

Study of the FLG transferring technique on grids and the particle angular scattering characteristics for next-generation space TOF instruments with higher mass resolution

PengHui Xu^{1,2}, JiJie Ma³, LingGao Kong^{3*}, AiBing Zhang^{1,2*}, WenJing Wang¹, and LiYuan Ma¹

¹National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China;

²University of Chinese Academy of Sciences, Beijing 100049, China;

³Institute of Science and Technology for Deep Space Exploration, Nanjing University, Suzhou Campus, Suzhou Jiangsu 215163, China

Key Points:

- An FLG transfer technique that reaches an optimal balance among minimal thickness, high graphene coverage, and increased grid open fraction was adapted for TOF system application.
- The FLG sample exhibited lower angular scattering (scattering half-angle: 1.33°–4.76°) than conventional amorphous carbon foils (scattering half-angle: 1.56°–11.02°).
- Findings demonstrate the potential of FLG for next-generation space plasma instruments and provide a foundation for further investigation.

Citation: Xu, P. H., Ma, J. J., Kong, L. G., Zhang, A. B., Wang, W. J., and Ma, L. Y. (2026). Study of the FLG transferring technique on grids and the particle angular scattering characteristics for next-generation space TOF instruments with higher mass resolution. *Earth Planet. Phys.*, 10(6), 1–13. <http://doi.org/10.26464/epp2026073>

Abstract: Carbon foils are widely used in time-of-flight (TOF, a measurement method that derives particle velocity from flight time over a defined spatial interval) mass spectrometers. Yet their accuracy is constrained by thickness-induced scattering and fragility. Atom-thick and possessing superior mechanical strength, graphene introduces less angular scattering and delivers improved mass resolution, thereby offering a compelling alternative for space-based TOF systems. Nonetheless, the application of graphene into such systems remains constrained by challenges in transferring it onto mesh grids, which is a key step for its integration into TOF systems. Hence, to achieve an optimal balance among minimal thickness, high graphene coverage, and a high grid open fraction, we optimized and adapted a graphene transfer technique suitable for space applications and successfully prepared several few-layer graphene (FLG, graphene with more than 3 atomic layers) samples using this technique. These samples, with 2 nm thickness, a grid open fraction of 40%, and a graphene coverage exceeding 95%, were subsequently irradiated with ion beams to characterize their angular scattering behavior, yielding half-width at half-maximum (HWHM) values and scattering half-angles. Computer simulation of the angular scattering experiment was also conducted to validate the experimental measurements. For FLG, scattering half-angles ranged from 1.33° to 4.76°. Under identical ion species and energy conditions, carbon foils exhibited scattering half-angles between 1.56° and 11.02°. These results indicate that FLG induces less angular scattering than carbon foils, thereby enhancing measurement accuracy in TOF systems. These findings demonstrate the potential of FLG for next-generation space plasma instruments and provide a foundation for further investigation. Further development of large-area (>1 × 1 cm) FLG transfer techniques is still recommended for practical space application.

Keywords: few-layer graphene (FLG); carbon foil; angular scattering characteristics; time-of-flight (TOF) system; space plasma instrumentation

1. Introduction

Amorphous carbon foils (CF) are widely utilized in space plasma detection and are integrated into many spacecraft-borne instruments, primarily for ion mass spectrometry and the detection of

energetic neutral atoms (ENAs) via time-of-flight (TOF, a measurement method that derives particle velocity from flight time over a defined spatial interval) measurements (Fuselier et al., 2009; McComas et al., 2009, 2017; Funsten et al., 2013; Delcourt et al., 2016). In TOF measurements, particle properties are derived from the flight time between a start and a stop signal, which are generated as ions or ENAs traverse a start foil and subsequently reach a detector. Research indicates that the thickness of carbon foils significantly affects the scattering angle distribution (Funsten et al., 1993) and energy loss (Allegrini et al., 2015b) in the ions and

First author: P. H. Xu, xupenghui19@mails.ucas.ac.cn

Correspondence to: L. G. Kong, lgkong@nju.edu.cn

A. B. Zhang, zhab@nssc.ac.cn

Received 16 JUN 2026; Accepted 03 AUG 2026.

First Published online 11 SEP 2026.

©2026 by Earth and Planetary Physics.

ENAs traversing the carbon foils. Increasing foil thickness leads to broader scattering angles, greater energy loss, and heightened energy straggling, all of which degrade the accuracy and resolution of TOF measurements. The typical nominal thickness of carbon foils is 0.5–2.0 $\mu\text{g}/\text{cm}^2$ (2.5–10 nm) (Allegrini et al., 2016). Although thinner foils could enable more precise TOF measurements, they are more fragile and not suitable for space applications (McComas et al., 2004). This trade-off between measurement performance and mechanical robustness fundamentally limits further optimization of TOF performance.

As a material with a two-dimensional (2D) lattice, graphene may become an ideal candidate for ultrathin TOF foils (Allegrini et al., 2016) because graphene achieves a significantly reduced thickness (0.34 nm per atom layer) (Novoselov et al., 2004) compared to conventional carbon foils. It has also been demonstrated that graphene exhibits substantial mechanical strength (Young's modulus: 1.0 ± 0.1 TPa) and elasticity (third-order elastic stiffness: -2.0 ± 0.4 TPa) (Lee et al., 2008), enabling it to withstand the vibrational stresses encountered during launch. These characteristics all contribute to the improvement of the TOF system's detection efficiency, making graphene a promising alternative to conventional carbon foils in TOF systems. To facilitate the application of graphene in TOF systems, a deeper comprehension of graphene's angular scattering characteristics is essential. Moreover, considering the different responses of graphene to particles with varying atomic numbers (Ebert et al., 2014; Allegrini et al., 2015a), investigations of angular scattering characteristics with multispecies particles would advance the application of graphene in space plasma instrumentation.

Similar to carbon foils, graphene should also be transferred onto mesh grids for integration into TOF systems. Mesh grids act as target substrates, with their grid lines providing structural reinforcement for the graphene layer. The graphene spanning the grid cells is self-suspended. Typically, such mesh grids require large cell apertures and a high open-area ratio to ensure the detection efficiency of the TOF system. However, increasing the grid cell aperture enlarges the suspended span of the self-suspended graphene, thereby promoting crack formation within the grid cells. This crack proliferation consequently harms the intactness of graphene across the mesh grid (Zeiger et al., 2019), which finally degrades the detection efficiency of TOF systems. In the field of graphene transfer, several efforts have focused on transferring graphene to TEM (Transmission Electron Microscope) grids. Yet the target substrates in these cases are either pre-coated with holey carbon films (Cho et al., 2014; Gonçalves et al., 2015; Zhang JC et al., 2017) or feature small cell apertures (Lee et al., 2016). The former effectively increases the overall thickness of graphene, whereas the latter decreases the open fraction of grids and thus the detection efficiency. Samples with such substrates are unsuitable for space applications. In the field of space applications, a limited number of researchers have attempted to produce mesh-supported graphene samples suitable for space applications. However, owing to the limitations of existing graphene transfer techniques, the transfer process in previous studies has mostly involved multiple transfer steps. In addition, the absence of material characterization in these studies, such as precise thick-

ness determination and coverage percentage examination, has rendered the actual status of graphene ambiguous, thereby undermining the validity of the results from graphene in particle scattering experiments. In 2014, Ebert et al. (2014) transferred 3–5 atom-layer graphene to 333 or 1000 lpi (lines per inch) nickel grids. In 2020, Vira et al. (2020) transferred 3-layer graphene to 2000 lpi nickel grids. Both studies relied on multiple transfer steps, which could introduce wrinkles and cracks, ultimately leading to nonuniformity in the graphene. Such structural defects compromise the intactness of the graphene and, in turn, diminish detection efficiency. On the other hand, although reducing the grid cell aperture facilitates the spanning of graphene across individual grid cells, it simultaneously lowers the open-area fraction of the mesh grid, thereby impairing overall detection performance. In 2019, Zeiger et al. (2019) transferred graphene to mesh grids whose cell aperture is 5 μm with a 9 μm pitch. Such grids, however, could block a significant proportion of particles during actual TOF measurements and thereby reduce the detection efficiency. In summary, existing graphene transfer techniques remain inadequate for meeting the detection efficiency requirements of TOF applications. Consequently, there is a clear need to develop a graphene transfer technique that achieves an improved balance among reduced graphene thickness, higher coverage percentage of graphene, and greater open fraction of grids.

Accordingly, we have optimized and adapted a graphene transfer technique and successfully prepared several few-layer graphene (FLG, graphene with more than 3 atomic layers) samples on copper grids for experimental evaluation. We further utilized these samples to investigate the particle angular scattering characteristics of various ions. An experiment was conducted to measure the angular scattering characteristics of FLG, complemented by computer simulations to verify the reliability of the experimental results. The angular scattering performance of FLG was compared with that of conventional carbon foils and with previously reported results, demonstrating the potential advantage of FLG for space TOF applications. Furthermore, strategies for optimizing the graphene transfer technique and signal detection in angular scattering experiments are discussed to support future investigations.

2. Graphene Transfer

Graphene transfer is the initial step of the experimental procedure and a critical part of sample preparation. Unlike continuous planar substrates such as glass or metal foils, grids offer a significantly reduced effective supporting area, making graphene more susceptible to damage due to insufficient adhesion. Therefore, transfer techniques must incorporate multiple strategies, including material selection and process optimization, to enhance adhesion between graphene and the grid lines, thereby preserving the intactness of graphene during and after the transfer process.

In terms of material selection, 6-atom-layer (~ 2.01 nm) FLG films were purchased from Chengdu Zhongke Times Nano Energy Tech Co., Ltd., which were synthesized by chemical vapor deposition (CVD) and spin-coated with poly(methyl methacrylate) (PMMA). Owing to the layer control technology of CVD (Liu HT and Liu YQ,

2017), the uncertainty in the number of graphene layers could be limited to ± 1 atom layer (Han J et al., 2016). The number of graphene layers is typically characterized by the Raman spectrum, and the intensity ratio of the G peak ($\sim 1580 \text{ cm}^{-1}$) to the 2D peak ($\sim 2700 \text{ cm}^{-1}$) serves as an indicator of the layer number (Ferrari et al., 2006). Figure 1 presents the Raman spectrum of the FLG used in this study, and the intensity ratio between these two peaks indicates that the FLG consists of 6 atomic layers. The 1500/2000 lpi copper TEM grids were selected as target substrates, which offer a satisfactory open fraction ($>40\%$ for 1500 lpi grids) and meet the requirements of space applications.

