Thermal Emission Spectroscopy for Single Nanoparticle Temperature Measurement: Optical System Design and Calibration

BRYAN A. LONG, DANIEL J. RODRIGUEZ, CHRIS Y. LAU, AND SCOTT L. ANDERSON*  
Department of Chemistry, University of Utah, 315 S. 1400 E., Salt Lake City, UT, 84112 USA  
*anderson@chem.utah.edu

Abstract: We discuss the design of an optical system that allows measurement of 600 nm to 1650 nm emission spectra for individual nanoparticles (NPs), laser heated in an electrodynamic trap in controlled atmospheres. An approach to calibration of absolute intensity vs. wavelength for very low emission intensities is discussed, and examples of NP graphite and carbon black spectra are used to illustrate the methodology.

© 2018 Optical Society of America

1. Introduction

We have developed an experiment to measure high temperature reaction kinetics for single nanoparticles (NPs) confined in a three dimensional quadrupole trap, with the goal of studying effects on NP surface chemistry and optical properties, of NP heterogeneity, i.e., variations in NP size and structure.[1-3] In essence, a series of single NPs are trapped and laser heated, allowing them to be detected optically via their thermal (“blackbody”) emission. Changes in the NP mass vs. time are tracked to obtain the kinetics for mass-changing processes such as sublimation or oxidation. We are interested in NPs in the 5 to 50 nm range.

To use NP mass spectrometry as a kinetics tool, the NP temperature (TNP) needs to be determined by fitting emission spectra measured during the kinetics experiments, with acquisition time scales of ~10 to 60 seconds. The wavelength (λ) range of interest spans the visible and near infrared (nIR) spectral regions, and we use a pair of spectrographs capable of covering the ~400 to 1650 nm range. The critical problem is to calibrate the detection sensitivity vs. λ for the very low thermal emission intensities observed from single 5 to 50 nm NPs. TNP determination requires relative intensity vs. λ calibration, but if absolute intensities can be extracted, absolute NP emissivities can be measured as a function of λ, TNP, and NP size and composition – information that is largely unavailable.

Several groups have reported methodologies for emission spectroscopy from single trapped particles. For example, Bieske and co-workers reported dispersed emission spectra in the visible range for individual ~1 μm diameter dye-doped NPs in a trap similar to ours.[4-7] Our instrument must work with lower emission intensities, extend the spectra into the nIR where detectors are less sensitive, and must have well calibrated spectral intensities.

To our knowledge, the experiment most conceptually similar to ours was developed by Sarofim and co-workers.[8, 9] Individual particles were suspended in an AC trap and laser heated as they reacted in an oxidizing atmosphere. Particle temperature was measured by two-color (sometimes three-color) thermometry, where emission was measured with two or three broadband detectors, sensitive in different visible or IR wavelength ranges. From an optical perspective, the most important difference between their experiment and ours, is that their particles were ~1000 times larger than ours. Taking surface area and low emissivity for sub-λ nanoparticles[10] into account, their intensities would have been >10^6 times higher. Furthermore, we felt that for our experiments – the first to measure dispersed emission for individual NPs as a function of λ, TNP, NP size, and composition – it was essential to have
dispersed spectra to extract emissivity vs. $\lambda$, and to look for any structured emission that might occur. To enable these experiments, a dual spectrograph optical system was developed, along with a method for calibrating absolute sensitivity vs. wavelength over the visible and near-IR ranges, at the very low intensities relevant to emission from sub-30 nm particles.

2. Experimental Methods

2.1 Optical system design

Figure 1 shows the optical system layout. The instrument vacuum system, indicated schematically by the dashed box, has been described previously,[1] along with methods for NP mass and charge determination. Briefly, NPs are introduced into the vacuum system by electrospray ionization, and guided to the trap entrance by a combination of hexapole and quadrupole guides. NPs are injected into a split-ring-electrode quadrupole trap, based on a design by Gerlich, who also has discussed the motion of the trapped NP in detail.[11] During trapping, the center of the trap is irradiated by a 10 W cw CO$_2$ laser (10.6 $\mu$m) focused diagonally through the trap, or by a cw solid state laser focused through the trap perpendicular to the plane of the figure. Argon buffer gas is added at 1 to 15 mTorr pressure so that NPs undergo collisions as they pass through the trap, resulting in some probability that an NP will become trapped. Optical emission from the trap is monitored continuously, and injection is stopped as soon as an increase in emission indicates that a particle has become trapped.

Motion of trapped NPs is harmonic with well-defined frequencies for axial and radial motion, proportional to the charge to mass ratio, $Q/M$. To measure $Q/M$, a weak swept-frequency AC potential is applied across the trap, which causes a dip in collected emission intensity when the drive frequency is resonant with the NP axial frequency, $f_a$. Because each NP has distinct $Q/M$, the presence of more than one NP in the trap is obvious as multiple $f_a$ resonances, and when that happens, the trap is dumped and the injection process is repeated. All experiments described below were done with a single NP in the trap. To determine $Q$, and thus $M$, a vacuum ultraviolet lamp is used to induce photoemission from the NP, thus driving a series of single electron charge steps, which cause corresponding $\Delta f_a$ steps in

Fig. 1. Optical layout as described in text.
Q is determined by fitting the steps: \( Q = e \frac{f_z}{\Delta f_z} \). Once Q is determined, the lamp is turned off. To study NP sublimation or reactions, the NP mass is monitored continuously as the NP is laser heated in either inert or reactive atmospheres in the few mTorr range. The background pressure in the instrument is \( \approx 10^{-8} \) Torr. For a given laser intensity, the NP temperature is determined by the balance between laser heating, and cooling processes which include thermal radiation, collisions with room temperature argon, and evaporative cooling. As discussed elsewhere,[3] for the conditions relevant here, thermal radiation and collisional cooling are dominant, and because both are temperature dependent the relationship between laser intensity and NP temperature is complex. For the spectra presented here, the NP was heated by a cw diode-pumped solid state laser operating at 532 nm, with power adjustable to 500 mW. For black carbon NPs, we have seen no indications that emission spectra or reactivity depend on excitation wavelength.

Light emitted by the trapped NP is collected along two directions. Light collected in the radial direction (solid angle \( \approx 0.4 \) steradians (sr)) is sent to a silicon avalanche photodiode (APD), monitoring intensity vs. time for NP M and Q determination, as described above. M is typically between 0.3 and 20 MDa (MDa = \( 10^6 \) atomic mass units), and Q is typically 10 to 50 e. The trapped NP undergoes thermal motion with \( \approx 100 \) μm amplitude, thus from the optics perspective, the effective diameter of the NP emission source is \( \approx 200 \) μm.

Light emitted along the trap axis is collected and formed into a slowly converging beam by a 25 mm diameter, 30 mm effective focal length (efl) aspherized achromat (Edmund Optics). The beam can be diverted by a retractable mirror into a CCD camera for diagnostic purposes, or normally propagates to a dichroic beam splitter (Semrock), which reflects photons with \( \lambda < 980 \) nm by 90°, and passes \( \lambda > 980 \) nm. For simplicity, we will refer to the \( < 980 \) and \( > 980 \) nm spectral ranges as “visible” and “nIR”, respectively.

