

Deexcitations of the projectile dominating EUV-photon emission upon transmission of keV ions through solids

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(Received 29 January 2026; accepted 5 May 2026; published 19 May 2026)

We measure the photon emission induced by energetic Ne and He ions transmitted through thin single crystalline Si foils. The emitted photons are detected with a delay line microchannel plate detector. Our measurements show that photon emission detectable from the rear surface of the membranes is multiple times more likely than photon emission from the front surface of the membrane. It can be deduced that photon emission from electronic deexcitation of the sample can only play a minor role, while the vast majority of detected photons are emitted by excited projectiles freely decaying behind the sample. Utilizing shadowing effects, we can show that a large proportion of excited projectiles travels several centimeters before decaying. The photons observed in the present approach are another accessible observable reporting on ultrafast processes during ion-matter interaction.

DOI: [10.1103/physreva.113.052812](https://doi.org/10.1103/physreva.113.052812)

I. INTRODUCTION

The interaction of medium-energy ions with matter is a current topic of interest [1–3]. While the interaction processes at MeV and GeV projectile energies are largely understood in their underlying concepts, this is not the case at medium and low-energy ions (i.e., keV projectile energies and below). Once the projectile velocity is of the same order as the velocity of, largely delocalized, valence and conduction electrons, the electronic structure of the sample during the interaction with the intruding ion can no longer be regarded as static and a purely atomistic picture is oversimplified. In this sense, the energy deposition of keV ions in matter is a complex interplay of multiple processes in many body physics. Developing a better understanding of these interactions might enable a further exploitation of the benefits of ions as mixed electronic and nuclear probes in ion beam analysis established for MeV ions [4]. At lower energies and thus penetration depth, energy resolution and thus depth resolution can be increased, enabling advanced characterization of the growing amount of nanoscale materials, maintaining benefits as weak matrix effects and highly accurate quantification. Among others, available techniques include low-energy particle induced x-ray emission (LE-PIXE) [5] as well as Rutherford

backscattering (RBS) which is often just called medium-energy ion scattering (MEIS) at keV energies [6]. The altered character of the interaction of the energetic ions with the electronic subsystem in the keV regime should also be reflected in the observable deexcitation processes. Therefore, photons created upon ion impact represent an opportunity to study the combined electronic system of the ion and target material. In time-of-flight medium-energy ion scattering, a characteristic photon peak can be temporally resolved in the spectra and is commonly used to calibrate the timescale and the system resolution [7,8].

In this context, strong matrix effects in the yield of ion-induced photon emission have been earlier observed in backscattering geometries, e.g., SiO₂ emits about 50 times less photons than pure Si [9]. Recent research in the regime of keV ion energies revealed a strong dependence of ion-electron interaction in the form of energy deposition, and thus the electronic excitation of the target and projectile ion, on probed interaction distances, crystallinity, and experimental geometry [10–13]. We now perform a follow-up investigation of ion-induced photon yields as a potential deexcitation channel of these interaction processes targeting both backscattering and transmission geometries as well as single crystalline self-supporting target systems.

The idea of investigating photon emission, particularly of projectiles in transmission geometry, has from the 1960's to the 1980's, been employed as a common research method to obtain improved understanding of atomic physics, with its own conferences themed beam foil spectroscopy (BFS) [14]. BFS was mostly but not exclusively performed at MeV projectile energies and carbon foils as targets, with measurements at keV projectile energies found generally rare. The aim of BFS was mainly to use a (carbon) foil to create exotic,

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highly-excited states in the projectile, with the subsequent decay being observed downstream the foil so that properties such as transition energies and lifetimes could be extracted. Only very few works investigated the excitation processes or different sample systems [15,16]. BFS on transitions with energies of more than 10 eV is even more rare, as this puts additional demands on the spectrometer. The combination of keV projectiles, single crystalline sample system, and >10 eV transition energy has, to the best of our knowledge, not been investigated yet.

For He and Ne projectiles, as employed in this work, previous measurements at keV projectile energies were restricted to transition energies below 10 eV in the He case [17–19] and an incomplete dataset of Ne transitions above 10 eV [20]. At keV energies for both He and Ne, we also find no different “foil” for the excitation than a carbon target. The effects of crystallinity and surface quality remain uninvestigated with the exception of the search for resonant excitations in MeV ion channeling (see, e.g., [21,22]). With the growing understanding of transitions in atomic physics, the popularity of BFS declined, and since the 1990’s, only very few beam foil spectroscopy experiments were performed. Today, sufficiently thin self-supporting samples exist for many elements and include single crystals of semiconductors such as Si, SiC, or Ge as well as two-dimensional (2D) materials. Performing experiments in analogy to beam-foil spectroscopy on a variety of well-defined sample systems therefore offers an opportunity to contribute to the understanding of ion matter interaction, especially at keV ion energies, potentially shedding light on excitation channels. It is also of specific interest to investigate transitions above 10 eV, as these represent transitions to the ground state of the projectile and thus can be considered to be a major fraction of all transitions.