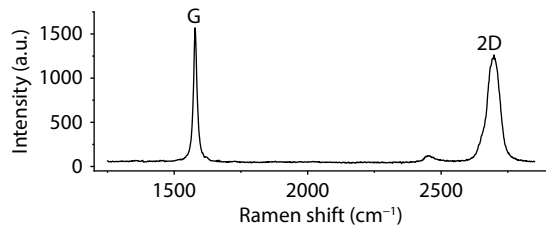


Figure 1. Raman spectrum of FLG. With the G peak ($\sim 1580 \text{ cm}^{-1}$) on the left and 2D peak ($\sim 2700 \text{ cm}^{-1}$) on the right, the intensity ratio of the two peaks indicates that the FLG has 6 atomic layers.

The transfer process is illustrated in Figure 2. FLG films coated with PMMA were first floated on ultrapure (UP) water and then transferred to TEM grids. No chemical etching or other solutions were used to remove the original copper substrate during this process, thereby minimizing contamination of the FLG samples. Insufficient chemical etching could contaminate FLG with oxidized metal particulates, which create more scattering process and subsequently degrade the angular scattering performance of FLG (Liang XL et al., 2011). After drying in air, samples were heated under vacuum to enhance the adhesion between FLG and copper grid lines (Song YQ et al., 2021). Finally, PMMA was removed by acetone vapor.

All FLG samples were inspected via optical microscopy (OM) to

check the percentage of coverage. Figure 3 presents a micrograph of a 1500 lpi FLG sample at 1000 $\times$ magnification. Because graphene materials are highly transparent (with an optical absorption of 2.3% per atom layer; Nair et al., 2008), SEM (Scanning Electron Microscope) characterization was additionally employed to corroborate the OM observations. Figure 4 displays an SEM micrograph of a 1500 lpi FLG sample. The region in Figure 4 is a representative area selected to estimate the overall coverage. In the SEM image, the cracks appear black, whereas the graphene-covered areas appear gray. The proportion of black area within grid cells was calculated to be 2.43%. Subsequently, based on OM observations, the overall condition of the sample is comparable to that of this representative region, so the estimated coverage percentage exceeds 95%. The checking results of the coverage percentage indicate good FLG coverage ($>95\%$). Compared with the relationship between the coverage percentage and the open fraction of grids from Zeiger et al. (2019), the checking results demonstrate that our graphene transfer technique reaches a better balance among reduced thickness, higher coverage percentage of FLG, and higher open fraction of grids. The relationship reported by Zeiger et al. (2019) reveals an empirical limit between the coverage percentage of FLG and the open fraction of grids at a given FLG thickness, both of which influence the detection efficiency of TOF systems. The boundary of the limit expands with increasing FLG thickness. However, thicker FLG compromises angular scattering performance and, consequently, the mass resolution of TOF systems. Despite the theoretical minimum thickness of graphene being 0.34 nm (1 atomic layer), an appropriate compromise in FLG thickness remains necessary to achieve an optimal balance among FLG thickness, coverage percentage, and open fraction of grids, thereby facilitating the application of FLG into TOF systems.

3. Angular Scattering Testing Setups

After the graphene transfer, the angular scattering experiment was conducted to evaluate FLG particle scattering performance. At the same time, covered by carbon foils with a $0.7 \mu\text{g}/\text{cm}^2$

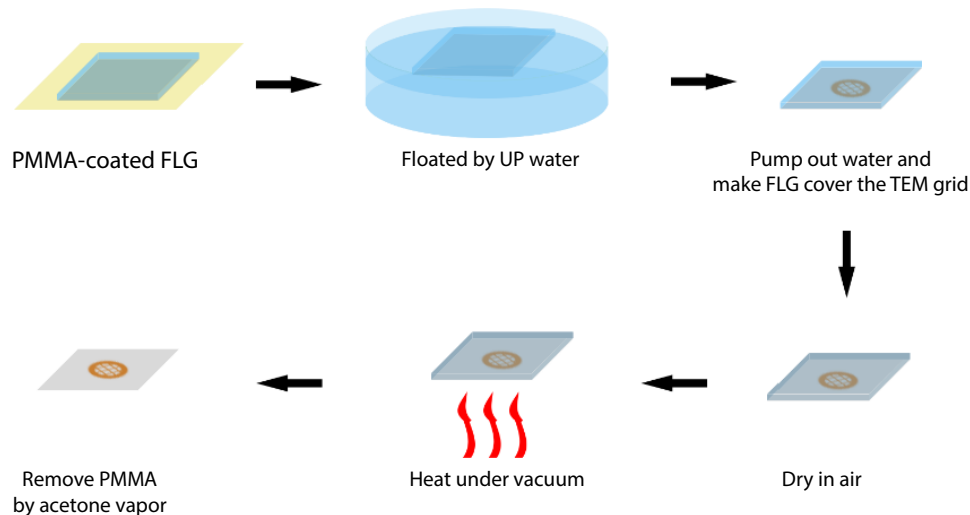


Figure 2. FLG transfer process. The gray membrane represents FLG, the pale blue membrane on the FLG represents PMMA, and the orange circular grid represents the TEM grid as a target substrate.

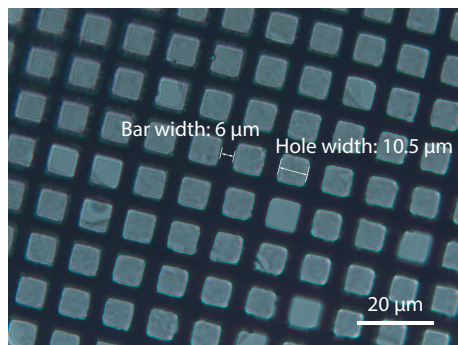


Figure 3. OM photo of an FLG sample. The grid cells with misty black shadows are covered with FLG, whereas more transparent grid cells are not.

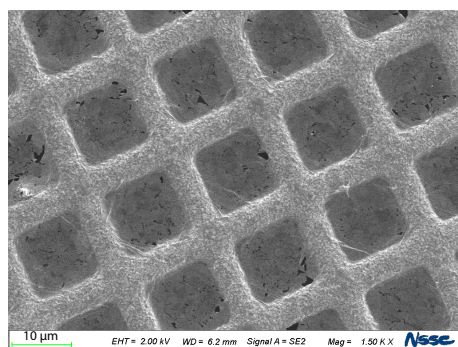


Figure 4. SEM photo of an FLG sample. The rough grid lines appear in light gray and the grid cells covered with FLG appear in dark gray. Some black holes in the grid cell are cracks on FLG.

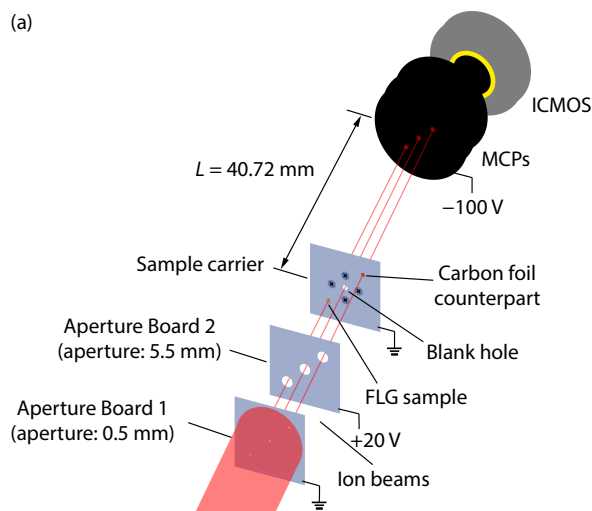
(3.5–5.0 nm) nominal thickness, some carbon foil counterparts were also prepared for comparison, whose grids were the same as those of the corresponding FLG samples. The FLG sample and the carbon foil counterpart were both subjected to the angular scattering measurements.

Experimental testing of angular scattering was performed in the

CALibration System of Space Plasma Instrument (CASSPI) at the National Space Science Center (NSSC), Chinese Academy of Sciences (CAS). Figure 5 illustrates the experimental apparatus inside the vacuum chamber. In vacuum of 1.6×10^{-4} Pa, incident ion beams were generated by an ion source capable of producing multiple ion species, including H^+ , N^+ , and Ar^+ , across a range of incident energies. The ion source delivered a beam with a scattering half-angle of 1° and an energy straggling of 2%. Relevant experimental parameters and configurations, such as installation positions and voltages, were adopted with reference to the work of Vira et al. (2020).

The apparatus system was designed for the detection of ion beams transmitted through FLG and carbon foils. It consisted of the mechanical part and the detector. The mechanical part secured the samples and detector, incorporating aperture boards and a shield. The detector, responsible for signal acquisition, included MCPs (MicroChannel Plates) and an ICMOS (Intensified Complementary Metal Oxide Semiconductor). Positioned along the beam path between the ion source and the first MCP were three plates: Aperture Board 1 (AB1), Aperture Board 2 (AB2), and Sample Carrier (SC). AB1, with a 0.5 mm aperture, served to limit ion flux and align the beam, whereas AB2, featuring a 5.5 mm aperture, was placed to suppress secondary electrons emitted from AB1 and the SC. The SC was designed with three holes, each spaced at least 20 mm apart to prevent cross-contamination. Two of these holes held an FLG sample and a carbon foil counterpart, respectively, whereas the third remained empty as a blank aperture. A shield structure was installed between the SC and the first MCP to reduce background noise originating from the ion source and the apparatus system. The contribution to scattering from the TEM grids themselves was confirmed to be negligible, as established in prior references and corroborated by similar tests conducted earlier.