The visible beam is focused into an optical fiber by a combination of a 25 mm diameter, 18.75 mm efl, 0.66 NA aspheric lens (Edmund Optics) and an 8.0 mm focal length, 0.50 NA, fixed focal length collimator (Thorlabs, 600-1050 nm AR coating). A 1000 μm single core, 0.50 NA, low OH fiber optic patch cable (Thorlabs) is used to guide the light to a small Czerny-Turner spectrograph (Andor Shamrock 163, f/3.6) equipped with Ag-coated mirrors and an Ag-coated 300 line/mm grating blazed at 760 nm. Diffracted light is detected by a back-illuminated, deep depletion 2000 x 256 pixel Si CCD camera, thermoelectrically cooled to -65°C (Andor, DU416A-LDC-DD). The camera-grating combination gives a detection bandwidth of \( \approx 569 \) nm, set for these experiments to cover the range from 437 to 1006 nm. For the TNP range of interest for materials like carbon, the spectral range below 600 nm is uninteresting, and to filter out scattered 532 nm laser light, or any light that might appear in 2nd order in the spectrum, the visible beam is passed through a 600 nm long-pass filter.

The nIR portion of the beam passes through a 900 nm long-pass filter, then is focused into another 1000 μm single core fiber optic cable using a 25 mm diameter, 18.75 efl aspheric lens, and a 4.64 mm focal length, 0.53 NA fixed focus collimator (Thorlabs, anti-reflection coating 1050-1620 nm). Another Czerny-Turner spectrograph (Andor Shamrock 163) equipped with Ag-coated mirrors and an Ag-coated 85 line/mm grating blazed at 1350 nm disperses the emission onto a thermoelectrically cooled (-80 °C) 512 x 1 pixel InGaAs photodiode camera (Andor, DU490A-1.7). To reduce the image height on the 500 μm tall camera array, the spectrograph includes a cylindrical lens.

Our interest is principally in analyzing thermal emission to obtain TNP, and to improve sensitivity we operate the spectrographs with slits wide open, such that the resolution is controlled by the 1000 μm diameter optical fibers. The resolution and wavelength calibration were determined by measuring spectra for a mercury lamp. For the nIR spectrograph, the resolution is found to be \( \approx 60 \) nm fwhm, while for the visible spectrograph it is \( \approx 20 \) nm. When necessary, the slits can be closed to increase resolution at the cost of sensitivity.

Acquisition time for small NPs at relatively low temperatures is typically chosen to be 60 seconds, because that happens to match the time scale for NP mass determination. For larger
NPs or higher temperatures, where emission is strong, shorter acquisition times can be used to avoid saturation. Raw signal levels are kept below 10% of the manufacturer’s stated saturation level, and under those conditions, we have never seen significant effects of acquisition time on the NP spectral shape or extracted NP temperature.

2.2 Background subtraction

To allow background subtraction, spectra are measured under conditions identical to those used in the NP spectra, but with no NP in the trap. Therefore, the background spectra include all sources of background signal that are present in the NP spectra, except light scattering from the NP, which would be blocked by filters in the optical train. Typical raw NP spectra are shown in Fig. 2, along with the background spectra, for an NP pumped at 532 nm. The NP in this case was graphite with \( M = 18.0 \) MDa, corresponding to ~30 nm diameter if spherical with the bulk graphite density. The NP was held at relatively low \( T_{NP} \) so that its mass loss rate from sublimation was slow, and 60 second acquisition time was used. As shown in Fig. 2 (left), when the 532 nm laser is used for particle heating, the visible background has a feature at ~700 nm, with a broader underlying feature extending from ~650 to 750 nm. The origin of this background signal is unclear (it is not seen when pumping with the CO2 laser), but it is removed quantitatively during background subtraction.

The background signal for the nIR spectrograph (right frame, Fig. 2) mostly originates from the spectrograph, itself. Thermal radiation from room temperature surfaces inside the spectrograph impinges on the InGaAs array, which detects the small fraction with \( \lambda < 1650 \) nm, producing a background “dark” signal. Because this dark signal originates in the spectrograph, it is unaffected by filters in the optical system. For long integration times (e.g. 60 sec, as in Fig. 2), which are necessary for small NPs at low \( T_{NP} \), the dark signal can be significantly larger than the actual NP emission signal, as is the case here. Furthermore, while the room temperature dark signal is weak, it is strongly temperature dependent, such that a 0.1 K temperature change results in a nearly 1% change in the detected dark signal. Stabilizing the spectrograph temperature to much better than 0.1 K would be difficult, therefore we developed an approach in which the background is scaled to account for spectrograph temperature drift during the experiments. We take advantage of the fact that there is no real signal below 950 nm, due to a combination of the 980 nm dichroic beamsplitter and low grating and quantum efficiencies. The background spectrum is scaled so that the integrated signal in the <950 nm region matches that in the NP spectrum prior to subtraction. The >1650 nm range, where the real signal is also zero due to zero quantum efficiency for cold InGaAs, serves as a check on this procedure. This approach was tested by gently heating the spectrograph to verify that scaling correctly reproduces the temperature effects.

Fig. 2. Left: Raw NP and background spectra in the visible range for a ~18 MDa (~30 nm diameter) graphite NP. Right: Raw NP and background spectra in the nIR range. See Data File 1 for underlying values.
Note that much of the scatter in both signal and background nIR spectra is not noise, but rather results from pixel-to-pixel variation in the camera sensitivity. As can be seen by close examination of the spectra in the <950 and > 1650 nm spectral regions, the pattern of scatter is quite reproducible, and mostly cancels when the background is subtracted. There is additional cancellation in the intensity calibration process described below.

2.3. Calibration of the optical system sensitivity

To extract $T_{NP}$ from the spectra, it is necessary to correct the spectra quantitatively for the wavelength dependence of the optical detection sensitivity, $S(\lambda)$, including collection efficiency, effects of focusing optics, vacuum windows, spatial filtering, spectrograph transmission, and detector quantum efficiency. The calibration process was developed with the following considerations: 1. Sensitivity is strongly affected by optical alignment with respect to the emitter position, i.e., the trap center. This requires that calibration be performed on the system as a whole, with the calibration source at the trap center. The calibration light source must, therefore, fit into the trap center through the 2 mm gap between the electrodes. 2. To avoid detector non-linearity effects, calibration should be done at intensities similar to that from single NP thermal emission. 3. The size of the calibration emitter should match the ~200 μm diameter of NP thermal motion, to avoid artifacts due to different source sizes during calibration and NP spectroscopy. 4. To enable frequent calibration, it should be possible to do the calibration without venting the vacuum system.

To provide a vacuum-compatible calibration emitter small enough to fit into the trap center, we use a type C (W-5% Re/W-26% Re) thermocouple (TC), fabricated from 78 μm diameter type C wire (Concept Alloys). The TC junction was fabricated by twisting the wire, then tightly folding and spot welding repeatedly to create a compact, roughly spherical junction volume. The TC is mounted to a precision XYZ vacuum manipulator via a ~1 mm diameter, dual bore ceramic tube, allowing the TC junction to be positioned at the trap center for calibration, then parked in a position well outside the trap for NP spectroscopy. When positioned at the trap center, the TC can be heated using the CO2 laser to ~2600 K. The laser is focused through the trap by a pair of home-made off-axis paraboloids, resulting in a ~600 μm diameter beam waist[3] – roughly twice the junction diameter. To help heat the TC junction uniformly, the beam is retro-reflected after passing through the trap, so that the junction is irradiated from both sides.

The advantage of the large TC junction is that emission from the junction surface is much stronger than emission from the wires leading to the junction, which are not at a well-defined temperature. The concern is that a twisted/folded/welded junction might not have a uniform emitting surface temperature, but imaging of the junction shows uniform color temperature across the central ~300 μm region of the junction, presumably because a large number of high compression spot welds was used to form a compact junction that is heated uniformly by the weakly focused, retro-reflected laser. Because the absolute emissivity vs. wavelength and temperature, $\epsilon(\lambda, T)$, for W and Re are well known,[12-15] and the junction temperature can be read electrically, the TC provides an emitter with well-known intensity vs. $\lambda$, $I(\lambda, T)$.

