Absorption coefficients of the negative helium ion

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ABSTRACT
Free–free absorption coefficients of the negative helium ion are calculated by a phase-shift approximation, using continuum data that accurately account for electron–atom correlation and polarization. The approximation is considered to yield results within a few per cent of numerical values for wavelengths greater than 1 μm, over the temperature range 1400–10 080 K. These coefficients are expected to give the best current estimates of He⁻ continuous absorption.

Key words: atomic data – atomic processes – stars: atmospheres – infrared: general.

1 INTRODUCTION
He⁻ is an important source of continuous opacity in the atmospheres of certain stars depleted in hydrogen. The interpretation of observations and the construction of models of the atmospheres of such stars require reliable continuous absorption coefficients of this negative ion. Free–free transitions are solely responsible for the radiative absorption, as He⁻ only exists in a metastable form. So far, there have been no suitable laboratory measurements of this mechanism, and theory provides the thermally averaged He⁻ free–free cross-sections used in astrophysical applications. The strong connection between the calculation of absorption coefficients and the theory of electron–atom collisions has been successfully exploited to evaluate free–free radiative transitions of negative ions. The continuum functions used in computations of free–free dipole matrix elements are the same wavefunctions as those arising in electron–atom collision studies. The scattering of electrons by neutral helium occupies a very special position in atomic and molecular physics. Apart from being one of the most extensively researched systems, by both theoretical and experimental means, e + He differential cross-sections (DCS) provide a benchmark for electron–atom and electron–molecule scattering systems generally. The most trustworthy way of calibrating cross-sections from crossed-beam experiments is by the relative flow method (Srivastava, Chutjian & Trajmar 1975). This technique puts DCS on an absolute scale by comparing intensities of scattered electrons, using the same apparatus, from two target species, one of which is known, and keeping as many parameters constant, in both experiments, to ensure proper flow conditions. This is accomplished by adjusting the capillary driving pressure, so that the mean free path for each gas at the entrance of the capillary array is the same in both experiments. Under these conditions, the DCS [(dσ/dΩ )(θ)] of the two species (labelled 1 and 2) are related by

\[ I_1 N_1(\theta) P_1 \left( \frac{d\sigma}{d\Omega} (\theta) \right)_1 \cdot I_2 N_2(\theta) P_2 \left( \frac{d\sigma}{d\Omega} (\theta) \right)_2. \]  

where \( I \) refers to the electron beam current, \( P \) to the driving pressure and \( N(\theta) \) to the scattered electron count rate. The standard species adopted in a number of current applications is helium; see, for example, recent experiments for e + H \(_2\) by Brunger et al. (1991), and for e + N \(_2\) by Brennan et al. (1992). The consensus is that the e + He scattering data of Nesbet (1979) are the most accurate for any system, for energies below 19 eV, currently available. These were used as the basis of calibration in the molecular scattering experiments referred to earlier.

Because of the common set of wavefunctions involved, He⁻ free–free absorption coefficients are expected to have the same high precision as scattering cross-sections. The situation for this negative ion is that the most recent free–free computations of Bell, Berrington & Croskery (1982) show significant changes over earlier estimates (John 1968; Bell, Kingston & McIlvane 1975, and others), with increases as high as 20 per cent at low temperatures. Since thermal averaging of free–free matrix elements tends to smooth out differences from alternative methods and approximations, changes in absorption coefficients above 10 per cent were not expected. In an earlier paper (John 1994a), we discussed these anomalies with reference to the soft photon limit. It is possible to extend discussion to higher frequencies in the IR range, as a result of improved methods for approximating matrix elements (John 1993, 1994b). These techniques, which express matrix elements in terms of phase shifts, were developed for the computation of free–free transitions of the negative hydrogen ion, and, in the present paper, we adapt these methods to evaluate free–free absorption from the
negative helium ion. In order to achieve high precision in continuum states in electron–helium interactions, it is necessary to make a multiconfiguration representation of the target with ten or more orbitals and apply configuration interaction methods. Here, we limit discussion to cases that attain this level of sophistication.

