Experimental observations of temperature effects in the near-field regime of the Casimir–Polder interaction

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Abstract

We investigate the temperature dependence of the Casimir–Polder interaction on the electrostatic limit. This unusual phenomenon relies on the coupling between a virtual atomic transition and a thermal excitation of surface polariton modes. We first focus on the scenario in which a Cs(8P3/2) atom is next to a CaF$_2$ or BaF$_2$ surface. Our theoretical predictions show a strong temperature dependence of the van der Waals coefficient at experimentally accessible conditions. A series of spectroscopic measurements performed in a specially designed Cs vapor cell containing a CaF$_2$ tube is presented. Our results illustrate the sensitivity of atom–surface interaction experiments to the quality and chemical stability of the surface material and emphasize the need for using more durable materials, such as sapphire. Finally, we discuss selective reflection experiments with Cs(7D3/2) in an all-sapphire cell that clearly demonstrate a temperature-dependent van der Waals coefficient.

Keywords: Casimir–Polder interaction, near field thermal emission, laser spectroscopy, van der Waals coefficient

(Some figures may appear in colour only in the online journal)

1. Introduction

Interactions between neutral but polarizable objects are ubiquitous and fundamental for our understanding of the physical world. A typical example is the long-range atom–surface force, most commonly known as the Casimir–Polder interaction [1]. In the near field, it is most commonly described as the interaction between the fluctuating dipole and its image, whereas in the far field it becomes easier to portray it as a distance-dependent Lamb shift because of the modification of vacuum or thermal fluctuations by the reflective boundary [2].

The temperature dependence of the Casimir–Polder interaction is an important consideration when comparing theory and experiment, and temperature corrections are fundamental for any precision measurement involving atoms close to surfaces [3, 4]. On a more practical side, atom–surface interactions at non-zero temperatures can be of relevance for atom or molecule chips [5–9] and for miniaturized frequency references or clocks [10, 11].

Although the effects of thermal fluctuations on the Lamb shift were demonstrated in a high-precision experiment in the early 1980s [12], the Casimir–Polder interaction was observed several years later [13] and its temperature dependence was more elusive. The only measurement demonstrating such effects was made at distances of approximately 5–10 μm, when the strength of the interaction is extremely small. Critical to experimental success [14] was an enhancement attributable to an out-of-equilibrium effect [15], when
the surface is held at a higher temperature with respect to its surrounding environment.

Looking much closer at the surface, typically at approximately 100 nm, the shift of an atomic level takes the familiar form of $-C_3 \frac{\mu}{r^3}$, where $C_3$ is the van der Waals coefficient. The classical picture of an atom interacting with its image is less accommodating for thermal effects, because the reflected field of a dipole antenna does not fundamentally depend on temperature [16, 17]. This intuition is supported by quantum electrodynamics (QED) calculations for an atom or molecule in front of a perfect or dispersion-less conductor [18].

However, material dispersion and especially surface polaritons are of great importance in the near field. In this regime, thermal emission is dominated by surface excitations and becomes almost monochromatic in contrast to the well-known broadband black body spectrum [19, 20]. Similarly, the van der Waals interaction is dominated by the resonant coupling between atom dipole transitions and surface polaritons. This is usually relevant for excited-state atoms whose couplings in the mid-infrared range coincide with surface excitations of common dielectrics. It was demonstrated that the coupling between a virtual atomic emission and a surface mode excitation can lead to extraordinary effects such as atom–surface repulsion or even giant attraction [21, 22]. The inverse effect requires a thermal excitation of the polariton modes that can now be coupled to an atomic absorption and leads to a temperature-dependent van der Waals interaction [2, 21, 23, 24]. This exotic behavior is only accessible when the thermal energy is comparable with that of the atomic transition (i.e., $\hbar \omega = k_B T$). For room temperatures, this dictates a transition wavelength of approximately 50 $\mu m$.