Regarding electrical configuration, AB1 and the SC were grounded, whereas AB2 was biased to +20 V. The front surface of the MCP was maintained at -100 V to suppress secondary elec-



(b)

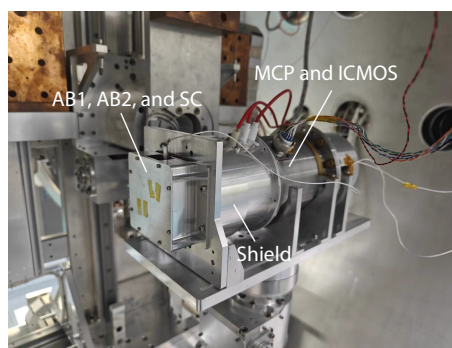


Figure 5. The apparatus system in the vacuum container. Panel (a) illustrates the internal structure of the apparatus system, and panel (b) shows a real photo of the apparatus system.

trons. The distance (L) between the SC and the front face of the MCP was 40.72 ± 0.26 mm. Placed behind the MCP, an IC MOS captured and recorded grayscale images with a spatial resolution of 0.110 mm/pixel. The grayscale image represented the positional distribution of ion flux. Upon striking the MCP, scattered ions generated electrons, which subsequently produced photons captured by the IC MOS. Consequently, the grayscale at each pixel corresponds to the local ion flux.

4. Data Analysis

Figure 6 illustrates the complete workflow of the data analysis. The original grayscale images were captured by IC MOS during each measurement. Firstly, background is removed from these grayscale images. Then these images were converted to the ion flux distributions. A total of 100 ion flux distributions were then averaged to one distribution for diminishing the instability of the ion source and the detector. After that, regions of signal spots in the distribution image were extracted in an adequate size. The pixel signals of these regions were then summarized to the x - or y -axis for fitting. The overexposed pixels were removed before fitting for a better signal recognition. Last, Gaussian fitting was introduced to fit the distribution of pixels and obtain the results, which were displayed in the form of half-width at half maximum (HWHM) and scattering half-angles.

Signals produced by incident H^+ , N^+ , and Ar^+ beams at incident energies of 5, 10, 15, and 20 keV were acquired and recorded as grayscale images by the IC MOS. Figure 7 presents a representative grayscale image, using 20 keV Ar^+ as an example. The upper subplot shows the original grayscale map, with a linear color scale representing the signal intensity distribution. Three regions (b, c, and d) with bright spots are identified for comparison. The bottom-left one (b) corresponds to the FLG, the central one (c) to the blank aperture, and the top-right one (d) to the carbon foil. Region (e) serves as a background noise reference. The four lower contour maps illustrate the grayscale distributions of regions (b)–(e), with exponential color bars. Because the ion flux used in the experiment is large, the IC MOS may be overexposed in the

center area of the region, which is shown in dark red in the contour maps of Figure 7. Those surrounding pixels affected by scattered ions appear in cyan. In contrast, the region without signals, such as region (e), is colored mainly in blue. Compared to region (c), the central overexposed areas of (b) and (d) are reduced, whereas their surrounding scattering-induced areas are larger and exhibit higher intensity. These observations indicate that the ion beam successfully penetrated and scattered from both the FLG and the carbon foil.

Angular scattering characteristics were derived from the distribution of ion counts. Because the grayscale value of a pixel is not linearly proportional to the ion counts at that pixel (Li LS et al., 2016), each grayscale image was converted into a ion flux distribution image, where the flux is directly proportional to ion counts.

Using a calibration method similar to that used by Li LS et al. (2016), a calibration experiment of the detector was carried out to establish the relationship between ion flux and grayscale. With the corresponding ion flux measured by a Faraday cup, the grayscale images can be converted to ion flux distributions according to the calibration results. The total ion flux in the effective image region was divided by the effective pixel number to derive the ion flux per pixel. The relationship between ion flux and grayscale follows a logarithmic function, which is fitted based on experimental grayscale calibration data. The logarithmic relationship is presented in Figure 8. And the expression of the relationship between the per-pixel ion flux (I_f) and the grayscale value (G_s) is

$$G_s = 14.235 \ln(I_f + 0.074) + 36.124. \quad (1)$$

To mitigate the effects of flux instability from the ion source, each distribution image for analysis was averaged over 100 original distribution images. Similar to Figure 7, each averaged image presented three distinct spots corresponding to the blank aperture, the FLG sample, and the carbon foil counterpart. Each spot was extracted as a region of interest within a 200×200 pixel window for fitting because an inadequate size of the selected region could degrade the fitting results of the signal (Nicolaou et

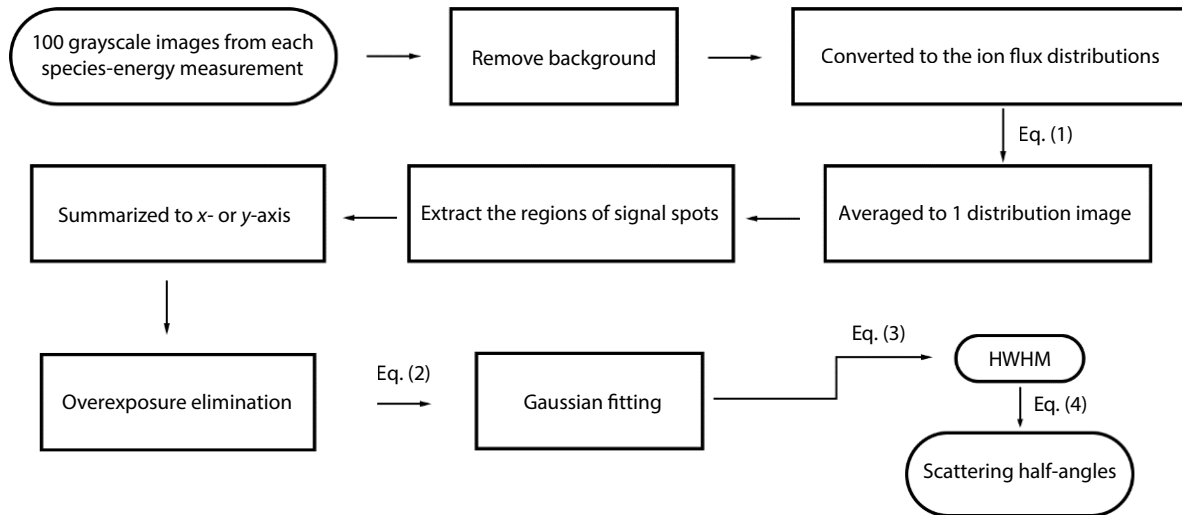


Figure 6. Workflow of data analysis. After several steps of data analysis, HWHM and scattering half-angles were derived from the original grayscale images.

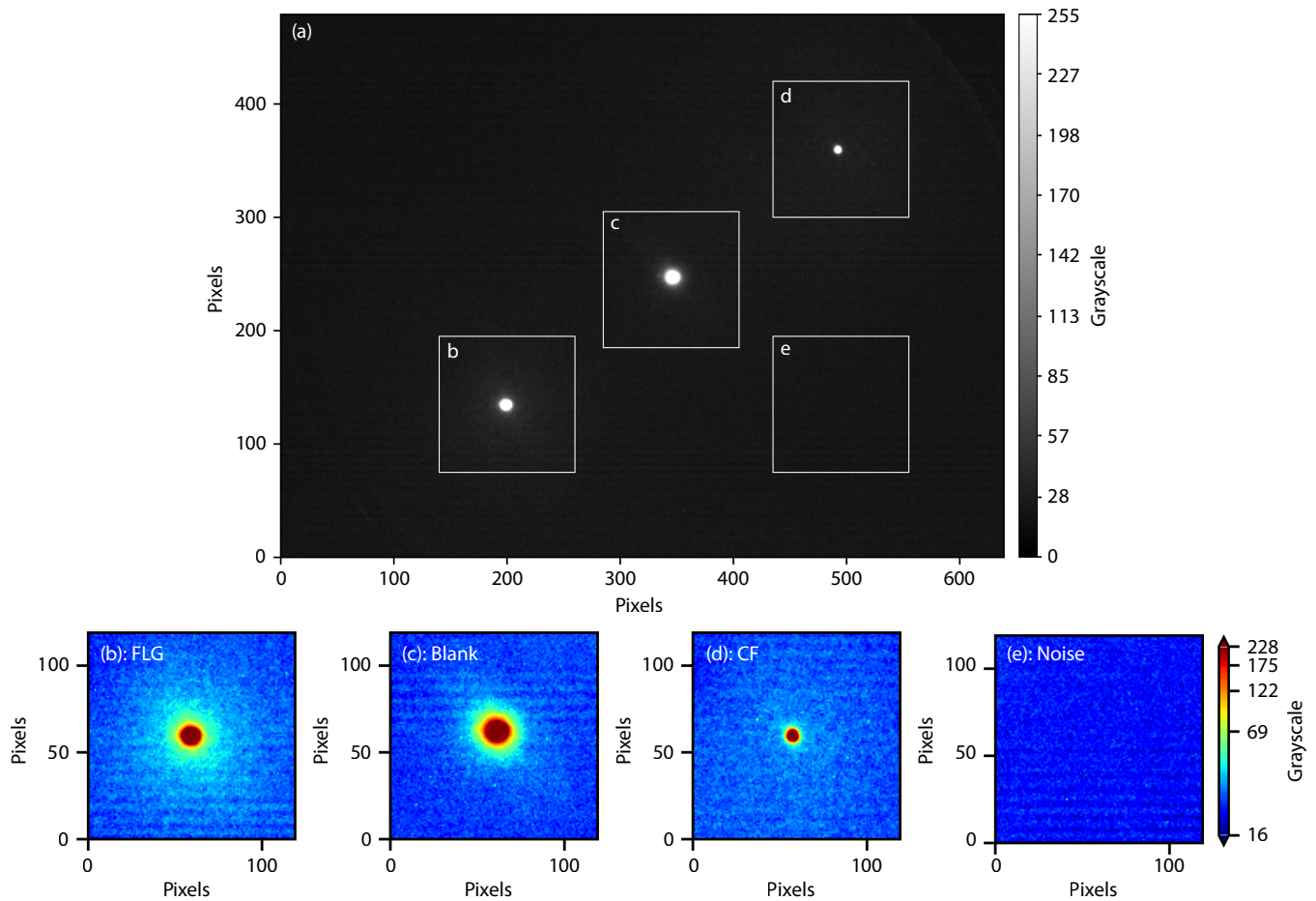


Figure 7. An original grayscale image and its contour subplots. Panel (a) displays an original grayscale image of 20 keV Ar⁺, with a linear color bar. Panels (b)–(e) present the contour maps of regions (b)–(e), which correspond to the signals from FLG, blank aperture, the carbon foil, and background noise, respectively. The color bars in panels (b)–(e) are in exponential forms. The exposed area in regions (b)–(d) are colored in dark red, whereas the surrounding pixels affected by scattered ions are colored in cyan. Regions (b) and (d) show more scattering-induced areas than region (c), which indicate that the ion beam penetrated and scattered from FLG and the carbon foil.