Performing wavelength dispersive measurements of EUV and soft x-ray photons above 10 eV is challenging, as their wavelengths are still too large to be diffracted on a crystal, while their energy is too small to use classical silicon detectors, which commonly detect photons above 200 eV [23]. Many setups resolving specific transitions in this photon energy range use very small, strong photon sources and spatially large pathways in the spectrometer to separate the spectral lines (see, e.g., [24]). Therefore, resolving wavelengths between 10 eV and 200 eV is challenging in BFS, as the beam is usually a very weak photon source, limited by tolerable beam currents on the sample, with the photon emission being additionally spread out over several centimeters behind the sample. For studying 2D materials or thin single crystals, even the beam currents in the μA range used in classical BFS can be considered to be inapplicable, as they would rapidly deteriorate single crystalline samples [25].

Due to the aforementioned limitations, we performed non-wavelength-resolving measurements of the photon emission in a time-of-flight approach utilizing a classical delay line MCP detector [26]. While our approach cannot resolve the energy of the EUV photons, a chopped beam with sub-ns time resolution gives us the ability to indirectly study beam foil excitations and lifetimes while maintaining fA currents and thus no sample degradation. We want to acknowledge that EUV wavelength resolving microchannel plate (MCP) based setups existed [27,28], but were exclusively limited to $>\mu\text{A}$

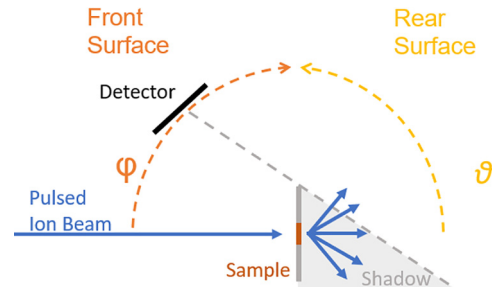


FIG. 1. Schematic top view of the experimental setup. The exemplary sketched shadow existing in backscattering measurements is used to determine the nature of the photons as spectral lines of the freely decaying projectiles.

currents and MeV ion energies due to the previously discussed constraints.

II. EXPERIMENT AND METHODS

Our experiments were performed at the time-of-flight medium-energy ion scattering (ToF-MEIS) setup located at Uppsala University [29,30]. We used electrostatically chopped ion beams of 300 keV $^4\text{He}^+$ and $^{22}\text{Ne}^+$ ions with <1 ns pulse length which were transmitted through 50-nm and 200-nm thick single crystalline Si membranes, commercially available from Norcada [31]. The experimental geometry is sketched in Fig. 1 (top view). The used detector is a RoentDek delay line MCP detector located at a distance of 290 mm from the sample [26]. The circular detector features a diameter of about 120 mm corresponding to acceptance angles of $\pm 11.5^\circ$. If a particle is hitting a channel opening of the MCP, the detection efficiency of ions is expected to be 100%, whereas the detection efficiency of photons has a threshold at 10 eV and remains rather constant at about 10% for EUV and soft x-ray photons above 13 eV [32,33]. As for any particle there is only a 54% chance to hit a channel opening upon impinging on the detector, these values get effectively reduced to 54% of the initial value (i.e., 54% for ions and 5.4% for photons) for particles impinging on the detector. The detector is rotatable between 0° and 160° scattering angle from the primary ion beam direction. In this work, the detector position is expressed by the angles φ or ϑ , which gives the detector angle to the front and rear surface normal, respectively. If the incoming ion beam matches the front surface normal, φ can be adjusted to values between 20° and 90° and ϑ can be adjusted to values between 0° and 90° . In the described ToF setup, photons created upon ions impinging on the sample arrive at the detector well before any other particle species originating from the ion pulse and hence form a distinct peak that is separated about 85 ns (180 ns) from the transmitted He (Ne) projectiles. The here-performed investigation of photon yields reports on the photons being part of this photon peak and is hence limited to sufficiently short-lived decays with transitions rates above 10^7 Hz. No photon peak is visible if measurements are recorded without the sample. A more detailed description of the ToF-measurements can be found in [8] and [30], an extended ToF spectrum is shown in the Appendix.