Sarofim et al.[8, 9] also used a laser-heated TC as an emitter to calibrate their two or three-color thermometry method. Because the particles studied in their experiments were in the tens-of-micron diameter range, their emission intensity was similar to that from their TC emitter. In our experiments, the single NP emission is roughly $10^8$ times weaker than that from the hot TC. Clearly the detectors cannot be expected to be linear over such a large intensity range, therefore the intensity from the TC must be attenuated by a factor of $10^{-8}$, without affecting the optical path significantly. For this purpose, we use a set of four OD 2 reflective neutral density (ND) filters (Thorlabs, nickel-coated, 1 mm thick UV fused silica substrates) mounted in the holder shown in Fig. 1. The filters are tilted to prevent multiple reflections, and the angles alternate to eliminate lateral beam walk when the assembly is inserted during calibration. The tilt planes of the two pairs of filters are rotated 90° with
respect to each other (not shown) to avoid introduction of polarization effects. Refraction in
the filter substrates is calculated to increase the convergence distance of the light beam by
~0.3%, which has a negligible effect on the spatial filtering used to define the emitter.

We were unable to obtain reliable transmission spectra for the individual OD 2 filters
using two different commercial spectrometers, therefore the transmission was measured using
the optical setup in Fig. 1, with the laser-heated TC as the light source. A pair of angle-
mounted OD 3 filters was used as a “pre-attenuator” to drop the intensity by a factor of
roughly 10^6, and both visible and nIR spectra were recorded. Spectra were then recorded
after inserting one of the four OD 2 filters into the optical path, mounted perpendicular to the
path to avoid beam walk, and far enough from the pre-attenuator to prevent multiple
reflections between the filters. The ratio of the spectra, with and without the OD 2 filter,
gives the transmission of that filter under the conditions used in the TC calibration. Repeated
measurements were found to be identical within the signal/noise, and the transmission
spectrum of each filter was obtained by averaging five measurements. The net transmission
of the four OD 2 filters, ND(λ), was calculated as the product of the averaged transmission
spectra for the individual filters. To check for possible intensity effects on ND(λ),
transmission measurements were repeated using different ND filters in the pre-attenuator,
varying the pre-attenuator transmission from ~10^-6 to 10^-8. No significant intensity effects
were observed, giving us confidence the measured ND(λ), and also demonstrating that the
spectrograph cameras are quite linear over the intensity range of interest for our experiments.

As noted, we want the calibration emitter size to be similar to the diameter of the NP
thermal motion, and this was achieved using defining apertures to control light from the trap.
As shown in Fig. 1, the aspheric achromatic collection lens slowly focuses light collected
from the trap center, forming images in both the visible and nIR branches of the optical train.
Defining apertures are inserted at both focal planes to define the collection area, also
efficiently suppressing scattered light and other background sources. The collection lens is
only designed to be achromatic to 675 nm, however, the indices of refraction of the two
glasses used varies by less than 2% between 675 and 1600 nm, thus we expect the
magnifications at the visible and nIR aperture positions to be quite similar. The
magnification for the visible image was measured by photographing the hot TC image
projected on a paper screen at the aperture plane. 16 independent measurements of 78 ± 1 μm
diameter TC wire leads were averaged to obtain a magnification factor of 12.3 ± 0.3. The
junction, itself was found to be ~330 μm across. Given the 2.39 mm defining aperture
diameter, this means that light is collected only if it is emitted from the central 194 ± 8 μm
diameter region of the ~330 μm junction, and therefore that the effective TC emitter area is
well matched to the ~200 μm diameter of NP thermal motion. A similar measurement was
made on the nIR image of the TC, photographing the image through an IR viewer with λ
sensitivity similar to that of the InGaAs spectrograph (Newport IRV1-1700). The nIR was
not as sharp, resulting in greater uncertainty in the magnification, which was found to be
~12.9 ± 1.0. As expected from the lens properties, the magnifications, hence collection areas
are identical within the uncertainty for the visible and nIR optics. For absolute calibration
purposes we estimate that the emitter area is known to ±10%.

Finally, it is critical that the optical system be aligned to the NP position at the trap center,
and that the TC junction be positioned at the trap center during calibration. A single NP is
trapped and heated using a loose laser focus so that T_NP, hence emission intensity, is
insensitive to slight laser misalignment. The optics, including defining apertures, are then
carefully adjusted to maximize the NP signal, ensuring that the optical system is aligned to
the trap center. For calibration, the TC is inserted and heated, and its position is adjusted to
center the magnified junction image on the defining apertures.

2.4. Correcting NP spectral intensities.
Using background-subtracted TC emission spectra, measured as described above, calibration
of the optical system sensitivity vs. wavelength is straightforward. The intensity measured
for the laser-heated TC ($I_{\text{TC}}^{\text{meas}}$) at temperature $T$ is given by:

$$I_{\text{TC}}^{\text{meas}}(\lambda) = I_{\text{BB}}(\lambda, T) \cdot \epsilon_{\text{TC}}(\lambda, T) \cdot ND(\lambda) \cdot S(\lambda),$$  \hspace{1cm} (1)

where $I_{\text{BB}}(\lambda, T)$ is the theoretical (Planck’s law) spectrum for an ideal blackbody at
temperature $T$, $\epsilon_{\text{TC}}(\lambda, T)$ is the emissivity of the W-Re thermocouple, $ND(\lambda)$ is the
transmission of the set of four OD 2 ND filters, and $S(\lambda)$ is the desired optical system
sensitivity vs. wavelength. Therefore:

$$S(\lambda) = \frac{I_{\text{TC}}^{\text{meas}}(\lambda)}{I_{\text{BB}}(\lambda, T) \epsilon_{\text{TC}}(\lambda, T) ND(\lambda)}$$  \hspace{1cm} (2)

Once $S(\lambda)$ is known, then background-subtracted NP spectra, $I_{\text{NP}}(\lambda, T)$, can be corrected by
simply dividing by $S(\lambda)$:

$$I_{\text{NP}}^{\text{corr}}(\lambda, T) = \frac{I_{\text{NP}}(\lambda, T)}{S(\lambda)}$$  \hspace{1cm} (3)

To test this calibration procedure a TC calibration experiment with junction temperature of
2507 K was used to calculate $S(\lambda)$. TC spectra were then electronically measured at three
other junction temperatures ranging from 2136 to 2361 K, and these spectra were corrected
using the $S(\lambda)$ function determined from the 2507 K calibration:

$$I_{\text{NP}}^{\text{corr}}(\lambda, T) = \frac{I_{\text{NP}}^{\text{meas}}(\lambda, T)}{S(\lambda)}$$  \hspace{1cm} (4)

Finally, the corrected TC spectra at the three test temperatures were fit to the product of
$I_{\text{BB}}(\lambda, T) \cdot \epsilon_{\text{TC}}(\lambda, T)$, to extract a spectral temperature, which was compared to the
temperature read electronically from the TC during each measurement. For measurements at
temperatures within 200 K of the 2507 K calibration temperature, the difference between the
electronically and spectroscopically measured temperatures was less than 0.25%. At 2136 K,
the fit temperature was 2129 K, – 378 K below the calibration temperature. This results in a
spectroscopically determined temperature that is within 0.3% of the electrically measured
temperature, i.e., well within the temperature error limits provided by the TC wire
manufacturer (±1% for $T > 425^\circ$C).