This reasoning essentially excludes ground state atoms and, in general, places heavy constraints on the appropriate atom surface system. An extensive study of materials [25] suggests that Cs(8P$_{3/2}$) dipole couplings 8P$_{3/2}$ $\rightarrow$ 7D$_{5/2}$ and 8P$_{3/2}$ $\rightarrow$ 7D$_{5/2}$ at 39 $\mu m$ and 36 $\mu m$, respectively (figure 1), can couple resonantly to CaF$_2$ and BaF$_2$ surface polaritons at 24 $\mu m$ and 35 $\mu m$, respectively. The dielectric properties of these materials were experimentally measured as a function of temperature [26]. We detail the theoretical predictions of the temperature dependence of the van der Waals coefficient for Cs(8P$_{3/2}$) against CaF$_2$, BaF$_2$ and sapphire surfaces. We also describe the corresponding experiments that were inconclusive because of surface quality deterioration. Finally, we briefly describe for a successful series of experiments against Cs(7D$_{5/2}$) a sapphire interface that will be reported in detail elsewhere.

2. Theoretical predictions

In the near field, the atom–surface interaction induces a free energy shift that is given by $-C_3 \frac{\mu}{r^3}$. The van der Waals coefficient depends on the surface as well as the atom and its given energy state $|i\rangle$. To calculate $C_3$, one needs to sum the contribution of all allowed dipole couplings $|i\rangle \rightarrow |j\rangle$, for which a perfect reflector is proportional to the square of the electric dipole moment matrix element $\langle i|D|j\rangle$. In the case of a real surface, this has to be multiplied by an image coefficient $r_{im}$, which depends on the dielectric properties of the surface. Ignoring the dispersive response of the material, the image coefficient is simply given by $r = (\epsilon - 1) / (\epsilon + 1)$, independent of ambient temperature, and is consistent with the classical picture of a dipole interacting with its own image in front of a surface with finite reflectivity. A complete QED description [16] is required to account for surface dispersion. A few theoretical studies have dealt with this problem in the past [23–25] and have shown that there are two contributions to the image coefficient. The first resembles a distance-dependent Lamb shift attributable to vacuum and thermal fluctuations covering the entire frequency spectrum. The second is reminiscent of the interaction between a classical oscillating dipole and its own reflected field [27]. For convenience, the former dispersive contribution will henceforth be referred to as non-resonant, $r_{nr}$, whereas the latter will be referred to as resonant, $r_{res}$.

For an upward coupling, $|i\rangle \rightarrow |j\rangle$ the resonant term takes the form:

$$n_{res} = -2\text{Re}[S(\omega_{nr})] \cdot n(\omega_{oi}, T)$$  \hspace{1cm} (1)

where $\omega_i = \omega_j - \omega > 0$ is the transition frequency and the factor $S(\omega_{oi}) = (\epsilon(\omega_{oi}) - 1) / (\epsilon(\omega_{oi}) + 1)$ is the complex surface response from which the polariton modes are defined and $n(\omega_{oi}, T) = \left[ 1 / \left( e^{\hbar \omega_{oi} / k_B T} - 1 \right) \right]$ is the mean occupation number of each mode by photons. The term in equation (1) owes its existence to temperature. In the case of a downward transition, $\omega_i < 0$, the resonant term has a similar temperature dependence given by $n(\omega_{oi}, T) = n(\omega_{oi}) + 1$ but survives even at zero temperatures because of spontaneous emission [23].

In reality, an atomic level $|j\rangle$ has numerous couplings and isolating the resonant term of a given transition is extremely difficult. In figure 2, we show the real part of the surface response as a function of frequency for calcium fluoride, barium fluoride and sapphire, with surface resonances at 24 $\mu m$, 35 $\mu m$ and 12 $\mu m$, respectively. In table 1 we show the temperature dependence of the most dominant dipole couplings, starting from the 8P$_{3/2}$ level, for each of these three materials.
**Table 1.** Contribution of each dipole coupling to the $C_3$ van der Waals coefficient between Cs($8P_{3/2}$) and (a) CaF$_2$, (b) BaF$_2$ and (c) sapphire at different temperatures. $C_3$ is measured in kH$_2$µm$^3$ and the temperature is measured in Kelvin. The negative sign denotes a downward transition. The $C_3$ value, given by the sum of each individual contribution, is also shown at the end of each table. The contributions to $C_3$ were calculated using measurements of the dielectric constant at room temperature [26].