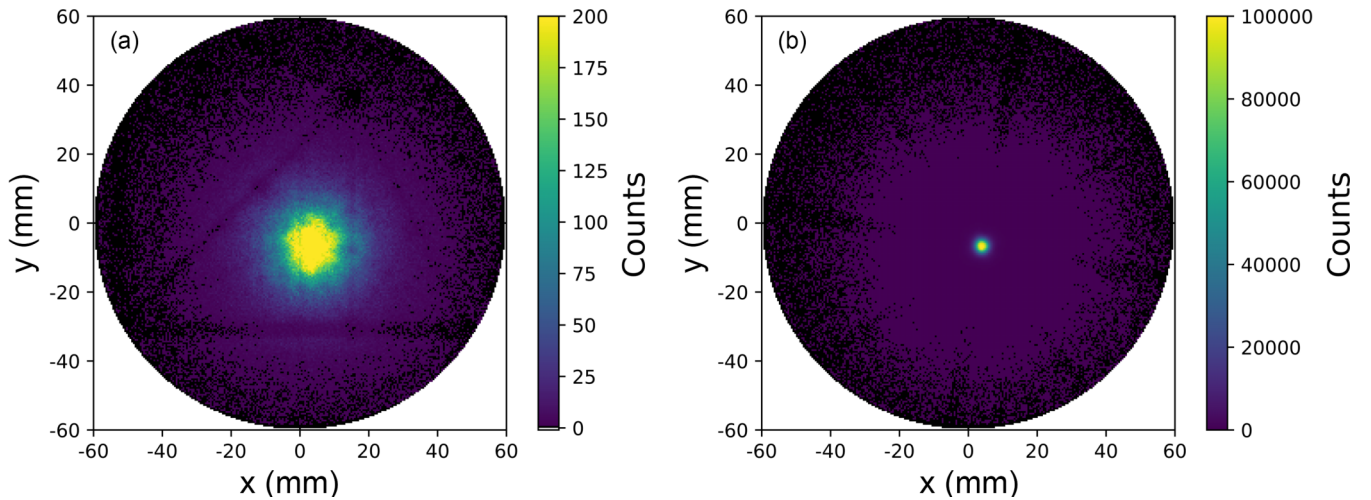


FIG. 2. Exemplary measurements of the ion distribution in (a) pseudorandom and (b) channeling alignments at $\vartheta = 0^\circ$ scattering angle. The measurements were recorded on the 200-nm Si membrane. The channeling distribution is, as expected, found much narrower. Both measurements show the blocking pattern of the planes of the Si crystal.

To investigate photon emission, we performed measurements of the photon yield at various scattering angles in transmission and backscattering in a random and 100 channeling geometry on the previously described Si membranes as well as backscattering measurements on a Si bulk sample aligned in random geometry. The (100) orientation of the single crystalline membranes was ensured by aligning the channel with the direct ion beam of $<1\text{ mm}^2$ diameter. A pseudorandom alignment was then achieved by turning the sample 4.5° and 11.5° around the two main axes of the crystal. Note that turning around two axes results in a small out-of-plane contribution to φ and ϑ which is not displayed in Fig. 1. The distributions of the transmitted ions along channeling and random geometry at $\vartheta = 0^\circ$ scattering angle are shown in Fig. 2. The random orientation of the Si bulk sample was ensured by a 5° incident angle with respect to the (100) surface. To properly normalize the photon yield, all measurements, including the Si bulk sample, were normalized by the number of impinged ions. To determine this number, the ion current transmitted through the Si membranes was measured before and after every photon measurement by recording the ions in the (100) alignment at 0° scattering angle for 2 minutes. In these reference measurements, nearly all ions hitting the sample should impinge on the detector, as surface large-angle scattering on the entrance side of the foil is highly unlikely. As the reference current for a measurement, we use the mean value of the currents before and after the measurement. Since we cannot determine the exact current during a measurement [except the transmission measurements at 0° and (100) geometry], there is a potential systematic uncertainty in the normalization. We expect this uncertainty due to nonlinear current drifts to be small; the accuracy can be later estimated from the small scattering of the final dataset.

To further investigate the processes at or behind the rear surface, measurements in a similar situation as sketched in Fig. 1 ($\varphi = 60^\circ$) are recorded. At this backscattering angle, photons are able to reach the detector from the front surface. Photons originating from the rear surface can also be observed, given they are transmitted through the sample. If

photons are to be emitted by the freely decaying projectile far behind the sample, these are directly visible once the projectile leaves the area shadowed by the sample and sample holder.