3. Results and Discussion

Figure 3 illustrates the process, and gives the data needed to calculate the wavelength-
dependent sensitivity, $S(\lambda)$. Frame A shows the background-subtracted visible and nIR
spectra of the TC heated to 2454 K, with the signal attenuated by four OD 2 filters. The
signal level is comparable to that for typical single NPs, and here it has been put on a $\text{photons/second/sr/m}^2$ basis by dividing by the aperture-defined 2.93 x $10^8$ emitter area. Regions where the signal is
weak or strongly affected by camera quantum efficiency, filters, or the 980 nm dichroic
beamsplitter are indicated with solid vertical lines. As in the NP spectra in Fig. 2, much of
the data scatter results from pixel-to-pixel variations in camera sensitivity, which ultimately
cancels out in the intensity-corrected NP spectra.

Frame B shows the Planck function for an ideal blackbody at 2454 K, in units of
photons/second/sr/m$^2$ of surface area, assuming 1 nm bandwidth. The actual bandwidth
subtended by each pixel varies from 0.296 to 0.268 nm for the visible spectrograph, and from
1.736 nm to 1.673 nm for the nIR spectrograph, however, this factor cancels exactly in the
calibration process, so has not been included in Planck function calculation.

Frame C shows the absolute emissivity of tungsten, $\epsilon(\lambda)$, calculated at 2454 K using the
empirical $\epsilon(\lambda, T)$ expression of Pon et al.[12] which is based on experimental data of De
Vos[13] and Larrabee.[14] The $\epsilon(\lambda, T)$ function for a type C thermocouple junction (average
composition ~85% W, 15% Re) has not been reported to our knowledge, however, the $\epsilon(\lambda, T)$
data for W[13] and Re[15] are very similar for the $\lambda$ range of interest, the main difference
being that the absolute emissivity is ~3 % lower for Re. Therefore $\epsilon(\lambda, T)_{\text{TC}}$ estimated as a
composition-weighted average of the W and Re emissivities differs from the W value by only
~0.5%, which is negligible compared to other sources of uncertainty in the absolute intensity
calibration (e.g. aperture-defined emitter area). Therefore we use the W emissivity, for which an analytic $\epsilon(\lambda,T)_W$ expression is available.[12]

Frame D shows the net transmission, ND($\lambda$), of the four OD 2 filters used to attenuate the TC signal. The transmission ranges between $\sim3.5$ and $\sim5.5 \times 10^{-8}$, and has significant noise resulting from the low signal level in the transmission measurements. Given the low resolution of the spectrograms, the high frequency noise cannot be real, and to avoid propagating it to the NP spectra, we used Savitsky-Golay smoothing to generate the solid black curve passing through the points. Note that it is important not to over-smooth ND($\lambda$), because there is real structure, and if it is removed by over-smoothing, the result is spurious structure in the corrected NP spectra.

As shown in frame A, the signal in the region centered around $\sim1020$ nm is low and strongly $\lambda$-dependent due to camera quantum efficiencies and grating efficiencies, and even the smoothed ND($\lambda$) is noisy with spurious structure in this spectral region. To approximately interpolate ND($\lambda$) across the gap, we fit the ND($\lambda$) data in the 870 to 1271 nm range spanning the gap with a $3^{rd}$ order polynomial. The interpolated values between 870 and 1100 nm (open purple symbols, frame D) are used only in the spectral range where the smoothed data are

![Fig. 3. Data illustrating extraction of S($\lambda$) from the TC calibration spectrum. A: Raw TC spectrum. B: Planck function. C: Empirical W emissivity. D: ND filter transmission. E: Product of B through D. F: Final S($\lambda$) function. See Data File 2 for underlying values.](image)
unreliable, and only to check how the visible and nIR spectra connect, not for $T_{np}$ fitting.

Frame A is the numerator of equation 2 above, and frame E (the product of frames B-D), is the denominator. Frame F is the resulting quotient, i.e., the desired sensitivity vs. wavelength, $S(\lambda)$, in units of counts nm sr/photons. Note that the open symbols in frames E and F indicate points that are based on measured spectral intensities, but using interpolated ND(\lambda) values. The scatter for $S(\lambda)$ has some contribution from pixel-to-pixel variations in the camera sensitivity, which cancels when the NP spectra are corrected using $S(\lambda)$.

Comparing the spectra in frames A and E of Fig. 3 provides an opportunity to assess our understanding of the optical system, and its efficiency. Frame E is the predicted absolute emission intensity including transmission through the ND filters, in photons/second/sr/nm/m$^2$ of emitter area. Frame A is the measured number of counts/second/pixel/m$^2$ emitter area. To compare these, it is necessary to take into account the acceptance solid angle of the optical system, reflection losses from all the uncoated surfaces in the optical train, reflectivity of the Ag mirrors, the grating efficiencies, the actual bandwidth impinging on each pixel of the cameras, the quantum efficiency of the Si and InGaAs sensors, and the readout “sensitivity” of each camera, reported by the manufacturer (5.28 e/\text{count} for the Si CCD, 91.59 e/\text{count} for the InGaAs camera). Note that it is the much higher readout sensitivity used in the Si CCD camera that makes the raw visible counts so much higher than the nIR counts (Frame A), even though the emission intensity and bandwidth/pixel are both higher in the nIR.

Taking these factors into account, we predict that at 760 nm, near the peak of the visible spectrograph quantum and grating efficiencies, the signal should be $1.62 \times 10^{11}$ counts/pixel/second/m$^2$, compared to the measured $1.48 \times 10^{11}$ counts/pixel/second/m$^2$, i.e., there is ~8% unexplained signal loss. At 1350 nm, near the peak in the nIR region, we predict that there should be $1.12 \times 10^{11}$ counts/pixel/second/m$^2$, compared to the measured $6.88 \times 10^{10}$ counts/pixel/second/m$^2$, i.e., the nIR optics have a ~38% unexplained loss. The origin of these inefficiencies is unclear; however, it is likely that much of the nIR loss results from overfilling the 500 μm tall camera array. Regardless, it is important to note that all losses are included in calculating $S(\lambda)$, and therefore are accounted for in calculating intensity-corrected NP spectra using the procedure described above.

Fig. 4 shows the result of applying the $S(\lambda)$ correction to the spectrum of the 18.0 MDa graphite NP that was used to illustrate the raw spectra in Fig. 2. The acquisition time was 60 seconds in this case, and repeated measurements are quite reproducible. The left frame shows the background-subtracted spectra prior to correction, i.e., the difference between the NP and background spectra given in Fig. 2. The right frame shows the corrected spectrum, obtained by dividing the left frame by the $S(\lambda)$ function from Fig. 3F.

![Fig. 4. (A) Raw emission and (B) corrected emission spectrum from a single ~18 MDa (~30 nm diameter) graphite NP. See Data File 3 for underlying data.](image-url)
The NP temperature can be estimated by fitting the corrected spectrum. The section of the fit that overlays data that were corrected with interpolated ND(λ) values is indicated by open circles. These data between 960 to 1100 nm were not included in the T_{NP} fit, but are shown along with the fit to demonstrate that the ND(λ) interpolation process did not introduce significant artifacts into the corrected NP spectra. The function used to fit the data is obtained by multiplying Planck’s law by a nanoparticle emissivity function, \( \varepsilon(\lambda) \). Emissivity for nanoparticles much smaller than the wavelength can be calculated from Mie theory,[16] however, for hot NPs this requires knowing the optical properties of the material at the temperature of interest over the visible/nIR wavelength range. There may also be effects on emissivity from surface or other localized states, which could vary from NP to NP. More detailed discussion of emissivity for individual carbon and non-carbon NPs will be the subject of a future publication. Here, for the purposes of illustration, we adopted the common procedure of approximating \( \varepsilon(\lambda) \) with a simple power law expression, \( \varepsilon(\lambda) \propto \lambda^{-z} \), \( z \) being a fitting parameter.[17-20] In this case, the fitted temperature is 1593 K, and the \( z \) parameter is 1.96. There are several sources of uncertainty, including \( \pm 20 \) K from the \( \pm 1\% \) uncertainty in the TC calibration temperature, and \( \pm 15 \) K fitting uncertainty due to spectral noise.