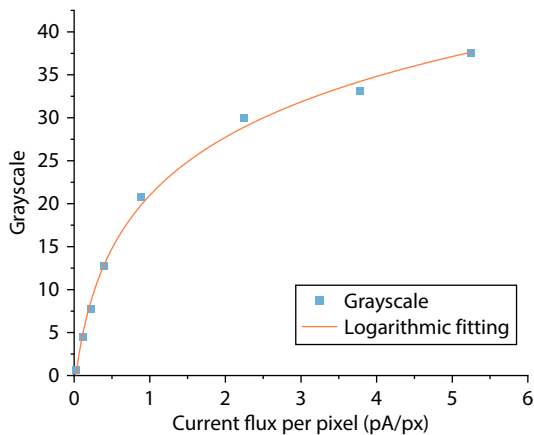


Figure 8. Logarithmic relationship of the ion flux and the grayscale. The blue dots are the measured grayscales at the corresponding ion flux, and the orange curve is the logarithmic fitting result.

al., 2022).

The distribution image of the ion flux in the cropped region was

then summarized to the x - and y -axes, respectively, for Gaussian fitting. Before Gaussian fitting, however, some overexposed pixels needed to be eliminated. Overexposure resulted from perpendicular ions that experienced minimal scattering after traversing the FLG or carbon foil owing to the very high incident flux (Allegrini et al., 2026). The flux used in this experiment was substantially greater than in comparable studies (Lüthi, 2003; Holeňák et al., 2021) owing to the sensitivity requirements of the ICMOS. The ion flux at the pixels of the overexposed parts would be exponentially amplified through the logarithmic relationship between ion flux and grayscale, which would obscure the true distribution of scattered ions. Consequently, pixels with flux exceeding the physically realistic range, which were 4–5 orders of magnitudes larger than that of the adjacent pixels, were identified and excluded to preserve the reliability of the Gaussian fitting. Figure 9 presents a sample that exhibits the effect of the overexposure elimination process. In the grayscale image, the central region of peak brightness corresponds to the overexposed area. The portion bounded by the two blue lines represents the corresponding region in the summarized x -axis or y -axis projection. Following overexposure elimination, these affected segments are excluded prior to Gaus-

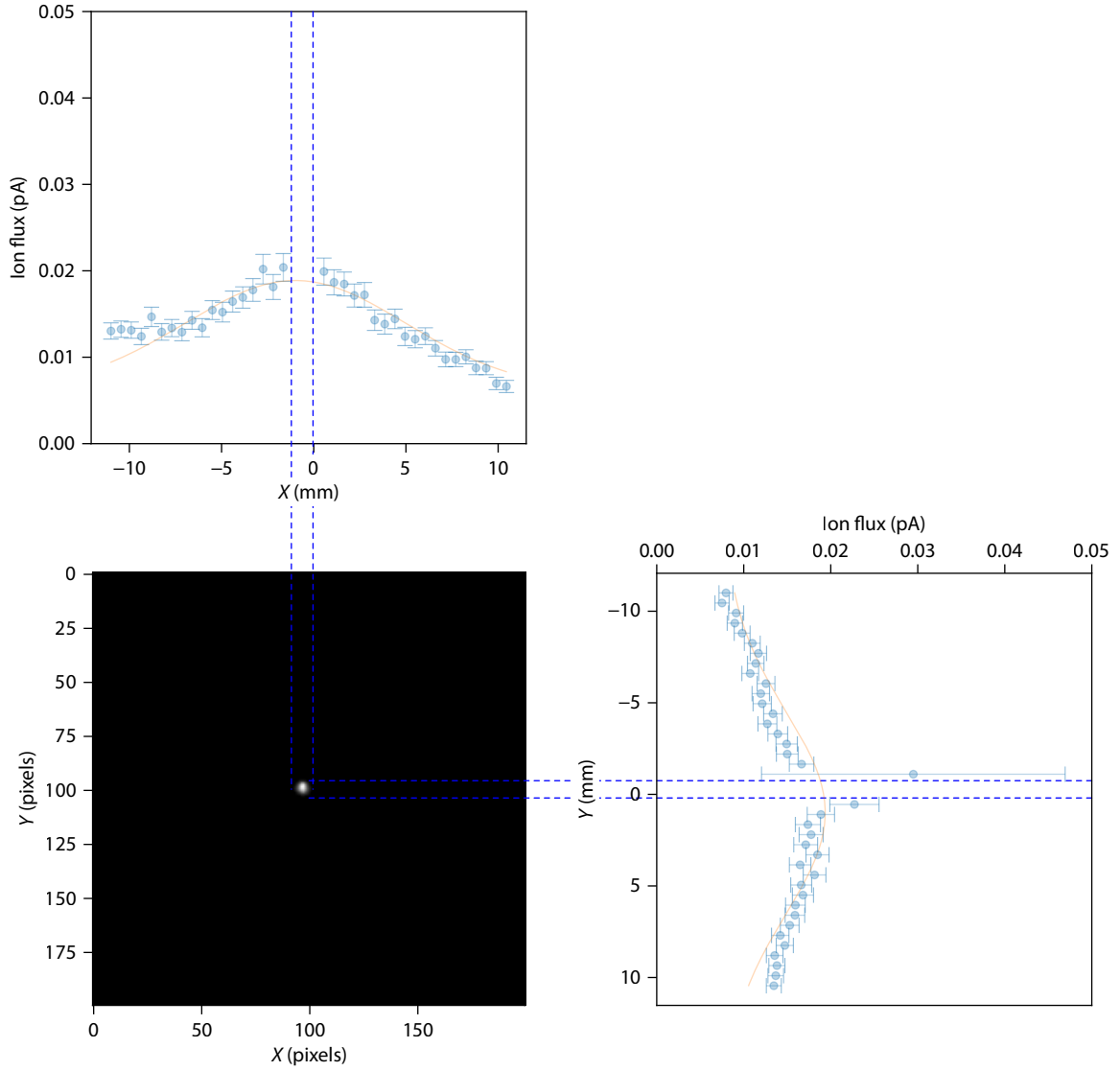


Figure 9. Sample of grayscale images and fitting results from the experiment. The lower-left panel shows the original grayscale image of a signal. The upper-left and the lower-right panels demonstrate the x- and y-axis axes projections, respectively. The blue dots with vertical error bars represent the ion flux on each pixel, and the orange curves are the fitting results. The pixels between the deep blue lines are removed in the overexposure elimination procedure, and these pixels adequately correspond to the overexposed region in the grayscale image.

sian fitting. The orange curve depicts the Gaussian fit obtained after overexposure elimination, demonstrating that the lower-intensity, broader components of the signal are well captured by the fitting procedure. To assess the validity of the overexposure elimination procedure, we quantified the removed pixels and converted these counts to a spatial width using the system resolution. The resulting width ranged from 0.77 mm to 1.5 mm. Considering the 0.5 mm aperture of the AB1 plate, the 2 mm sample diameter, and inherent resolution-related measurement uncertainty, the removed width of 0.77–1.5 mm did not significantly affect the reliability of the fitting results.

The Gaussian fitting was introduced to determine the radius of the ion scattering distribution (Vira et al., 2020). The Gaussian function for fitting could be described as

$$f(x) = Ae^{-\frac{(x-x_0)^2}{2\sigma_x^2}} + B, \quad (2)$$

where x_0 was the center of signal spots and σ_x was related to the radius of the ion scattering distribution. The HWHM from the Gaussian fitting results was regarded as the radius of the ion scattering distribution, which could be calculated by

$$r(\text{HWHM}) = \sqrt{2\ln 2}\sigma_x. \quad (3)$$

Scattering half-angles ($\varphi_{1/2}$) could be calculated by

$$\varphi_{\frac{1}{2}} = \arctan\left(\frac{r}{L}\right), \quad (4)$$

where r was the HWHM from the Gaussian fitting results, and L was the distance between the SC and the front face of the first MCP (40.72 mm).

The uncertainty in the HWHM arose from two components: the uncertainty inherent in the fitting procedure and the uncertainty associated with the spatial resolution of the detection system. The

uncertainty in the HWHM (σ_r) could be described as

$$\sigma_r = \sqrt{\sigma_{\text{fitting}}^2 + \sigma_{\text{resolution}}^2}, \quad (5)$$

where σ_{fitting} was the uncertainty from Gaussian fitting (on the basis of a 95% confidence interval), and $\sigma_{\text{resolution}}$ was the uncertainty from the spatial resolution, which was a constant value (0.055 mm for H^+ and 0.275 mm for N^+ and Ar^+). The σ_{fitting} included the uncertainties of the instability of the ion source and the detector sensitivity, which can be represented by the uncertainty of the ion flux. The uncertainty of the ion flux on each pixel had been calculated at the average procedure of 100 distribution images and had been given to the fitting process as an important parameter. The uncertainty in the scattering half-angle ($\sigma_{\varphi_{1/2}}$) was derived from the uncertainty in the HWHM through standard error propagation. The corresponding expression was

$$\sigma_{\varphi_{1/2}} = \frac{\frac{r}{L} \sqrt{\left(\frac{\sigma_r}{r}\right)^2 + \left(\frac{\sigma_L}{L}\right)^2}}{1 + \left(\frac{r}{L}\right)^2}, \quad (6)$$

where σ_L was the uncertainty of L and was a constant value mentioned above (0.26 mm). The r , L , and σ_r were the same as those in Equation (4) and Equation (5).