III. RESULTS

Figure 3 shows the obtained photon timing spectra of 300 keV Ne ions transmitted through the 200-nm-thick Si membranes. We distinguish between the front surface, where the ion is entering the membrane and the rear surface, where the ion is exiting the membrane. It is apparent that the photons show a decaying tail at the rear surface, which is not visible at the front surface.

Photon yields recorded upon the transmission of 300 keV He and Ne ions through the 200-nm-thick Si membranes are extracted from spectra as shown in Fig. 3 and normalized by the beam current (see Sec. II); the obtained results are plotted in Fig. 4. The x axis displays the angles φ and ϑ from Fig. 1, which are measured between the vector pointing to the center of the detector and the respective surface normal. The measurements depicted in Fig. 3 appear at $\varphi \approx 32^\circ$ and $\vartheta \approx 12^\circ$ due to the contributions of the sample rotation to φ and ϑ if measured with respect to the surface normal. The measured photon yield was corrected by the detection efficiencies of ions and photons and the proportion of covered solid angle to display the absolute photon emission in photons per incident ion. This absolute value assumes an isotropic photon emission. Due to uncertainties in the photon detection efficiency (set to 10% in agreement with [32] and [33]), the absolute value of the photon yield will have the same relative error as the photon detection efficiency. Nevertheless, the resulting symmetric uncertainty is expected to be below 30% and the same for all measurements.

Figure 4 shows that for both projectiles, photon emission from the rear surface is much more likely than photon emission from the front surface. For Ne projectiles, a potential slight difference between the channeling and random geometry is visible for the rear surface, but not for the front

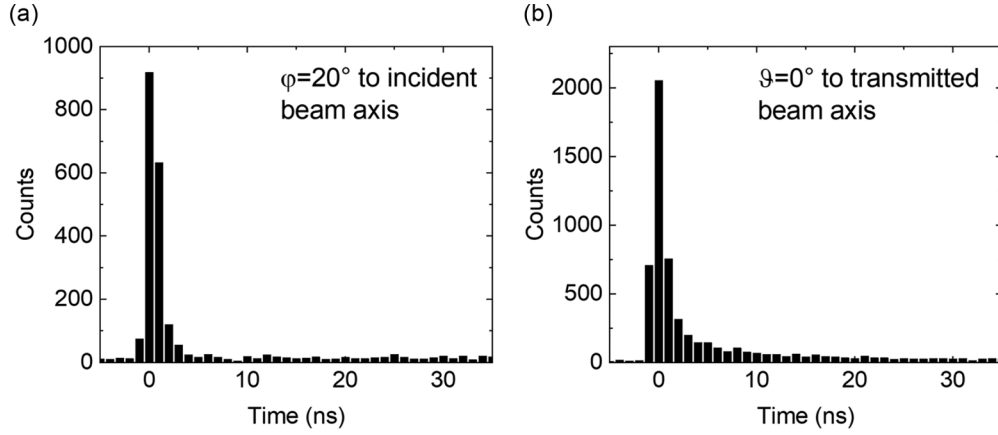


FIG. 3. Timing coordinates of photons created upon impact of 300-keV Ne ions at (a) the front (ion entry) and (b) the rear (ion exit) surface of the 200-nm Si membrane. The measurements are recorded in a random geometry with an ion pulse width of approximately 1 ns. In both measurements, the ion current is about 0.1 fA. The measurements are not normalized for ion current and recording time. For simplification, the stated values for φ and θ mark the detector position as sketched in Fig. 1 and are here measured with respect to the beam axis instead of the surface normal.

surface. For both projectiles, there seems to be no clear angular dependency in the photon emission at the rear surface. Also, for both projectiles, the measured front surface emission is smaller than what can be predicted from attenuation and reflection of the averaged measured emission at the rear surface, illustrated by the dashed or continuous lines. These predictions are assuming a 30, 40, and 50 eV photon source at the rear surface of the crystal isotropically emitting and the wavelength specific optical constants of silicon [34]. The photon energies were selected to roughly match those of common He and Ne spectral lines in the EUV range. While the intensity decrease is overall well predicted, the experimentally observed angular dependence of the emission from the front surface does not seem to follow these attenuation or reflection

curves and for very large angles to the surface normal, an unexpectedly large photon emission remains. However, at these high angles, the opening angle of the detector is not negligible. The angles displayed in Fig. 4 show the angle between the surface normal and the center of the detector while the detector covers an angular segment with a maximum width of 11.5° .