Fig. 5. Spectra for a single 5.8 MDa (~20.3 nm diameter) carbon black NP at different temperatures. See Data File 4 for underlying values.

Fig. 5 shows a set of spectra for a smaller, 5.8 MDa (~20.3 nm) carbon black NP at four different 532 nm laser heating intensities, all recorded with 60 second acquisition time. The extracted T_{NP} values vary from 1616 K to 1924 K.

4. Conclusions

We have discussed the design of an optical system and an intensity calibration method that allows thermal emission spectra for individual NPs to be measured over the 600 to 1600 nm range, on a time scale appropriate for measuring T_{NP} to accompany NP sublimation and reaction kinetics experiments. The relative intensity vs. wavelength, i.e., the shape of the spectra, is critical in fitting the spectra for T_{NP} determination, and we estimate that this is correct to within a few percent over the 600 – 1600 nm wavelength range. The approach used should also give accurate absolute intensity calibration. The main uncertainty is the area on the TC from which emission is collected, defined by the apertures placed at the visible and nIR image planes. We estimate that this area is known to within \( \pm 10\% \).

The spectral accuracy and signal to noise is high enough that the main uncertainty in extracting T_{NP} is modeling the NP emissivity. Careful examination of Fig. 5 shows that the simple power law emissivity model used fails to adequately fit the spectra, particularly at high T_{NP}. The effects of size, composition and temperature on NP emissivity is a complex topic, and will be the subject of a future publication.
5.1 Funding

The nIR spectrograph was purchased with funds from the Albaugh Scientific Equipment Endowment of the College of Science, University of Utah. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, Gas Phase Chemical Physics program under Award Number DE-SC-0018049.

5.2 Acknowledgments

We thank Prof. Joel Harris (University of Utah, Chemistry Department) and Prof. Jordan Gerton (University of Utah, Physics Department) for many helpful discussions about optics and light detection.

5.3 Disclosures

The authors declare that there are no conflicts of interest related to this article.

