraction grating.

In particular, according to our results for the photo cross sections discussed above, the information about the grating, which is encoded in the quantum state of the atom, can be fully decoded by measuring the momentum distributions of the emitted electrons and the recoil ions. However, while the full information about the grating could be read off from the recoil ion spectrum alone, the electron momentum distributions can provide the information only if conditions are set on the momentum of the recoil ions and even in such a case it will not be complete (in general the number of slits \( N_0 \) cannot be extracted from the electron spectra due to the 'saturation' effect, see subsection A of this Section).
D. A 'multi-site' atom versus a multi-atomic molecule

In our discussion of photo ionization of a 'multi-site' atom we stressed that clear (and profound) interference structures may arise in the spectra of emitted electrons and recoil ions and that they originate in a multi-site structure of the state of the atom passed through a diffraction grating.

Interference effects can play a substantial role in photo ionization of molecules. In this case their origin is a multi-site structure of the electron state caused by the presence of more than one binding center (nuclei).

The situation, in which an electron is simultaneously localized around more than one 'real' nuclei, is of course qualitatively different compared to that where a 'multiple localization' effectively arises due to alternating maxima and minima of the wave function of a single atom with just one 'real' nucleus. As a result, the interference effects in these cases will also qualitatively differ.

E. Experimental devises as a possible source of decorrelation

As we have seen, even in the single-slit case ($N_0 = 1$) the exact correlation between the momenta of the photo electrons and recoil ions is absent. However, a 'single-slit' case is essentially what one routinely encounters in experiments which use 'nozzle/skimmer' or 'collimator' devises. Therefore, their parameters should be taken into account when highly accurate experiments are performed. In particular, the necessity to do this was demonstrated in [6] where atom ionization by energetic charged projectiles was considered.

IV. CONCLUSIONS

We have considered photo ionization (breakup) of an atom which passed through a diffraction grating. Due to scattering on the grating the atom finds itself in a state whose wave function possesses a periodic space structure with alternating maxima and minima. In the momentum space this results in the appearance of the alternating allowed and forbidden momentum bands.

We have shown that such a multi-site structure of the atomic state qualitatively change the process of photo ionization compared to the case of a 'normal' atom. In particular, spectra of the emitted electrons and recoil ions demonstrate clear interference patterns arising due to one- or two-particle interference phenomena. This interference, however, has a qualitatively different character compared to that known to arise when molecules are photo ionized.

Our results also suggest that the full information about the atomic properties and the diffraction grating, which is stored in the multi-site state of an atom, can be extracted in the process of photo ionization by measuring the momentum spectra of the emitted electrons and recoil ions.

Unlike in photo ionization of a 'normal' atom or molecule, in the case of a 'multi-site' atom there is no mirroring between the momentum spectra of the photo electrons and recoil ions. In particular, the spectra of recoil ions display both one- and two-particle interference effects, which is not the case with the electron spectra where only the latter can be observed. Besides, the recoil-ion spectra contain also more information about the properties of the diffraction grating. The basic reason for these inequalities between the reaction fragments is a very large difference between the electron and nucleon masses which in the case of a 'multi-site' atom has a qualitatively different impact on the photo ionization process compared to the 'normal' case.

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