5. Results

Results of the data analysis are shown in the form of HWHM and scattering half-angles of various ions at different incident energies.

5.1 HWHM

HWHM is the radius of the positional distribution on the MCP and quantifies the degree of scattering induced by FLG or carbon foils. Results from the HWHM are displayed in Figure 10. Data are absent at certain incident energies owing to the lack of analyzable signals in the corresponding grayscale images. As shown in Figure 10, HWHM exhibits a negative correlation with incident energy and a positive correlation with atomic number, consistent with both experimental and simulated datasets. In comparison with carbon foils, FLG yields generally smaller HWHM values with reduced uncertainty, indicating that FLG induces less scattering than carbon foils when ions traverse the material.

To verify the effectiveness of the overexposure elimination, a simulation of the experiment was performed. The simulation model replicated the apparatus system described in the experimental setup. Two software packages were employed: SRIM (Ziegler et al., 2010) for simulating ion-foil interactions and SIMION (Dahl, 2000) for computing particle trajectories within the

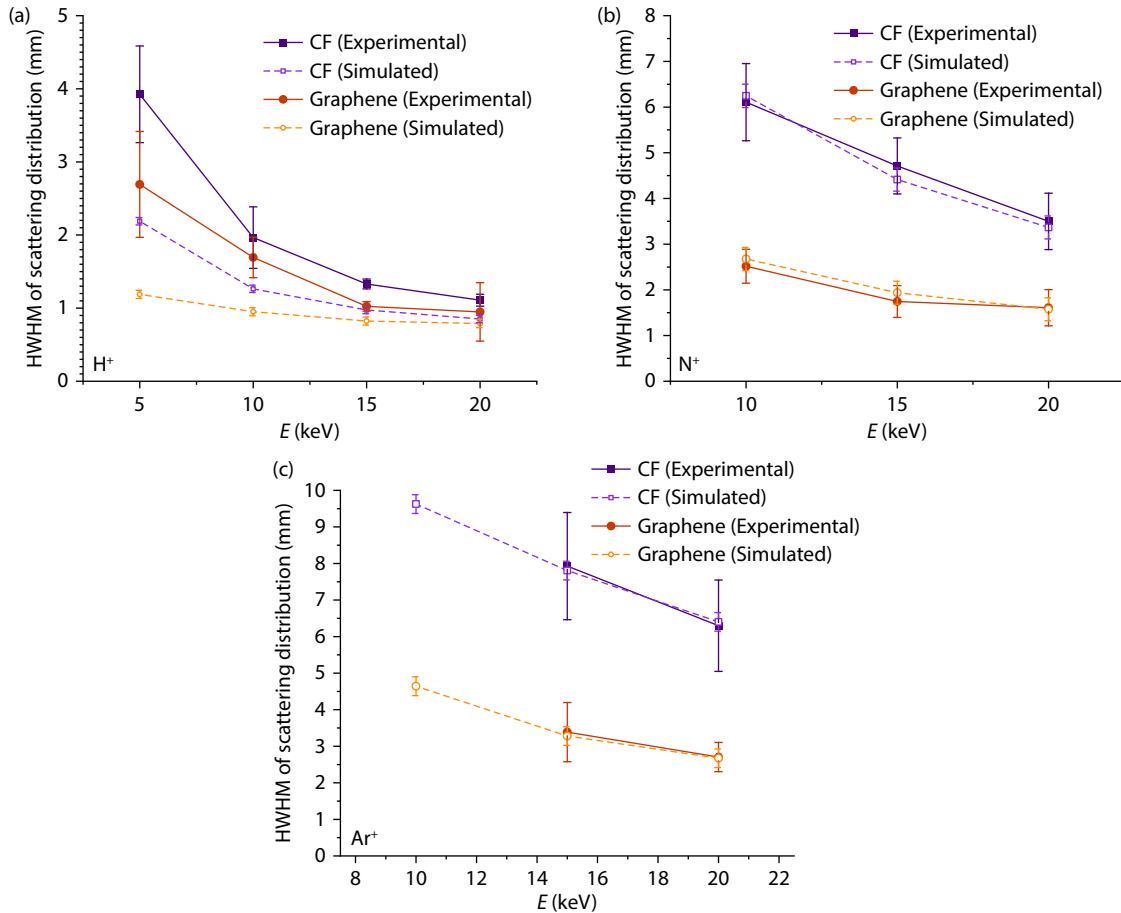


Figure 10. HWHM of FLG and carbon foils. All experimental results are noted by solid dots, whereas all simulated results are noted by hollow dots. Results from carbon foils are colored in purple and results from FLG are colored in orange. Panel (a) displays the results of H^+ , panel (b) displays the results of N^+ , and panel (c) displays the results of Ar^+ .

electrostatic fields of the system. The simulation approach followed a methodology established in prior work (Xu PH et al., 2025) focusing on a scenario similar to the experiment described above. First, SRIM was configured with the incident ion energy, ion species, foil thickness, and foil material. After SRIM execution, its output data were converted into input files for SIMION, into which the geometry and electric fields of the experimental apparatus had already been imported. The output of SRIM includes the transmitted position, the residual energy, and the velocity vector of ions, which are converted to the start position, the energy, the azimuth angle, and the elevation angle of ions, as the input of SIMION. SIMION then completed the simulation by tracking ion trajectories and recording their impact positions on the MCP. Finally, the positional distributions of ions striking the MCP were collected and processed using the same data analysis routine. The simulated HWHM values are included in Figure 10. The simulation results show statistical agreement with the experimental data, confirming the validity of the overexposure elimination procedure.

It is notable, however, that the experimental HWHM for H^+ is systematically larger than the simulated value. According to Equation (3), HWHM is derived from σ_x obtained via Gaussian fitting. To evaluate the fitting reliability, we normalized both the experimental and simulated results and plotted them together for direct display. Figure 11 presents such a display for 5 keV H^+ for carbon foil and 20 keV Ar^+ for FLG, respectively. In this figure, the blue and green dots denote the experimental and simulated data, respectively, whereas the orange and golden curves represent their corresponding Gaussian fits. A noticeable discrepancy between the simulation and experiment is observed for H^+ . The deviation of the experimental and simulated results could be caused by several effects. First, the existing simulation method may inadequately capture the actual physical processes governing H^+ transmission through the foil. Second, the overexposure elimination procedure disproportionately affects peak shape recognition when the HWHM is small, as is the case with H^+ . Moreover, the simulation of the experiment is operated without background

noise, which is not negligible in the real signal detection. The background noise with a high intensity degrades the accuracy of the fitting parameters (Nicolaou et al., 2022). Considering the finite resolution of the ICMOS, these effects amplify the discrepancy between the experiment and simulation, particularly for H^+ .

5.2 Scattering Half-angles

Scattering half-angles were calculated from HWHM using Equation (4), providing a direct measure of the angular deflection of transmitted ions. Results of scattering half-angles are presented in Figure 12. As shown in Figure 12, scattering half-angles exhibit a negative correlation with incident ion energy and a positive correlation with atomic number. Overall, scattering half-angles induced by FLG are consistently smaller than those produced by carbon foils, but the difference between FLG and carbon foils becomes more pronounced at lower incident energies and for ions with higher atomic numbers. Specifically, for H^+ , scattering half-angles of FLG range from 1.33° to 3.78° , whereas those of carbon foil range from 1.59° to 5.51° . For N^+ , FLG causes 2.26 – 3.54° scattering half-angles, whereas carbon foil causes 4.91 – 8.53° . For Ar^+ , scattering half-angles of FLG are 3.80 – 4.76° , and those of carbon foil are 8.79 – 11.02° .

Moreover, the influences of ion source divergence have been excluded by analyzing signals from the blank aperture. Signals from the blank aperture indicate the condition of incident ion beams at the FLG and the carbon foil, which mainly come from the influence of ion source divergence. By the convolution of Gaussian fitting, the contribution of ion source divergence in scattering half-angles of FLG and the carbon foil is less than 0.068° , which is smaller than the measured scattering half-angles by 2 orders of magnitude and could be negligible.

Our results were further compared with those reported in Ebert et al. (2014) and Vira et al. (2020), as also included in Figure 12. Generally, all these results are consistent with each other. In Ebert et al. (2014), FLG has two different thicknesses: 3–5 atom layers (1.01–1.68 nm) and $2 \times (3\text{--}5)$ atom layers (2.01–3.35 nm), which

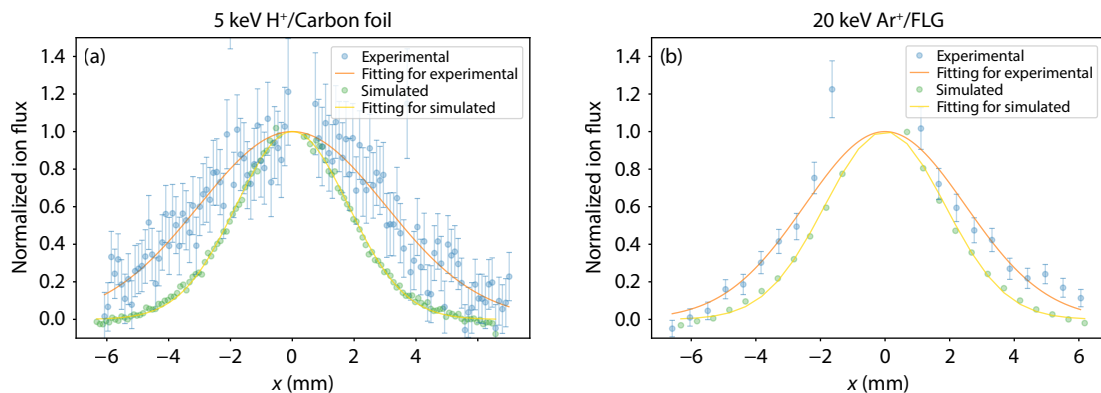


Figure 11. Normalized experimental and simulated fitting results of 5 keV H^+ and 20 keV Ar^+ . The experimental pixels are noted in light blue dots with error bars, whereas the simulated pixels are noted in light green dots. The fitting results of the experimental and simulated pixels are drawn in orange and gold, respectively. All elements in the same panel are normalized to the same coordinates. Panel (a) shows the fitting results of 5 keV H^+ from the carbon foil, and panel (b) displays the fitting results of 20 keV Ar^+ from FLG. Because the HWHMs of H^+ are lower than those of other ions, some effects amplify the discrepancy between the experiment and simulation.