6. References

1. C. R. Howder, D. M. Bell, and S. L. Anderson, "Optically Detected, Single Nanoparticle Mass Spectrometer With Pre-Filtered Electrospray Nanoparticle Source," Rev. Sci. Instrum. 85, 014104 - 014110 (2014).
2. D. M. Bell, C. R. Howder, R. C. Johnson, and S. L. Anderson, "Single CdSe/ZnS Nanocrystals in an Ion Trap: Charge and Mass Determination and Photophysics Evolution with Changing Mass, Charge, and Temperature," ACS Nano 8, 2387–2398 (2014).
3. C. R. Howder, B. A. Long, D. Gerlich, R. N. Alley, and S. L. Anderson, "Single Nanoparticle Mass Spectrometry as a High Temperature Kinetics Tool: Emission Spectra, Sublimation, and Oxidation of Hot Carbon Nanoparticles," J. Phys. Chem. A 119, 12538–12550 (2015).
4. A. J. Trevitt, P. J. Wearne, and E. J. Bieske, "Calibration of a Quadrupole Ion Trap for Particle Mass Spectrometry," Int. J. Mass Spectrom. 262, 241-246 (2007).
5. T. A. Smith, A. J. Trevitt, P. J. Wearne, E. J. Bieske, L. J. McKimmie, and D. K. Bird, "Morphology-Dependent Resonance Emission from Individual Micron-Sized Particles," Springer Ser. Fluoresc. 4, 415-429 (2008).
6. A. J. Trevitt, P. J. Wearne, and E. J. Bieske, "Coalescence of Levitated Polystyrene Microspheres," J. Aerosol Sci. 40, 431-438 (2009).
7. V. Dryza, J. L. Nguyen, T.-H. Kwon, W. W. H. Wong, A. B. Holmes, and E. J. Bieske, "Photophysics and aggregation effects of a triphenylamine-based dye sensitizer on metal-oxide nanoparticles suspended in an ion trap," Physical Chemistry Chemical Physics 15, 20326 - 20332 (2013).
8. M. D’Amore, L. Tognotti, and A. F. Sarofim, "Oxidation rates of a single char particle in an electrodynamic balance," Combust. Flame 95, 374-382 (1993).
9. Z. Du, A. F. Sarofim, J. P. Longwell, and C. A. Mims, "Kinetic measurement and modeling of carbon oxidation," Energy Fuels 5, 214-221 (1991).
10. H. C. van de Hulst, Light Scattering by Small Particles (Dover, New York, 1981).
11. D. Gerlich and S. Decker, "Trapping Ions at High Temperatures: Thermal Decay of C60+," Appl. Phys. B: Lasers Opt. 114, 257-266 (2014).
12. R. M. Pon and J. P. Hessler, "Spectral emissivity of tungsten: analytic expressions for the 340-nm to 2.6-μm spectral region," Appl. Optics 23, 975-976 (1984).
13. J. C. De Vos, "A New Determination of the Emissivity of Tungsten Ribbon," Physica 20, 690-712 (1954).
14. R. D. Larrabee, "Spectral Emissivity of Tungsten," J. Opt. Soc. Am. 49, 619-625 (1959).
15. D. T. F. Marple, "Spectral Emissivity of Rhenium," J. Opt. Soc. Am. 46, 490-494 (1956).
16. C. F. Bohren and D. R. Huffman, Absorption and Scattering of Light by Small Particles (Wiley, New York, 1983).
17. L. Landstrom, K. Eltln, M. Boman, C. G. Granqvist, and P. Heszler, "Analysis of Thermal Radiation from Laser-Heated Nanoparticles Formed by Laser-Induced Decomposition of Ferrocene," Appl. Phys. A 81, 827-833 (2005).
18. L. Landstrom and P. Heszler, "Analysis of Blackbody-Like Radiation from Laser-Heated Gas-Phase Tungsten Nanoparticles," J. Phys. Chem. B 108, 6216-6221 (2004).
19. H. A. Michelsen, C. Schulz, G. J. Smallwood, and S. Will, "Laser-induced incandescence: Particulate diagnostics for combustion, atmospheric, and industrial applications," Prog. Energy Combust. Sci. 51, 2-48 (2015).
20. E. A. Rohlfing, "Optical emission studies of atomic, molecular, and particulate carbon produced from a laser vaporization cluster source," The Journal of Chemical Physics 89, 6103-6112 (1988).
Proposed TOC thumbnail:
| Wavelength (nm) | Background Noise (mV) | IR Signal (mV) |
|----------------|----------------------|----------------|
| 437.661        | 19.55                | 19.6           |
| 437.958        | 19.55                | 19.6           |
| 438.524        | 19.55                | 19.6           |
| 438.548        | 19.55                | 19.6           |
| 438.844        | 19.55                | 19.6           |
| 439.139        | 19.55                | 19.6           |
| 439.457        | 19.55                | 19.6           |
| 439.734        | 19.55                | 19.6           |
| 440.072        | 19.55                | 19.6           |
| 440.329        | 19.55                | 19.6           |
| 440.618        | 19.55                | 19.6           |
| 440.944        | 19.55                | 19.6           |
| 441.210        | 19.55                | 19.6           |
| 441.508        | 19.55                | 19.6           |
| 441.805        | 19.55                | 19.6           |
| 442.092        | 19.55                | 19.6           |
| 442.292        | 19.55                | 19.6           |
| 442.486        | 19.55                | 19.6           |
| 442.943        | 19.55                | 19.6           |
| 443.757        | 19.55                | 19.6           |
| 443.873        | 19.55                | 19.6           |
| 444.167        | 19.55                | 19.6           |
| 444.462        | 19.55                | 19.6           |
| 444.758        | 19.55                | 19.6           |
| 445.059        | 19.55                | 19.6           |
| 445.345        | 19.55                | 19.6           |
| 445.641        | 19.55                | 19.6           |
| 445.948        | 19.55                | 19.6           |
| 446.264        | 19.55                | 19.6           |
| 446.532        | 19.55                | 19.6           |
| 446.826        | 19.55                | 19.6           |
| 447.121        | 19.55                | 19.6           |
| 447.417        | 19.55                | 19.6           |
| 447.714        | 19.55                | 19.6           |
| 448.009        | 19.55                | 19.6           |
| 448.304        | 19.55                | 19.6           |
| 448.601        | 19.55                | 19.6           |
| 448.896        | 19.55                | 19.6           |
| 449.191        | 19.55                | 19.6           |
| 449.487        | 19.55                | 19.6           |
| 449.781        | 19.55                | 19.6           |
| 450.076        | 19.55                | 19.6           |
| 450.372        | 19.55                | 19.6           |
| 450.667        | 19.55                | 19.6           |
| 450.952        | 19.55                | 19.6           |
| 451.206        | 19.55                | 19.6           |
| 451.501        | 19.55                | 19.6           |
| 451.806        | 19.55                | 19.6           |
| 452.101        | 19.55                | 19.6           |
| 452.402        | 19.55                | 19.6           |
| 452.703        | 19.55                | 19.6           |
| 453.034        | 19.55                | 19.6           |
| 453.329        | 19.55                | 19.6           |
| 453.624        | 19.55                | 19.6           |
| 453.919        | 19.55                | 19.6           |
| 454.212        | 19.55                | 19.6           |
| 454.506        | 19.55                | 19.6           |
| 454.806        | 19.55                | 19.6           |
| 455.104        | 19.55                | 19.6           |
| 455.397        | 19.55                | 19.6           |
| 455.692        | 19.55                | 19.6           |
| 455.987        | 19.55                | 19.6           |
| 456.282        | 19.55                | 19.6           |
| 456.578        | 19.55                | 19.6           |
| 456.873        | 19.55                | 19.6           |
| 457.169        | 19.55                | 19.6           |
| 457.464        | 19.55                | 19.6           |
| 457.759        | 19.55                | 19.6           |
| 458.055        | 19.55                | 19.6           |
| 458.350        | 19.55                | 19.6           |
| 458.646        | 19.55                | 19.6           |
| 458.940        | 19.55                | 19.6           |
| 459.236        | 19.55                | 19.6           |
| 459.531        | 19.55                | 19.6           |
| 459.828        | 19.55                | 19.6           |
| 460.121        | 19.55                | 19.6           |
| 460.417        | 19.55                | 19.6           |
| 460.712        | 19.55                | 19.6           |
| 461.007        | 19.55                | 19.6           |
| 461.301        | 19.55                | 19.6           |
| 461.598        | 19.55                | 19.6           |
| 461.893        | 19.55                | 19.6           |
| 462.188        | 19.55                | 19.6           |
| 462.481        | 19.55                | 19.6           |
| 462.779        | 19.55                | 19.6           |
| 463.074        | 19.55                | 19.6           |
| 463.367        | 19.55                | 19.6           |
| 463.669        | 19.55                | 19.6           |
| 464.252        | 19.55                | 19.6           |
|    |          |          |          |
|----|----------|----------|----------|
| 655.8348   | 19.61667 | 28.51667 |
| 657.1253   | 19.6     | 28.4     |
| 657.4123   | 19.6     | 28.43333 |
| 657.701    | 19.6     | 28.43333 |
| 657.987    | 19.6     | 28.73333 |
| 658.2784   | 19.6     | 28.73333 |
| 658.5671   | 19.6     | 28.33333 |
| 658.858    | 19.6     | 28.38333 |
| 659.1444   | 19.6     | 29.05    |
| 659.4311   | 19.55    | 29.68333 |
| 659.717    | 19.6     | 28.86667 |
| 660.0103   | 19.53333 | 28.38333 |
| 660.299    | 19.6     | 28.71667 |
| 660.5874   | 19.6     | 29.05    |
| 660.8762   | 19.53333 | 29.05    |
| 661.1647   | 19.55    | 28.7     |
| 661.4533   | 19.6     | 29.33333 |
| 661.7419   | 19.55    | 29.33333 |
| 662.0304   | 19.6     | 29.33333 |
| 662.3189   | 19.55    | 29.56667 |
| 662.6074   | 19.6     | 29.83333 |
| 662.8959   | 19.63333 | 30.0     |
| 663.1844   | 19.65    | 29.25    |
| 663.4739   | 19.66667 | 29.45    |
| 663.7614   | 19.6     | 29.3     |
| 664.0498   | 19.61667 | 29.65    |
| 664.3383   | 19.33333 | 29.55    |
| 664.6267   | 19.33333 | 29.55    |
| 664.9151   | 19.68333 | 29.53333 |
| 665.2055   | 19.68333 | 29.85    |
| 665.4915   | 19.33333 | 29.61667 |
| 665.7803   | 19.61667 | 29.51667 |
| 666.0687   | 19.33333 | 29.96667 |
| 666.357    | 19.6     | 29.5     |
| 666.6454   | 19.61667 | 29.93333 |
| 666.9337   | 19.68333 | 29.81667 |
| 667.222    | 19.65    | 30       |
| 667.5104   | 19.61667 | 29.96667 |
| 667.7967   | 19.6     | 29.93333 |
| 668.0869   | 19.68333 | 30.16667 |
| 668.3752   | 19.61667 | 29.98333 |
| 668.6515   | 19.66667 | 30.13333 |
| 668.9552   | 19.7     | 30.5     |
| 669.2999   | 19.68333 | 30.58333 |
| 669.5927   | 19.7     | 30.5     |
| 669.8864   | 19.71667 | 30.83333 |
| 670.1046   | 19.7     | 30.5     |
| 670.3972   | 19.68333 | 30.96667 |
| 670.6908   | 19.71667 | 30.71667 |
| 670.9891   | 19.61667 | 30.56667 |
| 671.2572   | 19.68333 | 30.88333 |
| 671.5454   | 19.65    | 30.7     |
| 671.8335   | 19.73333 | 30.83333 |
| 672.1216   | 19.65    | 31.03333 |
| 672.4097   | 19.65    | 31.26667 |
| 672.6978   | 19.71667 | 30.8     |
| 672.9858   | 19.65    | 31.03333 |
| 673.2739   | 19.68333 | 31       |
| 673.5619   | 19.81667 | 30.96667 |
| 673.85     | 19.78333 | 31.18333 |
| 674.138    | 19.76667 | 31       |
| 674.426    | 19.73333 | 30.9     |
| 674.714    | 19.7     | 31.36667 |
| 675.002    | 19.73333 | 31.36667 |
| 675.29     | 19.75    | 31.4     |
| 675.5779   | 19.71667 | 31.48333 |
| 675.8659   | 19.66667 |
| 676.1533   | 19.7     | 31.68333 |
| 676.4447   | 19.66667 | 31.6     |
| 676.7296   | 19.68333 | 31.58333 |
| 677.0175   | 19.71667 | 31.65    |
| 677.3054   | 31.75    |
| 677.5933   | 20.83333 | 31.48333 |
| 677.8811   | 19.81667 | 31.5     |
| 678.169    | 19.7     | 31.83333 |
| 678.4583   | 19.7     | 31.5     |
| 678.7466   | 19.71667 | 31.71667 |
| 679.0342   | 19.73333 | 31.86667 |
| 679.3202   | 19.71667 | 31.88333 |
| 679.608    | 19.71667 | 32.2     |
| 679.898    | 19.65    | 31.86667 |
| 680.1851   | 19.71667 | 32.06667 |
| 680.4713   | 19.71667 | 31.93333 |
| 680.759    | 19.61667 | 32.38333 |
| 681.0476   | 19.73333 | 32.36667 |
| 681.3344   | 19.7     | 32.55555 |
| 681.6221   | 19.75    | 32.33333 |
| 681.9098   | 19.73333 | 32.83333 |
| 682.1975   | 19.68333 | 32.15    |
| 682.4801   | 19.7     | 32.81667 |
| 682.7728   | 19.65    | 32.41667 |
| 683.0604   | 19.8     | 32.7     |
| 683.348    | 19.75    | 32.9     |
| 683.6356   | 19.73333 | 32.98333 |
| Time  | Value1 | Value2 | Value3 |
|-------|--------|--------|--------|
| 998.6216 | 19.55 | 24.68333 |
| 998.8907 | 19.51667 | 24.53333 |
| 999.1598 | 19.53333 | 24.45 |
| 999.4288 | 19.51667 | 24.05 |
| 999.6978 | 19.5 | 24.06667 |
| 999.9668 | 19.5 | 23.9 |
| 1000.236 | 19.51667 | 23.6 |
| 1000.505 | 19.63333 | 23.48333 |
| 1000.774 | 19.51667 | 23.31667 |
| 1001.043 | 19.51667 | 23.11667 |
| 1001.312 | 19.51667 | 22.75 |
| 1001.581 | 19.6 | 22.86667 |
| 1001.849 | 19.6 | 22.63333 |
| 1002.118 | 19.56667 | 22.53333 |
| 1002.387 | 19.51667 | 22.46667 |
| 1002.656 | 19.5 | 22.46667 |
| 1002.925 | 19.51667 | 22.28333 |
| 1003.193 | 19.55 | 22.18333 |
| 1003.462 | 19.48333 | 21.85 |
| 1003.731 | 19.53333 | 21.68333 |
| 1004.000 | 19.5 | 21.4 |
| 1004.268 | 19.56667 | 21.61667 |
| 1004.537 | 19.56667 | 21.33333 |
| 1004.806 | 19.55 | 21.33333 |
| 1005.074 | 19.53333 | 21.16667 |
| 1005.343 | 19.48333 | 21.06667 |
| 1005.611 | 19.56667 | 20.93333 |
| 1005.880 | 19.56667 | 20.96667 |
| 1006.149 | 19.53333 | 20.75 |
| Date       | Time   | Value  | Time   | Value  | Time   | Value  | Time   | Value  |
|------------|--------|--------|--------|--------|--------|--------|--------|--------|
| 7/16/2002 | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  |
| 7/16/2002 | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  |
| 7/16/2002 | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  |
| 7/16/2002 | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  |
| 7/16/2002 | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  |
| 7/16/2002 | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  |
| 7/16/2002 | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  |
| 7/16/2002 | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  | 7:30AM | 585.13  |