(a) CaF$_2$

| Cs($8P_{3/2}$) | $\lambda$ (µm) | $C_3$ (perfect reflector) | $C_3$ ($T = 0$) | $C_3$ ($T = 200$) | $C_3$ ($T = 400$) | $C_3$ ($T = 600$) | $C_3$ ($T = 800$) | $C_3$ ($T = 1000$) |
|---------------|-----------------|---------------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| $8S_{1/2}$    | −6.78           | 12.07                     | 2.17             | 2.19             | 2.17             | 1.27             | 0.38             | −0.56            | −1.52            |
| $7D_{3/2}$    | 39.05           | 5.32                      | 3.11             | 2.92             | 1.93             | 1.93             | 0.69             | −0.63            | −1.99            |
| $7D_{5/2}$    | 36.09           | 37.79                     | 21.8             | 19.98            | 11.19            | 1.19             | 0.19             | −11.5            | −23.48           |
| $9S_{1/2}$    | 8.94            | 11.63                     | 5.19             | 5.44             | 6.41             | 6.41             | 7.61             | 8.88             | 10.19            |
| $8D_{5/2}$    | 4.92            | 3.7                       | 1.51             | 1.75             | 1.71             | 1.71             | 1.9              | 2.09             | 2.3              |
| **Total**     |                |                           | 34.94            | 33.04            | 23.73            | 12.05            | −0.37            | −13.09           |

(b) BaF$_2$

| Cs($8P_{3/2}$) | $\lambda$ (µm) | $C_3$ (perfect reflector) | $C_3$ ($T = 0$) | $C_3$ ($T = 200$) | $C_3$ ($T = 400$) | $C_3$ ($T = 600$) | $C_3$ ($T = 800$) | $C_3$ ($T = 1000$) |
|---------------|-----------------|---------------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| $8S_{1/2}$    | −6.78           | 12.07                     | 3.14             | 2.86             | 2.09             | 1.23             | 0.34             | −0.56            | −1.83            |
| $7D_{3/2}$    | 39.05           | 5.32                      | 3.04             | 0.71             | −5.84            | −13.19           | −20.77           | −28.43           |
| $7D_{5/2}$    | 36.09           | 37.79                     | 21.07            | −11.44           | −105.46          | −211.34          | −320.54          | −431.09          |
| $9S_{1/2}$    | 8.94            | 11.63                     | 5.13             | 5.49             | 6.49             | 7.62             | 8.79             | 9.97             |
| $8D_{5/2}$    | 4.92            | 3.7                       | 1.52             | 1.58             | 1.75             | 1.94             | 2.13             | 2.33             |
| **Total**     |                |                           | 35.06            | 0.42             | −99.69           | −212.4           | −328.64          | −446.33          |

(c) Sapphire

| Cs($8P_{3/2}$) | $\lambda$ (µm) | $C_3$ (Perfect reflector) | $C_3$ ($T = 0$) | $C_3$ ($T = 200$) | $C_3$ ($T = 400$) | $C_3$ ($T = 600$) | $C_3$ ($T = 800$) | $C_3$ ($T = 1000$) |
|---------------|-----------------|---------------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| $8S_{1/2}$    | −6.78           | 12.07                     | 1.55             | 1.52             | 1.19             | 0.54             | −0.26            | −1.13            |
| $7D_{3/2}$    | 39.05           | 5.32                      | 3.9              | 3.92             | 3.87             | 3.75             | 3.6              | 3.44             |
| $7D_{5/2}$    | 36.09           | 37.79                     | 27.57            | 27.65            | 27.2             | 26.24            | 25.03            | 23.71            |
| $9S_{1/2}$    | 8.94            | 11.63                     | 7.32             | 7.37             | 7.98             | 9.21             | 10.73            | 12.4             |
| $8D_{5/2}$    | 4.92            | 3.7                       | 2.17             | 2.18             | 2.24             | 2.36             | 2.51             | 2.67             |
| **Total**     |                |                           | 44.14            | 44.27            | 44.13            | 43.78            | 43.32            | 42.84            |