Since the photon yields measured at the rear surface are at least three times higher than those measured at the front surface, it is expected that a large fraction of the photon emission is taking place at or behind the rear surface. Since the photon yields recorded in backscattering from a transmission sample are larger than those obtained from a Si bulk sample, the increased rear surface photon emission also seems to

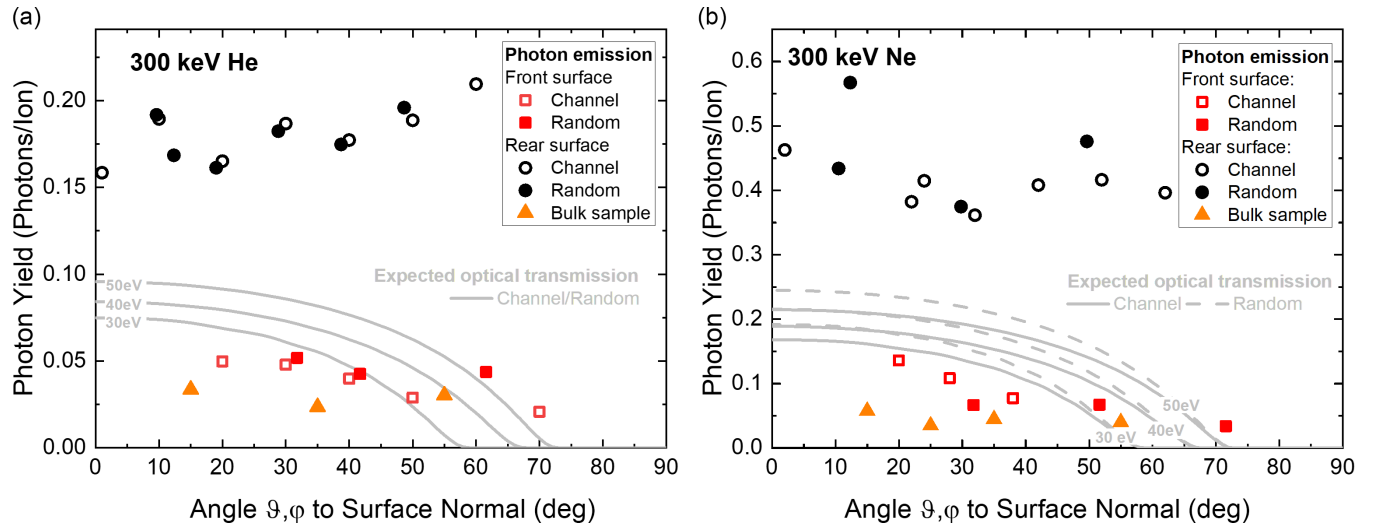


FIG. 4. Photon yield of (a) 300 keV He and (b) 300 keV Ne ions at the front (ion entry) and the rear (ion exit) surface of the 200-nm Si membrane and a Si bulk sample. The horizontal axis shows the recording angles φ and θ measured relative to the front and rear surface normal, respectively. The gray lines show the expected transmission of 30 eV, 40 eV, and 50 eV photons through 200-nm Si. Dashed lines: Expected photon transmission to the front surface for the averaged measured photon yield of Ne channeling trajectories at rear surface. Solid lines: Expected photon transmission for the averaged measured photon yield of Ne random (all He) trajectories at the rear surface. The expected transmission rises with increasing photon energy.

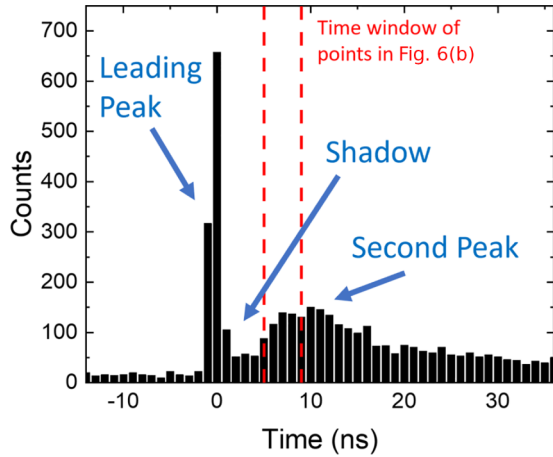


FIG. 5. Timing of photons recorded at $\varphi = 60^\circ$ angle to the front surface normal for the Ne ion impinging on channeling geometry. The measurement is recorded on the 50-nm Si membrane and is not normalized for ion current or recording time.

impact the measurements on the front surface. The processes leading to the increased photon emission at the rear surface are further investigated utilizing the shadowing method explained in Sec. II. Figure 5 shows the timing of photons recorded at $\varphi = 60^\circ$ angle relative to the front surface normal for Ne ions impinging in channeling geometry.