**Note:** The table above represents the historical values of a specific parameter over a series of dates and times. The values are recorded at 7:30 AM on each date listed. The data seems to be consistent across the listed dates, indicating a steady pattern or trend. However, without more context or a specific question related to the data, the interpretation remains limited. Additional context or a specific query would be necessary to provide a more detailed analysis or answer.
| 841.0851 | 1.5601 | 806.727 | 1.5601 | 806.727 | 1.5601 |
| 841.0851 | 1.5601 | 835.027 | 1.5601 | 835.027 | 1.5601 |
| 841.0851 | 1.5601 | 825.774 | 1.5601 | 825.774 | 1.5601 |
| 841.0851 | 1.5601 | 835.045 | 1.5601 | 835.045 | 1.5601 |
| 841.0851 | 1.5601 | 825.743 | 1.5601 | 825.743 | 1.5601 |
| 841.0851 | 1.5601 | 835.016 | 1.5601 | 835.016 | 1.5601 |
| 841.0851 | 1.5601 | 825.728 | 1.5601 | 825.728 | 1.5601 |
| 841.0851 | 1.5601 | 835.061 | 1.5601 | 835.061 | 1.5601 |
| 841.0851 | 1.5601 | 825.762 | 1.5601 | 825.762 | 1.5601 |
| 841.0851 | 1.5601 | 835.036 | 1.5601 | 835.036 | 1.5601 |
| 841.0851 | 1.5601 | 825.792 | 1.5601 | 825.792 | 1.5601 |
| 841.0851 | 1.5601 | 835.003 | 1.5601 | 835.003 | 1.5601 |
| 841.0851 | 1.5601 | 825.827 | 1.5601 | 825.827 | 1.5601 |
| 841.0851 | 1.5601 | 835.076 | 1.5601 | 835.076 | 1.5601 |
| 841.0851 | 1.5601 | 825.857 | 1.5601 | 825.857 | 1.5601 |
| 841.0851 | 1.5601 | 835.101 | 1.5601 | 835.101 | 1.5601 |
| 841.0851 | 1.5601 | 825.878 | 1.5601 | 825.878 | 1.5601 |
| 841.0851 | 1.5601 | 835.118 | 1.5601 | 835.118 | 1.5601 |
| 841.0851 | 1.5601 | 825.892 | 1.5601 | 825.892 | 1.5601 |
| 841.0851 | 1.5601 | 835.132 | 1.5601 | 835.132 | 1.5601 |
| 841.0851 | 1.5601 | 825.905 | 1.5601 | 825.905 | 1.5601 |
| 841.0851 | 1.5601 | 835.145 | 1.5601 | 835.145 | 1.5601 |
| 841.0851 | 1.5601 | 825.918 | 1.5601 | 825.918 | 1.5601 |
| 841.0851 | 1.5601 | 835.158 | 1.5601 | 835.158 | 1.5601 |
| 841.0851 | 1.5601 | 825.929 | 1.5601 | 825.929 | 1.5601 |
| 841.0851 | 1.5601 | 835.168 | 1.5601 | 835.168 | 1.5601 |
| 841.0851 | 1.5601 | 825.938 | 1.5601 | 825.938 | 1.5601 |
| 841.0851 | 1.5601 | 835.178 | 1.5601 | 835.178 | 1.5601 |
|   |   |
|---|---|
| 966.885 | 3.142E+11 |
| 966.608 | 1.09E+11 |
| 966.148 | 1.205E+11 |
| 965.7229 | 1.209E+11 |
| 965.766 | 1.209E+11 |
| 965.8329 | 1.209E+11 |
| 966.0689 | 1.209E+11 |
| 966.2627 | 1.209E+11 |
| 966.5085 | 1.209E+11 |
| 966.7568 | 1.209E+11 |
| 967.003 | 1.209E+11 |
| 967.2497 | 1.209E+11 |
| 967.495 | 1.209E+11 |
| 967.7403 | 1.209E+11 |
| 968.0531 | 1.209E+11 |
| 968.2959 | 1.209E+11 |
| 968.5387 | 1.209E+11 |
| 968.7815 | 1.209E+11 |
| 969.0243 | 1.209E+11 |
| 969.2671 | 1.209E+11 |
| 969.510 | 1.209E+11 |
| 969.7528 | 1.209E+11 |
| 970.0056 | 1.209E+11 |
| 970.2584 | 1.209E+11 |
| 970.5112 | 1.209E+11 |
| 970.764 | 1.209E+11 |
| 971.0169 | 1.209E+11 |
| 971.2697 | 1.209E+11 |
| 971.5225 | 1.209E+11 |
| 971.7753 | 1.209E+11 |
| 972.0281 | 1.209E+11 |
| 972.2809 | 1.209E+11 |
| 972.5337 | 1.209E+11 |
| 972.7865 | 1.209E+11 |
| 973.0393 | 1.209E+11 |
| 973.2921 | 1.209E+11 |
| 973.5449 | 1.209E+11 |
| 973.7977 | 1.209E+11 |
| 974.0505 | 1.209E+11 |
| 974.3033 | 1.209E+11 |
| 974.5561 | 1.209E+11 |
| 974.8089 | 1.209E+11 |
| 975.0617 | 1.209E+11 |
| 975.3145 | 1.209E+11 |
| 975.5673 | 1.209E+11 |
| 975.8201 | 1.209E+11 |
| 976.0729 | 1.209E+11 |
| 976.3257 | 1.209E+11 |
| 976.5785 | 1.209E+11 |
| 976.8313 | 1.209E+11 |
| 977.0841 | 1.209E+11 |
| 977.3369 | 1.209E+11 |
| 977.5897 | 1.209E+11 |
| 977.8425 | 1.209E+11 |
| 978.0953 | 1.209E+11 |
| 978.3481 | 1.209E+11 |
| 978.5999 | 1.209E+11 |
| 978.8527 | 1.209E+11 |
| 979.1055 | 1.209E+11 |
| 979.3582 | 1.209E+11 |
| 979.611 | 1.209E+11 |
| 979.8638 | 1.209E+11 |
| Wavelength (μm) | Fit Wavelength (μm) | Interpolated Wavelength (μm) | Wavelength Counts/s | Temperature |
|-----------------|---------------------|-------------------------------|---------------------|-------------|
| 611.0648        | 463.6762             | 442.6586                      | 0.03333             | 945.45       |
| 604.995          | 423.3063             | 402.9875                      | 0.01667             | 901.13       |
| 602.0515         | 422.7719             | 387.6473                      | 0.08333             | 916.41       |
| 601.3742         | 422.0655             | 385.4712                      | 0.10281             | 901.94       |
| 600.0147         | 415.3916             | 375.9186                      | 0.14087             | 879.41       |
| 598.950          | 413.2508             | 372.9504                      | 0.03333             | 850.64       |
| 597.3476         | 411.3056             | 367.5985                      | 0.05000             | 830.13       |
| 595.961          | 409.9996             | 365.1286                      | 0.05000             | 800.64       |
| 594.689          | 408.6373             | 361.9045                      | 0.05000             | 770.13       |
| 593.388          | 407.4228             | 360.4741                      | 0.05000             | 739.64       |
| 592.136          | 406.3437             | 359.2775                      | 0.05000             | 709.13       |
| 590.916          | 405.3825             | 358.1985                      | 0.05000             | 678.64       |
| 589.725          | 404.4423             | 357.2344                      | 0.05000             | 648.13       |
| 588.554          | 403.5265             | 356.3854                      | 0.05000             | 617.64       |
| 587.394          | 402.6336             | 355.6514                      | 0.05000             | 587.13       |
| 586.244          | 401.7629             | 354.9324                      | 0.05000             | 556.64       |
| 585.098          | 400.9117             | 354.2284                      | 0.05000             | 526.13       |
| 583.955          | 399.0815             | 353.5384                      | 0.05000             | 495.64       |
| 582.796          | 397.2713             | 352.8624                      | 0.05000             | 465.13       |
| 581.627          | 395.4814             | 352.2004                      | 0.05000             | 434.64       |
| 580.438          | 393.7195             | 351.5524                      | 0.05000             | 404.13       |
| 579.241          | 391.9866             | 350.9204                      | 0.05000             | 373.64       |
| 578.023          | 390.2808             | 349.3034                      | 0.05000             | 343.13       |
| 576.779          | 388.5929             | 347.7014                      | 0.05000             | 312.64       |
| 575.501          | 386.9311             | 346.1134                      | 0.05000             | 282.13       |
| 574.184          | 385.3024             | 344.5404                      | 0.05000             | 251.64       |
| 572.825          | 383.7095             | 342.9824                      | 0.05000             | 221.13       |
| 571.395          | 382.1566             | 341.4384                      | 0.05000             | 190.64       |
| 569.903          | 380.6510             | 339.9084                      | 0.05000             | 160.13       |
| 568.314          | 379.1786             | 338.3924                      | 0.05000             | 130.64       |
| 566.679          | 377.7472             | 336.8904                      | 0.05000             | 100.13       |
| 565.048          | 376.3554             | 335.4014                      | 0.05000             | 70.64        |
| 563.354          | 374.9932             | 333.9264                      | 0.05000             | 40.13        |
| 561.639          | 373.6665             | 332.4654                      | 0.05000             | 10.13        |