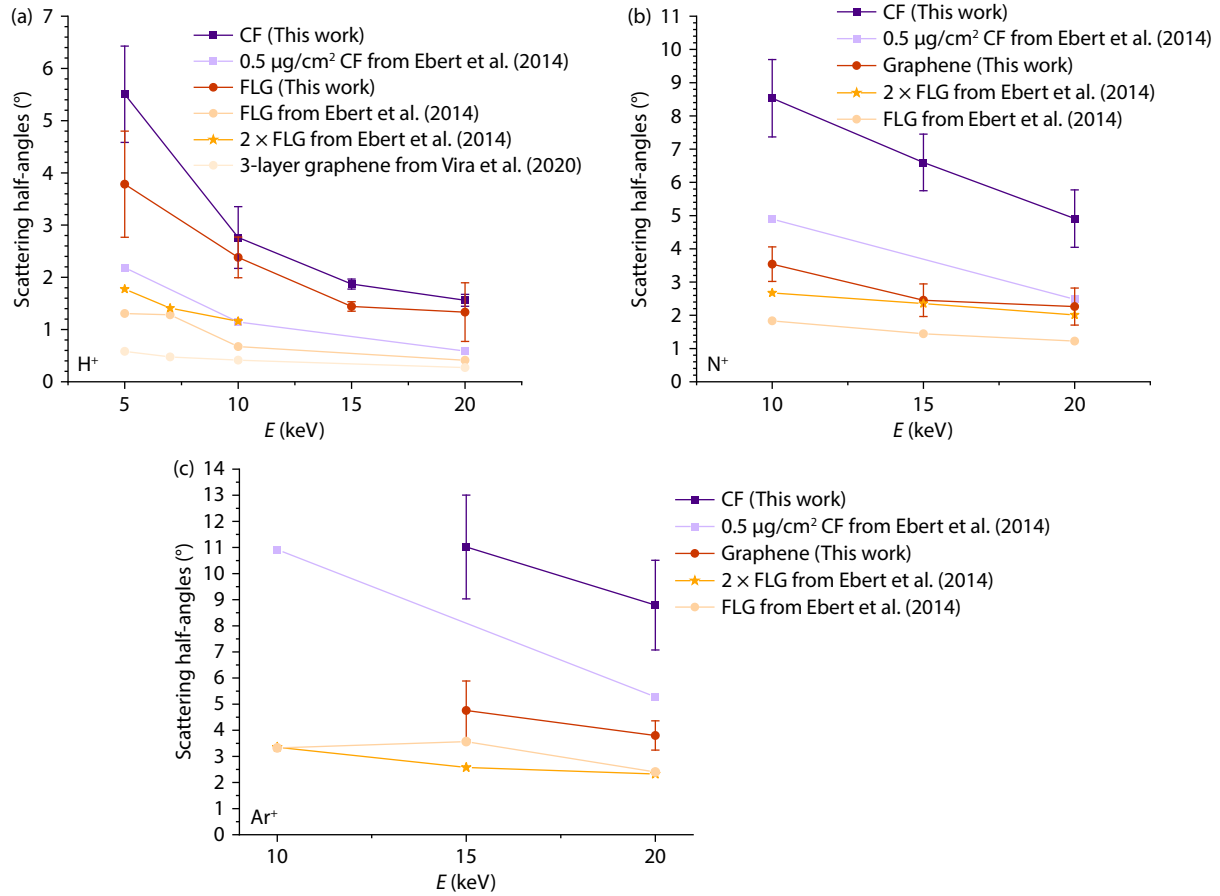


Figure 12. Scattering half-angles of FLG and carbon foils. Results of carbon foils and FLG from this work are noted in dark purple and dark orange, respectively. Results from Ebert et al. (2014) are noted in light purple, gold, and apricot for 0.5 $\mu\text{g}/\text{cm}^2$ carbon foil, 2 $\times$ FLG, and FLG, respectively. And results from Vira et al. (2020) are noted in pale orange.

are respectively noted as FLG and 2 $\times$ FLG. And the nominal thickness of carbon foils is 0.5 $\mu\text{g}/\text{cm}^2$. Our FLG results are similar to the results of 2 $\times$ FLG in Ebert et al. (2014), and our carbon foil (0.7 $\mu\text{g}/\text{cm}^2$) results are slightly larger than those in Ebert et al. (2014). This discrepancy can be explained by differences in foil thickness because thicker carbon foils generally induce greater angular scattering. In Vira et al. (2020), the thickness of graphene is 3 atom layers (~ 1.01 nm). Results in Vira et al. (2020) are lower than ours, and those in Ebert et al. (2014) are consistent with theoretical expectations that reduced thickness leads to smaller angular scattering.

To account for variations in thickness and energy, previous investigations have commonly adopted the foil constant (k_F) to evaluate the consistency of scattering half-angles measured under differing experimental conditions. According to Meyer (1971), Høgborg et al. (1970), and Funsten III et al. (1993), the foil constant (k_F) could be described as:

$$k_F = \varphi_{1/2} \cdot E, \quad (7)$$

where E is the ions' incident energy and $\varphi_{1/2}$ is the scattering half-angle. The k_F is fixed for a given combination of foil component and incident ion species and is proportional to the nominal thickness of the foil (Allegrini et al., 2026):

$$k_F \propto Nd, \quad (8)$$

where d is the thickness of the foil and N is the density of the foil. When the incident energy of ions is given, the theoretical prediction of the scattering half-angles in this paper could be derived from the scattering half-angles in previous studies. The predicted scattering half-angles ($\varphi_{1/2,p}$) in this paper could be defined as:

$$\varphi_{1/2,p} = \frac{k_{F,m}}{k_{F,r}} \varphi_{1/2,r} = \frac{N_m d_m}{N_r d_r} \varphi_{1/2,r} \quad (9)$$

where $k_{F,m}$ is the k_F of measured results, $k_{F,r}$ is the k_F of references, $\varphi_{1/2,r}$ is the scattering half-angles in references, N_m is the density of our foils, d_m is the thickness of our foils, N_r is the density of foils from references, and d_r is the thickness of foils from references. If the foil material is the same ($N_m = N_r$), Equation (9) could be written in

$$\varphi_{1/2,p} = \frac{d_m}{d_r} \varphi_{1/2,r}. \quad (10)$$

Combining with the scattering half-angles in Ebert et al. (2014) and Vira et al. (2020), Equation (10) could be used to obtain the predicted scattering half-angles as the theoretical prediction, excluding the influence of foil thickness in measured scattering half-angles. Figure 13 presents the predicted scattering half-angles and the measured scattering half-angles of our FLG and