as calculated using the QED theory described in [23] and data for the dielectric constants given in [26]. As can be verified in table 1, the temperature dependence of the $C_3$ coefficient is predominantly attributable to dipole couplings that are close to the respective polariton resonances. In the case of BaF$_2$ and CaF$_2$, these are the $8P_{3/2} \rightarrow 7D_{3/2}$ and $8P_{3/2} \rightarrow 7D_{5/2}$ couplings. In the case of sapphire, these couplings clearly are out of the range of the surface polariton and their temperature dependence is modest. It is worth noticing that the $8P_{3/2} \rightarrow 9S_{1/2}$ coupling at $8.94$ µm, which is closer to the sapphire surface resonance, practically cancels any temperature dependence induced by the dominant coupling at $36$ µm. A close examination of table 1 is very instructive. It reveals the complexity of the $C_3$ dependence on temperature and illustrates the importance of Casimir–Polder-type experiments for our understanding of the electromagnetic properties of materials and surfaces. It is also worth mentioning that the temperature dependence of the dielectric constant itself [26] has been here neglected when calculating the values in table 1. In figure 2, the dotted lines show the surface response when the surface is at $T = 770$ K. The effects are dramatic for the polariton resonances but not for the rest of the spectrum. Our predictions for $C_3$ are almost unaffected in the case of sapphire and CaF$_2$, but they need to be revised for BaF$_2$ [26].

### 3. Selective reflection experiments on the $6S \rightarrow 8P$ line

Frequency modulated (FM) selective reflection at the interface between a window and vapor is one of the few linear spectroscopic methods providing a signal with sub-Doppler resolution [10–16]. Extensive theoretical and experimental studies have shown that, in its simplest form, it is sensitive to atoms typically within a distance of $\lambda/2\pi$ from the surface of the window. This unique characteristic makes it ideal to probe atom–surface interactions in the near-field regime [20–23]. The van der Waals coefficient is measured by comparing the experimentally obtained spectra to a library of theoretical curves [22]. Using a fitting process, we extracted $C_3$, the transition line width $\Gamma$ and the collisional shift $\delta$. This well-established method has been repeatedly used in the past to measure the van der Waals coefficient [16–18]. Note that in most cases the shift of a given transition is governed solely by the van der Waals interaction of the high-lying state.

The experiments that are reported here were performed on the third resonance line of Cs at 388 nm [37, 38]. Initially, we used an extended cavity laser system with a diode emitting at the ultraviolet (UV) spectral range. Unfortunately, the power output was limited to 1 to 2 mW and the beam quality...
The CaF$_2$ tube is inserted inside the cell, almost in contact with the main body of the cell, onto which the sidearm is attached. A phire and the other one made of Y AG. A hole is drilled in the window and the main body of the cell, which is made out of the different thermal expansion coefficients between the CaF$_2$ interface. The temperature of the cell is controlled by independent ovens. The first and second ovens formed on the CaF$_2$ interface. The temperature of the cell is negligible and does not affect the selective reflection that is performed at low temperatures to ensure that Cs density within the gap stays very close to the BaF$_2$ polariton at 35 μm, on the wings of the CaF$_2$ polariton at 24 μm, and very far away from the sapphire polariton at 12 μm.

Eventually, this source was replaced by an amplified, frequency-doubled 780 nm laser diode with a final output power of approximately 100 mW at UV wavelengths. This frequency source had the additional advantage of allowing us to scan both the 6S$_{1/2}$ → 8P$_{1/2}$ line at 387.6 nm and the 6S$_{1/2}$ → 8P$_{3/2}$ line at 388.8 nm. The source with the UV diode was frequency modulated by applying a voltage on the piezoelectric element attached to the grating of the extended cavity laser. The frequency-doubled source was modulated by double-passing the beam through an acousto-optic modulator. A saturated absorption was performed in a slightly heated (~80 °C) sapphire vapor cell. Additionally, we used a stable Fabry–Perot cavity with a free spectral range of 83 MHz as a frequency marker. These auxiliary experiments allowed us to determine the absolute frequency of the laser throughout our scans with an accuracy of a few MHz.

In figure 3, we show the vapor cell in which selective reflection measurements were performed. The design was identical to the one described in a previous publication [35], but this time no impurities were present. The fabrication of a vapor cell with CaF$_2$ windows was technically challenging because of the different thermal expansion coefficients between the window and the main body of the cell, which is made out of sapphire. The cell has a T-shape, with one window made of sapphire and the other one made of YAG. A hole is drilled in the main body of the cell, onto which the sidearm is attached. A CaF$_2$ tube is inserted inside the cell, almost in contact with the YAG window. The small gap between the tube and the window is approximately 100 μm. This part of the cell is kept at low temperatures to ensure that Cs density within the gap stays negligible and does not affect the selective reflection that is performed on the CaF$_2$ interface. The temperature of the cell is controlled by independent ovens. The first and second ovens control the temperature of the sapphire window and the CaF$_2$ tube, respectively. The third controls the sidearm (reservoir) temperature and, therefore, the Cs density inside the cell. To avoid Cs condensation on the tube or the window, the upper part of the cell is always kept at slightly higher temperatures than the sidearm. Repeated attempts to fabricate a similar cell with a BaF$_2$ tube were unsuccessful because of the fragility and chemical instability of the material at high temperatures [39].