Figure 5 shows that in a large-angle front surface measurement, a second broader peak appears a few ns after the leading photon peak. We interpret this second peak to be the reemerging tail of the photon emission at the rear surface. While the exemplary shown spectrum was recorded for Ne in a (100) channeling geometry, a similar behavior is visible for Ne in a random sample orientation. The same effect is visible for He projectiles, however, for this projectile choice the second peak is less pronounced. This difference is somewhat expected because the tail visible in the photon emission if recorded from the rear surface is overall less pronounced for He. As the employed detector features a delay-line system, for every count in Fig. 5 a spatial coordinate can be assigned. This

spatial coordinate is plotted in Fig. 6(a) for the leading peak and in Fig. 6(b) for the first 4 ns of the second peak. The time window plotted in Fig. 6(b) is marked with red dashed lines in Fig. 5.

In Fig. 6(a) a spatially nearly evenly distributed photon yield is observed for the leading peak with a light tendency to decrease towards the right. In contrast to this, the spatial coordinates corresponding to events from the first 4 ns of the second peak, shown in Fig. 6(b), show a sharp edge in the middle of the detector. This observation is in good agreement with the interpretation of the second peak arising from photons emitted by freely decaying projectiles that have left the area shadowed by the sample holder. The timescale observed for this shadowing effect fits well to the velocity of the Ne projectiles of approximately 1.6 mm/ns.

IV. DISCUSSION

The photon emission differs drastically between the front and rear surfaces. For both projectiles, the photon yields obtained from the front surface of a transmission sample are higher than those obtained from a silicon bulk crystal. As the projectile paths in the bulk sample and membrane do not differ until the projectile is exiting the membrane, the higher yield on transmission samples must be an effect of the projectile exiting the membrane. The photon emission within the transmission sample itself must be even smaller than observed for the bulk crystal as photons emitted in a depth below 200 nm even increase the yield.

Already, the time spectrum of the recorded photons (Fig. 3) shows that photons detected from the rear surface exhibit a tail which is not observed for the front surface. Also, the angular distribution of the photon yields (Fig. 4) differs between the two surfaces: the emission from the rear surface is found to be isotropic, whereas emission from the front surface is much lower and shows a tendency to decrease somewhat towards higher detection angle φ . This angular dependency of the photon emission at the front surface would be analogous to the observations of Lohmann *et al.* [9] for photon emission during keV ion implantation. We, therefore, interpret this behavior as

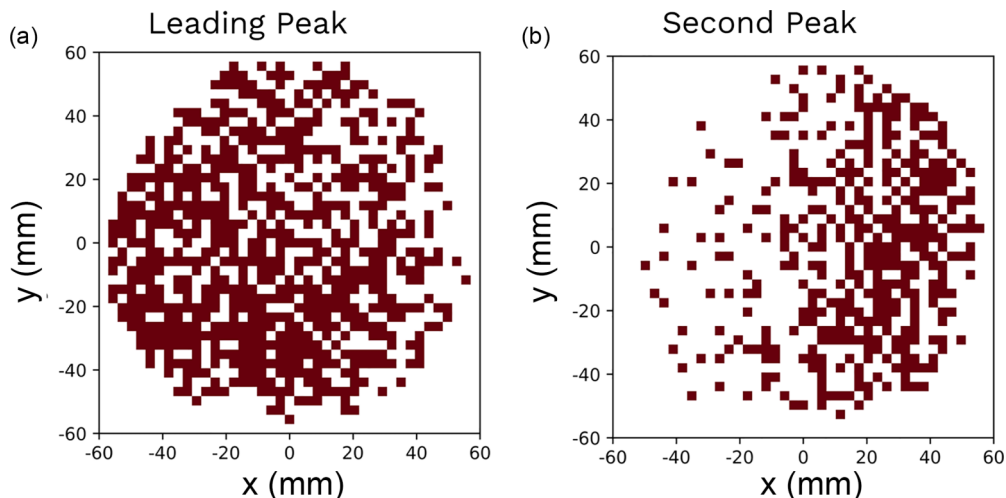


FIG. 6. Spatial coordinates of the photons displayed in Fig. 5.

the increased attenuation of photons within the Si crystal due to the increased path length and increased reflection on the silicon-vacuum interfaces towards higher angles.