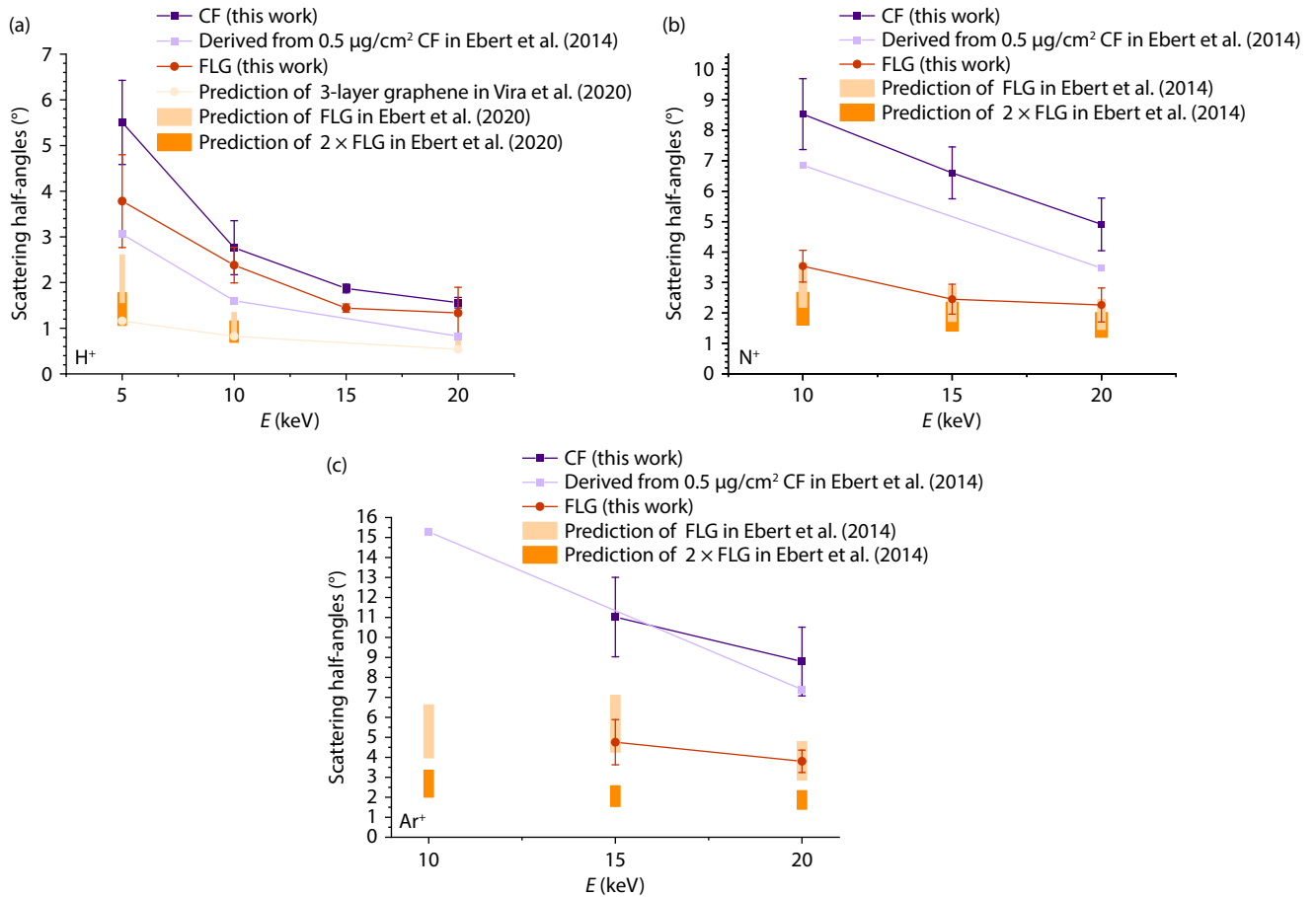


Figure 13. The predicted scattering half-angles and the measured scattering half-angles of our FLG and carbon foil. Results from the measurement of FLG and the carbon foil are still noted in dark purple and dark orange symbols with error bars, respectively. Results derived from 0.5 μg/cm² carbon foils in Ebert et al. are noted in light purple symbols. Results derived from FLG in Ebert et al. are noted in solid apricot floating columns. Results derived from 2 × FLG in Ebert et al. are noted in hollow gold floating columns. And results derived from 3-layer graphene in Vira et al. are noted in pale orange.

carbon foil.

Generally, considering different experimental conditions, the measured scattering half-angles of this work remain consistent with the predicted scattering half-angles. However, the measured scattering half-angles from H⁺ are systematically larger than the predicted scattering half-angles. The larger values observed for H⁺ arise from the propagation of HWHM deviation, which originates from the discussion in the last paragraph of Section 5.1 and subsequently influences the H⁺ results in Figure 13 through Equations (3), (4), and (10).

6. Discussion

Results of this study have already demonstrated the superiority of FLG over carbon foils in terms of angular scattering characteristics. However, it is still necessary to undertake further investigations, such as the optimization of the graphene transfer process and the improvement of signal detection.

6.1 Optimization of Graphene Transfer Process

Although our graphene transfer technique achieves an improved balance among three key factors (reduced graphene thickness,

higher coverage percentage of graphene, and higher open fraction of grids), the FLG samples described above remain unsuitable for direct space applications because of their limited size on the grid support. Our FLG samples feature a circular mesh area with a diameter of 2 mm (~0.03 cm² in area). For reference, carbon foil samples employed in space instrumentation typically exceed 1 cm² in area. For example, some typical sizes of carbon foils appear in 4 × 15 mm, 4 × 80 mm, and 10 × 16 mm (Allegri et al., 2016). Scaling FLG samples to a comparable size is essential for advancing detection efficiency in practical implementations. The area of FLG samples is proportional to the sensitivity of the TOF systems (Wüest et al., 2007). That means the TOF sensitivity can be increased by ~30 times with a 1 cm² foil sample.

In terms of thickness, 6 atomic layers is still considered relatively thick for FLG because the upper boundary of FLG is typically defined as 10 atomic layers (Sun et al., 2018). Preliminary attempts in our study have demonstrated that our transfer method is also applicable to three-atomic-layer graphene, indicating its potential for handling thinner materials. According to the simulation by SRIM, the lowest incident energy for transmitting the graphene would decrease from ~90 eV to ~40 eV if the atomic

layer of graphene is reduced from 6 to 3. The simulation also indicates that thinner graphene has less energy loss and straggling. Therefore, further refinement of the transfer technique will be required to achieve even fewer atom layers of graphene.

6.2 Improvement of Signal Detection

The reliability of results on angular scattering characteristics depends on data quality, which is reflected in the uncertainty of the HWHM. Lower uncertainty corresponds to better data quality. As expressed in Equation (5), the uncertainty in HWHM originates from two primary sources: the intrinsic resolution of the measurement system and the uncertainties introduced during image fitting. Furthermore, when the uncertainty in HWHM numerically approaches one of these contributing factors, that factor can be identified as the dominant source. If measurement resolution is the primary contributor, future efforts to improve signal detection should concentrate on enhancing imaging resolution. Conversely, if image fitting uncertainty dominates, attention should shift toward increasing the instrument's sensitivity to weak signals. A large fitting uncertainty indicates that the data analysis process struggles to reliably identify valid signals, indicating the need for improved detector sensitivity to compensate for the limitations of the fitting procedure.

The dominant source of HWHM uncertainty varies with ion species, leading to distinct strategies for improving signal detection tailored to each ion species. For H^+ ions, the uncertainty in HWHM is more closely associated with the $\sigma_{\text{resolution}}$ (0.055 mm), indicating that the measurement error is fundamentally limited by instrumental resolution. In contrast, for N^+ and Ar^+ ions, the HWHM uncertainty (ranging from 0.349 to 1.465 mm) is closer to the fitting standard deviation (ranging from 0.214 to 1.439 mm correspondingly), implying that the error arises mainly from limitations in fitting quality. This suggests that effective signals for N^+ and Ar^+ are weaker and more difficult to detect than those for H^+ . Comparison with the simulation further supports this interpretation. In simulations, all signals are intrinsically effective, so the limit of the uncertainty in HWHM is dominated by the resolution of the xy coordinate grids (0.100 mm for H^+ and 0.500 mm for N^+ and Ar^+ in the simulation). These findings indicate that improving the resolution of the detector would enhance measurements of H^+ signals, whereas increasing detector sensitivity would benefit measurements of N^+ and Ar^+ signals because the experimental ion flux already exceeds typical levels.

7. Conclusion

A graphene transfer technique suitable for space applications has been adapted, and its advantages and limitations have been discussed. This updated technique achieves an improved balance among reduced graphene thickness, high coverage percentage of graphene, and a large open fraction of grids. With this method, several FLG and carbon foil samples were prepared on 1500/2000 lpi TEM copper grids with over 40% open fraction. Raman spectrum, OM, and SEM characterization were introduced to determine the precise thickness (6 ± 1 atomic layer, or 2.01 ± 0.34 nm) and the coverage percentage ($>95\%$) of FLG samples. A corresponding experimental setup was constructed for angular

scattering measurements with 5–20 keV H^+ , N^+ , and Ar^+ ions. The experiment was complemented by simulations performed using a combined SRIM-SIMION approach. Experimental and simulated data were processed via Gaussian fitting, with results presented in terms of the HWHM of the positional distribution and the derived scattering half-angles.

Analysis of the HWHM and scattering half-angles reveals that FLG yields smaller values than carbon foils, indicating reduced angular scattering during ion transmission. In our results, the scattering half-angles of FLG range from 1.33° to 4.76° , whereas those of carbon foil range from 1.56° to 11.02° . These results are consistent with the previous studies. In TOF systems, weaker angular scattering translates to more precise flight-time measurements, thereby enhancing mass resolution. Furthermore, the uncertainty components of HWHM are analyzed to guide improvements in signal detection. These findings demonstrate the superiority of FLG over carbon foils for TOF-based applications and support its potential as a viable alternative in future space plasma instrumentation. For the engineering implementation of graphene in satellite-borne instruments, further characterization of ion transmission characteristics, such as charge state, energy straggling, and TOF spectra compared to carbon foils, should be conducted to deepen the understanding of its performance. Additionally, the graphene transfer process must be advanced to achieve larger-area ($>1 \times 1$ cm), high-coverage, and thinner samples suitable for practical space applications.

Acknowledgments

Thanks to Dr. Yuqing Song and Prof. Zhongfan Liu for the suggestion on graphene transfer. This study is supported by the project of Negative Ion Analyzer on Chang'E-6 (Grant No. E3C041H001); China's Space Origins Exploration Program (SPO, GJ11020217, GJ11010208, GJ11020405).

References

- Allegrini, F., Bedworth, P., Ebert, R. W., Fuselier, S. A., Nicolaou, G., and Sinton, S. (2015a). Energy loss and straggling of 1–50 keV H, He, C, N, and O ions passing through few layer graphene. *Nucl. Instrum. Methods Phys. Res. Sect. B: Beam Interact. Mater. At.*, 358, 223–228. <https://doi.org/10.1016/j.nimb.2015.06.028>
- Allegrini, F., Ebert, R. W., Nicolaou, G., and Grubbs, G. (2015b). Semi-empirical relationships for the energy loss and straggling of 1–50 keV hydrogen ions passing through thin carbon foils. *Nucl. Instrum. Methods Phys. Res. Sect. B: Beam Interact. Mater. At.*, 359, 115–119. <https://doi.org/10.1016/j.nimb.2015.07.098>
- Allegrini, F., Ebert, R. W., and Funsten, H. O. (2016). Carbon foils for space plasma instrumentation. *J. Geophys. Res.: Space Phys.*, 121(5), 3931–3950. <https://doi.org/10.1002/2016JA022570>
- Allegrini, F., Ebert, R. W., Pontoni, A., and Nicolaou, G. (2026). Angular scattering of 1–50 keV H, He, C, N, Ne, and Ar ions passing through thin carbon foils. *J. Geophys. Res.: Space Phys.*, 131(4), e2026JA035275. <https://doi.org/10.1029/2026JA035275>
- Cho, Y., Yang, J. M., van Lam, D., Lee, S. M., Kim, J. H., Han, K. Y., and Chang, J. (2014). Transmission electron microscopy specimen preparation for layer-area graphene by a direct transfer method. *Appl. Microsc.*, 44(4), 133–137. <https://doi.org/10.9729/AM.2014.44.4.133>
- Dahl, D. A. (2000). SIMION for the personal computer in reflection. *Int. J. Mass Spectrom.*, 200(1–3), 3–25. [https://doi.org/10.1016/S1387-3806\(00\)00305-5](https://doi.org/10.1016/S1387-3806(00)00305-5)
- Delcourt, D., Saito, Y., Leblanc, F., Verdeil, C., Yokota, S., Fraenz, M., Fischer, H.,