**Note:** The table includes columns for wavelength, interpolated wavelength, wavelength counts per second, and temperature, with data points ranging from 600nm to 640nm.
| X  | Y  | Z  | W  | V  |
|----|----|----|----|----|
| 785.1531 | 2803.036 | 2498.036 | 10.0167 | 9.6167 |
| 785.1531 | 2803.036 | 2498.036 | 10.0167 | 9.6167 |
| 785.1531 | 2803.036 | 2498.036 | 10.0167 | 9.6167 |
| 785.1531 | 2803.036 | 2498.036 | 10.0167 | 9.6167 |
| 785.1531 | 2803.036 | 2498.036 | 10.0167 | 9.6167 |
| 785.1531 | 2803.036 | 2498.036 | 10.0167 | 9.6167 |
| 785.1531 | 2803.036 | 2498.036 | 10.0167 | 9.6167 |
| 785.1531 | 2803.036 | 2498.036 | 10.0167 | 9.6167 |
| 785.1531 | 2803.036 | 2498.036 | 10.0167 | 9.6167 |
| 785.1531 | 2803.036 | 2498.036 | 10.0167 | 9.6167 |
| 785.1531 | 2803.036 | 2498.036 | 10.0167 | 9.6167 |
| 785.1531 | 2803.036 | 2498.036 | 10.0167 | 9.6167 |
| 785.1531 | 2803.036 | 2498.036 | 10.0167 | 9.6167 |
| 785.1531 | 2803.036 | 2498.036 | 10.0167 | 9.6167 |
| Wavelength (μm) | Emission (ph/s/sr/m^2) | Temperature (K) |
|----------------|------------------------|-----------------|
| 2.06          | 0.013                  | 1616            |
| 2.16          | 0.018                  | 1667            |
| 2.36          | 0.026                  | 1756            |
| 2.56          | 0.032                  | 1924            |

Thermal blackbody emission from a single carbon black nanoparticle being heated to four different temperatures.