The shadowing effect in Figs. 5. and 6 shows that the tail visible at the rear surface is due to excited projectiles decaying freely behind the sample. In fact, this seems to be the case for nearly all recorded photons. To decay via photon emission on a ns timescale, the excited electron and lower-level hole of an excited projectile need to fulfill the dipole selection rules for spin and orbital angular momentum. For excitations fulfilling this condition, a large amount already decays within less than a ns [35,36], which is in accordance with observations in Fig. 3. The visible tail can then be understood as the remaining small proportion of excited states that decays on a timescale of several 10 ns. Since many more, relatively long-lived states exist for Ne, when compared to He, the tail is much more pronounced there. For 300 keV He (Ne), a maximum of 1-ns flight time corresponds to approximately 3.8 (1.6) mm distance behind the sample. Therefore, these fast photon transitions are still visible through the thin sample when the front surface is observed. For transitions of neutral He and singly charged He^+ , detectable photon energies are restricted to 20 eV to 53 eV. These are the transitions ending in the ground state, higher-order transitions are usually below the 10-eV detection limit or too long-lived [35]. For the expected $\text{Ne}^{0+} \rightarrow \text{Ne}^{4+}$ [37], the energy range is less well defined, however, the energy of most commonly observed photons should still be in the range of 20 eV to 50 eV [20]. Figure 4 shows that for the 30 to 50 eV range, the photon yield measured at the front surface of a transmission sample can be explained by photons emitted at the rear surface being transmitted through the sample. However, at high angles, the decrease of the photon yield predicted from transmission of 30 to 50 eV photons is stronger than the decrease observed in the measurement.

The photon yields obtained from a silicon bulk crystal are significantly lower than the photon yields obtained in backscattering geometries of a transmission experiment, however, both values remain in the same order of magnitude. The photon emission of up to 0.05 photons per ion from the silicon bulk crystal is too high to be solely based on backscattered particles as less than 1 of 1000 projectiles are backscattered (calculated from simulations with the binary collision approximation code TRBS [38]). Therefore, photons emitted by the sample itself must slightly contribute to the overall photon emission. However, to explain the increased photon emission of the 200-nm-thick sample compared with the bulk, photon transmission from the rear surface must strongly contribute to the photon peak observed at the front surface. We conclude that the photons measured at the front surface of a transmission sample consist of a contribution from both, freely decaying projectiles behind the sample and a smaller fraction of photon emission from the sample itself. The relatively large photon yields recorded on the rear surface of a transmission sample are completely dominated by photon emission from freely decaying projectiles.

The previously discussed small photon emission from the bulk sample is in agreement with the findings of Lohmann *et al.* [9], where strong angular dependencies and target

differences were measured. Photons emitted by the sample itself dominate the spectra on thick samples, but only if either ion or photon transmission through the sample are impossible. Inversely, it can be concluded that deexcitation by radiative transition in the EUV regime is, at least for the present system, a rare process when expected as a consequence of target excitation along the ion trajectory. This scarcity of EUV photon emission by the sample should also be present for the systems SiO_2 , C, TiN, and Au, which were previously shown to emit even less photons than the here-investigated Si bulk crystal [9].

As we show that the photon emission at the rear surface is completely dominated by freely decaying projectiles, the assumption of isotropic photon emission used for the calculation of absolute photon yields is valid. Therefore, the absolute values of about 0.17 photons per ion for He and up to 0.4 photons per ion for Ne give an average value of the photons emitted by a transmitted projectile. Projectiles with more than one excited electron are expected to usually decay via Auger electron emission [36]. The detection of cascades from one electron deexciting via multiple steps is also highly unlikely as for excited neutral and singly charged ions of both, He and Ne, the second photon would have too low energy to be detected [35,36]. This exclusion of multiphoton processes makes the measured absolute value of the photon emission also a minimum value of the fraction of excited projectiles leaving the sample.

A potential slight intensity difference in photon emission between channeling and random for the Ne projectiles is visible, especially at the rear surface, whereas no such difference is observable for He. There are two explanations for why to expect a potential difference in the yields observed in the Ne experiment: Increased photon emission by the sample itself, or different photon emission due to a different population of excited states of the transmitted projectiles. As shown in [37] the charge state distributions of Ne projectiles differ strongly between channeling and random in the Ne case, whereas no significant difference was found for He projectiles. Also, an increasing difference in electronic stopping, between channeling and random trajectories, i.e., electronic excitation of the target with increasing atomic number of the projectile has been observed [10].