- Fiethe, B., Katra, B., ... Michalik, H. (2016). The mass spectrum analyzer (MSA) on board the BepiColombo MMO. *J. Geophys. Res.: Space Phys.*, 121(7), 6749–6761. <https://doi.org/10.1002/2016JA022380>
- Ebert, R. W., Allegrini, F., Fuselier, S. A., Nicolaou, G., Bedworth, P., Sinton, S., and Trattner, K. J. (2014). Angular scattering of 1–50 keV ions through graphene and thin carbon foils: Potential applications for space plasma instrumentation. *Rev. Sci. Instrum.*, 85(3), 033302. <https://doi.org/10.1063/1.4866850>
- Ferrari, A. C., Meyer, J. C., Scardaci, V., Casiraghi, C., Lazzeri, M., Mauri, F., Piscanec, S., Jiang, D., Novoselov, K. S., ... Geim, A. K. (2006). Raman spectrum of graphene and graphene layers. *Phys. Rev. Lett.*, 97(18), 187401. <https://doi.org/10.1103/PhysRevLett.97.187401>
- Funsten, H. O., Skoug, R. M., Guthrie, A. A., MacDonald, E. A., Baldonado, J. R., Harper, R. W., Hendersom, K. C., Kihara, K. H., Lake, J. E., ... Chen, J. (2013). Helium, oxygen, proton, and electron (HOPE) mass spectrometer for the radiation belt storm probes mission. *Space Sci. Rev.*, 179(1–4), 423–484. <https://doi.org/10.1007/s11214-013-9968-7>
- Funsten, H. O., McComas, D. J., and Barraclough, B. L. (1993). Ultrathin foils used for low-energy neutral atom imaging of the terrestrial magnetosphere. *Opt. Eng.*, 32(12), 3090. <https://doi.org/10.1117/12.149187>
- Fuselier, S. A., Bochsler, P., Chornay, D., Clark, G., Crew, G. B., Dunn, G., Ellis, S., Friedmann, T., Funsten, H. O., ... Zaffke, S. (2009). The IBEX-Lo sensor. *Space Sci. Rev.*, 146(1–4), 117–147. <https://doi.org/10.1007/s11214-009-9495-8>
- Gonçalves, H., Fernandes, J., Moura, C., Schellenberg, P., Belsley, M., and Alves, L. (2015). Easy process to obtain suspended graphene flakes on TEM grids. *Mater. Res. Express*, 2(5), 055602. <https://doi.org/10.1088/2053-1591/2/5/055602>
- Han, J., Lee, J. Y., and Yeo, J. S. (2016). Large-area layer-by-layer controlled and fully Bernal stacked synthesis of graphene. *Carbon*, 105, 205–213. <https://doi.org/10.1016/j.carbon.2016.04.039>
- Høgberg, G., Nordén, H., and Berry, H. G. (1970). Angular distributions of ions scattered in thin carbon foils. *Nucl. Instrum. Methods*, 90, 283–288. [https://doi.org/10.1016/0029-554X\(70\)90682-8](https://doi.org/10.1016/0029-554X(70)90682-8)
- Holeňák, R., Lohmann, S., Sekula, F., and Primetzhofer, D. (2021). Simultaneous assessment of energy, charge state and angular distribution for medium energy ions interacting with ultra-thin self-supporting targets: A time-of-flight approach. *Vacuum*, 185, 109988. <https://doi.org/10.1016/j.vacuum.2020.109988>
- Lee, C., Wei, X. D., Kysar, J. W., and Hone, J. (2008). Measurement of the elastic properties and intrinsic strength of monolayer graphene. *Science*, 321(5887), 385–388. <https://doi.org/10.1126/science.1157996>
- Lee, Y. B., Jang, H., and Ahn, C. W. (2016). Formvar assisted graphene transfer for graphene TEM grid. *J. Nanosci. Nanotechnol.*, 16(2), 1810–1813. <https://doi.org/10.1166/jnn.2016.11954>
- Li, L. S., Liu, Y. A., Kong, L. G., Liu, D., Qiang, P. F., and Zhao, B. S. (2016). Detector for space thermal ion imaging. *Acta Photon. Sin.* (in Chinese), 45(4), 0423007. <https://doi.org/10.3788/gzxb20164504.0423007>
- Liang, X. L., Sperling, B. A., Calizo, I., Cheng, G. J., Hacker, C. A., Zhang, Q., Obeng, Y., Yan, K., Peng, H. L., ... Richter, C. A. (2011). Toward clean and crackless transfer of graphene. *ACS Nano*, 5(11), 9144–9153. <https://doi.org/10.1021/nn203377t>
- Liu, H. T., and Liu, Y. Q. (2017). Controlled chemical synthesis in CVD graphene. *Phys. Sci. Rev.*, 2(4), 20160107. <https://doi.org/10.1515/psr-2016-0107>
- Lüthi, B. S. (2003). Angular scattering of ions in thin carbon foils: simulations, measurements, and predictions for the PLASTIC instrument on STEREO. Bern: University of Bern.
- McComas, D. J., Allegrini, F., Pollock, C. J., Funsten, H. O., Ritzau, S., and Gloeckler, G. (2004). Ultrathin (~10 nm) carbon foils in space instrumentation. *Rev. Sci. Instrum.*, 75(11), 4863–4870. <https://doi.org/10.1063/1.1809265>
- McComas, D. J., Allegrini, F., Baldonado, J., Blake, B., Brandt, P. C., Burch, J., Clemmons, J., Crain, W., Delapp, D., ... Zoenchen, J. (2009). The two wide-angle imaging neutral-atom spectrometers (TWINS) NASA mission-of-opportunity. *Space Sci. Rev.*, 142(1–4), 157–231. <https://doi.org/10.1007/s11214-008-9467-4>
- McComas, D. J., Alexander, N., Allegrini, F., Bagenal, F., Beebe, C., Clark, G., Crary, F., Desai, M. I., De Los Santos, A., ... White, D. (2017). The Jovian Auroral distributions experiment (JADE) on the Juno mission to Jupiter. *Space Sci. Rev.*, 213(1–4), 547–643. <https://doi.org/10.1007/s11214-013-9990-9>
- Meyer, L. (1971). Plural and multiple scattering of low-energy heavy particles in solids. *Phys. Status Solidi B*, 44(1), 253–268. <https://doi.org/10.1002/pssb.2220440127>
- Nair, R. R., Blake, P., Grigorenko, A. N., Novoselov, K. S., Booth, T. J., Stauber, T., Peres, N. M. R., and Geim, A. K. (2008). Fine structure constant defines visual transparency of graphene. *Science*, 320(5881), 1308. <https://doi.org/10.1126/science.1156965>
- Nicolaou, G., Allegrini, F., Livadiotis, G., and Ebert, R. W. (2022). Effects of background noise on fit parameters of plasma scattering angle distributions. *Rev. Sci. Instrum.*, 93(10), 103305. <https://doi.org/10.1063/5.0069193>
- Novoselov, K. S., Geim, A. K., Morozov, S. V., Jiang, D., Zhang, Y., Dubonos, S. V., Grigorieva, I. V., and Firsov, A. A. (2004). Electric field effect in atomically thin carbon films. *Science*, 306(5696), 666–669. <https://doi.org/10.1126/science.1102896>
- Song, Y. Q., Zou, W. T., Lu, Q., Lin, L., and Liu, Z. F. (2021). Graphene transfer: Paving the road for applications of chemical vapor deposition graphene. *Small*, 17(48), 2007600. <https://doi.org/10.1002/sml.202007600>
- Sun, L. T., Xu, T., and Yin, K. B. (2018). Microstructural characterization of graphene and related 2D materials. In *Microstructural Characterization of Graphene and Related 2D Materials* (pp. 3). Chemical Industry Press.
- Vira, A. D., Fernandes, P. A., Funsten, H. O., Morley, S. K., Yamaguchi, H., Liu, F. Z., and Moody, N. A. (2020). Angular scattering of protons through ultrathin graphene foils: Application for time-of-flight instrumentation. *Rev. Sci. Instrum.*, 91(3), 033302. <https://doi.org/10.1063/1.5134768>
- Wüest, M., Evans, D. S., and von Steiger, R. (2007). *Calibration of Particle Instruments in Space Physics*. International Space Science Institute.
- Xu, P. H., Kong, L. G., Zhang, A. B., and Ma, J. J. (2025). Comparative simulation study of graphene and carbon foils in satellite-borne TOF system. *Chin. J. Space Sci.* (in Chinese), 45(3), 795–809. <https://doi.org/10.11728/cjss2025.03.2024-0156>
- Zeiger, B. R., Wieland Shields, M., Paul, B., Lopez, H., Grove, D., Arrowsmith, A., Smith, R., Primus, C., and Ayers, T. (2019). Graphene foils for neutral atom detectors. In *Proceedings of SPIE 11127, Earth Observing Systems XXIV* (pp. 84). San Diego: SPIE. <https://doi.org/10.1117/12.2529762>
- Zhang, J. C., Lin, L., Sun, L. Z., Huang, Y. C., Koh, A. L., Dang, W. H., Yin, J. B., Wang, M. Z., Tan, C. W., ... Peng, H. L. (2017). Clean transfer of large graphene single crystals for high-intactness suspended membranes and liquid cells. *Adv. Mater.*, 29(26), 1700639. <https://doi.org/10.1002/adma.201700639>
- Ziegler, J. F., Ziegler, M. D., and Biersack, J. P. (2010). SRIM – The stopping and range of ions in matter (2010). *Nucl. Instrum. Methods Phys. Res. Sect. B: Beam Interact. Mater. At.*, 268(11–12), 1818–1823. <https://doi.org/10.1016/j.nimb.2010.02.091>