2 THEORY

Free-free absorption coefficients of He\(^{-}\), at wavelength \(\lambda(\mu\text{m})\) and temperature \(T(\text{K})\), can be calculated from the standard dipole radiation formula:

\[
K_\lambda(T) = 2.043 \times 10^{-19}[1 - \exp(-\beta \Delta k^2)] \Delta k^2 T^{-5/2} \\
\times \int_0^\infty \exp(-\beta k^0) \sigma(k_0, k^2) \, dk^0 \, \text{cm}^3 \, \text{dyne}^{-1}
\]

\[\beta = 157873/(T \text{[K]}),\]

where \(k_0^2\) and \(k^2\) (given in Ryd 13.605 eV) refer to the initial energy and final energy of the electron undergoing a transition, \(\Delta k^2 = k^2 - k_0^2\) is the photon energy \(\lambda(\mu\text{m}) = 0.09113/\Delta k^2\), and

\[
\sigma(k_0, k^2) = 4(k_0 k_1)^{-1} \sum_{L=0}^\infty (L+1) [M(L, k_0^2; L+1, k^2)]^2
\]

\[+ M(L+1, k^2; L, k^2)]^2.
\]

\(M(L_0, k_0^2; L_1, k_1^2)\) correspond to the matrix elements for radiative transitions of the system between states of total orbital angular momentum \(L_0\), \(L_1\) and electron energies \(k_0^2\) and \(k_1^2\). Coefficients defined by equations (2) and (3) take account of selection rules, include stimulated emission and have been averaged over a Maxwellian distribution. \(K_\lambda(T)\) is expressed in units, per unit electron pressure, per neutral helium atom. The exponential factor in (2) ensures that results are strongly weighted to low-energy continuum states, and hence we only need consider elastic scattering. In free-free absorption, the dipole length formalism is considered the most accurate method of evaluating matrix elements, and, at low frequencies, these elements are dominated by integrals of radial functions of the electron undergoing transitions, and simplify to

\[
M(L_0, k_0^2; L_1, k_1^2) = \int_0^\infty \! r F_L(k_0, r) F_L(k_1; r) \, dr.
\]

Radial functions have the asymptotic form

\[
F_L(k^2; r) = \sin[kr - (L \pi/2) + \eta_L(k^2)] + [L(L+1)/(2kr)]
\times \cos[kr - (L \pi/2) + \eta_L(k^2)] + O(r^{-2}),
\]

so that dipole integrals can be expanded as a function of \(\Delta k^2:\)

\[
\int_0^\infty \! r F_L(k_0, r) F_L(k_1; r) \, dr
\]

\[= [\Delta k^2]^{-2} I(L_0, k_0^2; L_1, k_1^2) + O(1),
\]

where

\[
I(L_0, k_0^2; L_1, k_1^2) = \sin[(L_0 - L_1) \pi/2] \sin[\eta_L(k_0^2) - \eta_L(k_1^2)]
\times [2k_0^2 + (k_1^2 - k_0^2)(2 + L_1(L_1 + 1) - L_0(L_0 + 1))/2],
\]

where \(\eta_L(k^2)\) are the e–He scattering phase shifts. The approximation

\[
(\Delta k^2)^4 \sigma_L(k_0^2, k_1^2) = 4(k_0 k_1)^{-1} \sum_{L=0}^\infty (L+1) [M(L, k_0^2; L+1, k_1^2)]^2
\]

\[+ M(L+1, k_1^2; L, k_1^2)]^2,
\]

which we shall refer to as the 'phase-shift approximation', is an improvement on an earlier version (John 1966), where matrix elements were approximated by

\[
(\Delta k^2)^4 |M(L, k_0^2; L+1, k_1^2)|^2 = 2k_1^2 \sin[\eta_L(k_1^2) - \eta_L(k_1^2)]
\]

\[+ M(L+1, k_1^2; L, k_1^2)]^2,
\]

Equations (8) and (9) give identical results for s→p transitions \((L=0)\), Dalgarno & Lane (1966) gave the alternative approximation

\[
\sigma_L(k_0^2, k_1^2) = (\Delta k^2)^{-4} 4k_0 k_1 [k_0^2 Q_m(k_0^2) + k_1^2 Q_m(k_1^2)],
\]

where \(Q_m(k^2)\) is the momentum transfer cross-section (in units \(\pi a_0^2\)). This approximation can be expressed in a similar form to (9):

\[
(\Delta k^2)^4 |M(L, k_0^2; L+1, k_1^2)|^2 = 2k_1^2 \sin[\eta_L(k_1^2) - \eta_L(k_1^2)]
\]

\[+ M(L+1, k_1^2; L, k_1^2)]^2,
\]

since \(Q_m(k^2)\) is given by

\[
Q_m(k^2) = 4k^{-2} \sum_{L=0}^\infty (L+1) \sin^2[\eta_L(k^2) - \eta_L(k^2)].
\]