Typically, we record selective reflection spectra on the CaF$_2$ tube and the sapphire window simultaneously. Our well-established experimental protocol is as follows. First, for a given window temperature we vary the Cs vapor pressure, therefore changing the transition line width because of pressure broadening and the collisional shift. The same process is repeated for both the $F = 3 \rightarrow F' = 3, 4, 5$ and the $F = 4 \rightarrow F' = 3, 4, 5$ manifolds of the 6S$_{1/2}$ → 8P$_{3/2}$ transition, whose spectra are fundamentally different because of the different relative weight of the hyperfine transitions. Unfortunately, it soon became evident that the quality of the CaF$_2$ tube started to deteriorate after use at high temperatures in the presence of chemically aggressive Cs vapor. The most striking effect was the fact that the material became porous and Cs in the gas phase infiltrated the tube. This meant that a parasitic Doppler shaped absorption induced by Cs atoms inside the tube was always superimposed on the selective reflection spectrum.

We nonetheless finished an extensive series of measurements. In figure 4, we show two simultaneously recorded selective reflection spectra on the CaF$_2$ and sapphire interfaces. Initially, we attempted to fit the spectra by imposing the same parameters for the vapor line width $\Gamma$ (including pressure broadening) and for the collisional shift $\delta$, as compared with the saturated absorption reference, which should remain a fraction of $\Gamma$. This is a reasonable restriction under the assumption that the vapor pressure within the cell is only controlled by the Cs reservoir in the sidearm of the cell. However, in our case the porous CaF$_2$ tube also acts as an independent reservoir, making it impossible to assign a uniform value to $\Gamma$ and $\delta$ throughout the cell. We therefore fitted each spectrum independently and this gave satisfactory results, as can be verified in figure 4. Given the state of the CaF$_2$ tube, it was rather surprising that all of the measurements and fits allowed us to consistently extract the values for the $C_3$ coefficient that are shown in figure 5 as a function of the window temperature. The experimental results are at odds with theoretical predictions, which are also shown in the same figure.

Finally, we attempted to fit our experimental spectra using a potential of the form $-C_3 f^{z_3}$ to describe the interaction between the atom and the surface. This potential could result if the surface is electrically charged or somehow contaminated with Cs adsorbents [4, 40, 41]. For this purpose, a new library of curves was produced and the fitting process was repeated using $C_3$, $\Gamma$ (line width) and $\delta$ (collisional shift) as independent parameters. The quality of the fits was satisfactory; however, the values of $\Gamma$ and $\delta$ required to produce those fits were unreasonable and inconsistent with previous spectroscopic measurements on the 6S$_{1/2}$ → 8P$_{3/2}$ line [37]. In figure 6, we can see the collisional shift, as extracted from the fits of experimental spectra using both $-C_3 f^{z_3}$ (solid points) and $-C_3 f^{z_2}$ (open points). Data are

![Figure 2. The real part of the image coefficient for CaF$_2$, BaF$_2$ and sapphire as a function of wavelength [26]. The solid curve represents measurements at room temperature, whereas the dashed curve represents measurements made at $T = 770$ K. The position of the dominant dipole couplings is shown as a vertical dashed line. The dominant coupling $8P^{(3)}_{3/2} \rightarrow 7D_{3/2}$ at 36.09 μm is very close to the BaF$_2$ polariton at 35 μm, on the wings of the CaF$_2$ polariton at 24 μm, and very far away from the sapphire polariton at 12 μm.](image-url)
presented for both sapphire (circles) and CaF₂ (squares) windows. It is clear that, even at low pressures, one needs to impose a large positive collisional shift when fitting with a $-C_3/z^2$ potential, something that is artificial in normal conditions. Moreover, the previously reported collisional shift was approximately $-60 \text{ MHz Torr}^{-1}$ [37], a measurement that is only supported when fitting with $-C_3/z^3$ potential.