V. PERSPECTIVES

The results presented in this work show that photons recorded with a MCP detector in ion transmission experiments are mainly emitted by freely decaying projectiles behind the sample. We furthermore show that the photon emission by the projectiles is high and commonly much higher than the photon yields due to the sample itself. Hence, if low-energy PIXE or ionoluminescence using a continuous beam is to be performed on self-supporting targets such as 2D materials (i.e., wherever the projectile is transmitted through the sample), spectral lines of the projectile may dominate the energy dispersive photon spectra in the regime from 10 eV to 100 eV. Even if the projectile is not transmitted, photons emitted by backscattered projectiles or recoiled species can potentially dominate, particularly in backscattering geometry. This aspect might even become more important if it is considered that

(bulk) silicon was previously found to be a strong photon emitter if compared to other targets [9].

Our findings can be used for additional perspectives in beam foil spectroscopy. While measuring the photon energy on single crystalline thin films is challenging with noteworthy energy resolution between 10 eV and 200 eV, setups as the one used here give information about photon yields and lifetimes without facing the limitations explained in the Introduction. The measurements of time-resolved photon yields can be combined with coincidence measurements connecting photon yields with charge states [39], specific energy loss, or scattering angles. In such a way, experiments detecting photons can contribute to a better understanding of the charge exchange dynamics at keV projectile energies. Velocity-dependent measurements in the Å/fs range (here 16.22 Å/fs for 300 keV ^{22}Ne) can additionally give upper limits for the transition rates of competing deexcitation processes in the interaction with the solid such as interatomic coulombic decay [40,41].

We determine the fraction of excited projectiles leaving the sample to be in the order of several 10% and from the shadowing experiment, we additionally know that, in the present keV energy regime, many projectiles decay up to several cm behind the sample. Also, it can be assumed that a fraction of projectiles is additionally locked in excited states with lifetimes $\gg 30$ ns (i.e., they are nonradiative), which thus can even travel several meters. Due to the large spatial separation from the sample, this potentially makes the specific radiative and nonradiative states accessible in pump-probe experiments involving <ps lasers [42–44] while maintaining fA currents.

VI. CONCLUSION

We performed angular- and time-resolved measurements of photon yields from the interaction of 300 keV Ne and He projectiles transmitting solid samples. Our findings show that the yield of photons with energies above 10 eV is dominated by projectiles decaying freely behind the sample. Photon emission from the sample contributes only weakly to the overall yield. This behavior is trajectory independent and also at random trajectories, i.e., stronger electronic interaction with the sample, no significant photon emission from the sample could be detected. Even at the front surface, the majority of detected photons with energies above 10 eV originate from projectiles decaying directly behind the sample, as the attenuation is not sufficient to suppress these within 200-nm silicon.

These findings put some limits on low-energy PIXE and ionoluminescence techniques, e.g. when thinking of ultrathin or even 2D samples. At the same time, they open up possibilities to perform beam foil spectroscopy in exotic energy ranges of photons and projectiles, enabling insights on electronic interactions between ions and well-defined target systems.

ACKNOWLEDGMENTS

Accelerator operation is supported by the Swedish Research Council VR-RFI (Contract No. 2023-00155). C.F. acknowledges financial support from the DFG (CRC 1242 “Non Equilibrium Dynamics of Condensed Matter in the Time Domain”, Project No. 278162697) and from the Faculty of Physics.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX

The photon peak is well separated from peaks of any other particle species. For clarification, an extended ToF spectrum for 300 keV ^{22}Ne impinging in random geometry can be found in Fig. 7.

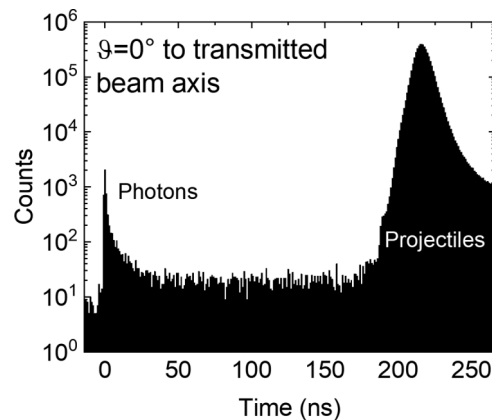


FIG. 7. Extended spectrum of 300 keV Ne transmitted through Si as shown in Fig. 3(b). Photons and transmitted projectiles are well separated.

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