These arguments lead to the conclusion that our measurements cannot be explained with a $-C_3/z^2$ potential, and that we can have relative confidence in the values extracted for the van der Waals coefficient. However, it seems that the chemical nature of the surface was significantly altered and this dramatically modifies the polariton resonances relative to what we have supposed for our theoretical calculations. Note, in particular, that an ideal roughness is assumed when converting the bulk properties of the material from measured values of the dielectric constant into surface polariton modes.

4. Selective reflection experiments on the $6P \rightarrow 7D$ line

The fragility of CaF₂ has forced us to turn our attention to different materials such as sapphire, which has been used for this purpose in the past and has been remarkably stable in the presence of alkali vapors [42, 43]. Moreover, technology allows the fabrication of all-sapphire vapor cells that can withstand very high temperatures. For our selective reflection experiments that are naturally sensitive to the quality of the windows, we have acquired specially designed all-sapphire vapor cell with a sidearm that can be heated to almost 1000°C, made by the group of Sarkisyan [43]. The main window was super-polished, with an average surface roughness of approximately 0.3 nm. This cell replaced a similar but much older one with windows of unknown quality that was initially used for our measurements.
As can be verified in table 1, the van der Waals coefficient for Cs(8P) near sapphire displays no temperature dependence [26]. Therefore, we needed to find another atomic level for which a dominant dipole coupling is closer to the sapphire polariton at 12 μm. An obvious candidate is Cs(7P1/2), whose coupling with 6D3/2 is at 12.15 μm [21]. Probing the weak 6S1/2 → 7P1/2 transition at 459 nm is, however, difficult because of the lack of low-noise laser sources at this wavelength [34]. Moreover, this coupling is so close to the sapphire polariton that it becomes sensitive to the surface quality and therefore it is challenging to ascertain a theoretical prediction.

Instead, we chose Cs(7D3/2) as our first candidate. This level has an upward coupling, 7D3/2 → 5F5/2, at 10.8 μm (figure 1), whereas the couplings at 36 μm and 39 μm are far from the sapphire resonance (figure 2). The relatively small transition wavelength suggests that temperature needs to be substantially increased before a change of the van der Waals coefficient can be observed. For our experiments, the atoms are first pumped with a high-power laser to the Cs(6P1/2) level, and from there selective observed. For our experiments, the atoms are first pumped with a

Figure 6. Values of the collisional shift as extracted from the fits of our experimental measurements. The solid circles (sapphire window) and squares (CaF2 window) represent the collisional shift obtained when fitting with a −C1/cz² potential. The open circles and squares represent the results obtained for −C2/cz² potential.

Figure 7. Selective reflection spectrum of the F = 4 → F’ = 3, 4, 5 manifold of the 6P1/2 → 7D3/2 transition. The experimental spectrum is shown with open dots. The sapphire window temperature was T = 500 K. The best fit (solid line) was obtained for C3 = 59 kHz μm³, Γ = 17 MHz and δ = 0. The dashed curves represent fits for which we imposed a C3 value different by ±15%.

5. Conclusions

We have provided an overview of selective reflection experiments aimed at measuring the temperature dependence of the Casimir–Polder interaction between an atom and a surface in the near-field regime. Initial measurements were performed in a specially designed cell containing a CaF2 tube on the 6S1/2 → 8P3/2 transition of Cs. Even though theoretical estimates predicted a strong variation of C3 with temperature, this was not observed. The reason for this surprising fact is the deterioration of the CaF2 tube, which makes it impossible to predict the polariton modes on which the temperature dependence of the van der Waals coefficient critically relies. For this reason, we did not further pursue the fabrication of a BaF2 cell even though the predicted thermal effects are huge. Instead, we focused on an all-sapphire cell. Our measurements on the 6P1/2 → 7D3/2 line of Cs show a C3 temperature dependence that agrees with our QED calculations. It is clear from our theoretical predictions that the temperature dependence of the van der Waals interaction is specific to the atom–surface system in question. In the future, one could take advantage of this phenomenon to tune or even eliminate atom–surface interactions at a specific temperature.

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