The phase-shift and Dalgarno & Lane methods give 'exact' free–free absorption coefficients at very low frequencies, but their reliability is reduced as wavelengths and temperatures are lowered. In a recent application to H\(^{-}\) absorption (John 1993, 1994b), it was found that the phase-shift method tended to overestimate coefficients, whilst the Dalgarno & Lane method underestimated values. For example, with the application of the close-coupling method including six target states (Bell & Berrington 1987), the most sophisticated H\(^{-}\) computation so far, for wavelengths greater than 0.9 \(\mu\text{m}\) and the temperature range 1400–10 080 K, the phase-shift method gave a fit of coefficients to numerical values to a standard deviation of 4.9 per cent, and the Dalgarno & Lane method gave a fit to a standard deviation of 7.5 per cent. The precision of approximate coefficients was improved by taking a suitably normalized linear combination of these methods:

\[
\sigma_L(k_0^2, k_1^2) = (1 - q) \sigma_L(k_0^2, k_1^2) + q \sigma_L(k_0^2, k_1^2).
\]

For example, taking \(q = 0.5\), that is the mean of the Dalgarno & Lane and phase-shift methods, reduced the standard deviation to 1.9 per cent. Extending the wavelength range to \(\lambda > 0.5 \mu\text{m}\), the standard deviation was 3.9 per cent. Even further improvements were possible by allowing \(q\) to have the following wavelength and temperature dependence:

\[
q = [5040 \alpha/\lambda T][1 + [5040 \alpha/\lambda T]]^{-1}.
\]

Choosing \(\alpha = 0.5\) reduced the standard deviation to 0.9 per cent for \(\lambda > 0.9 \mu\text{m}\), and to 1.3 per cent for \(\lambda > 0.5 \mu\text{m}\).
The most sophisticated theoretical calculation of electron–helium interactions undertaken so far has been made by Nesbet (1979); he made a comprehensive comparison of theoretical and experimental results. Nesbet's analysis was based on the matrix-variational method, with the 1S ground state, and 1P and 1D pseudo-states, of the helium target constructed from a 15-orbital-basis set (five s, five p, three d and two f), using configuration interaction theory. The orbitals were optimized to account for correlation and dipole and quadrupole polarizabilities of the atom. Theoretical DCS, total cross-sections and momentum-transfer cross-sections were within 2 per cent of their experi-

![Figure 1](https://academic.oup.com/mnras/article-abstract/269/4/871/982095)

Figure 1. Scaled He$^-$ free–free absorption coefficients $A_\lambda(T)$, calculated by the phase-shift and Dalgarno & Lane methods from the phases of Nesbet (1979). $K_\lambda$ is given in units of $10^{-26}$ cm$^4$ dyne$^{-1}$ and $\lambda$ is in μm. 1 – the phase-shift method; 2 – the Dalgarno & Lane method.

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mental counterparts. Effective range theory allows e+He elastic scattering phase shifts to be expressed in the form
\[
\tan \eta(k^2) = \left\{ \begin{array}{l}
\frac{\pi - A_0(k) k [1 + (4/3) \alpha_3 k^2 \ln k] - (1/3) \pi \alpha_3 k^2]}{\eta_1(k^2)}, \\
\eta_1(k^2) = A_1(k) k^2,
\end{array} \right.
\]

\[
\tan \eta_L(k^2) = \pi \alpha_3 k^2 (2L - 1) (2L + 1) (2L + 3)^{-1} \quad (L \geq 2),
\]

(15)

where \( \alpha_3 (1.384 \, a_0^3) \) is the polarizability of the target, and \( A_0(k) \) and \( A_1(k) \) are slowly varying functions of \( k \). Nesbet gave tables of coefficients for cubic spline fits for \( A_0(k) \) and \( A_1(k) \), thus making it possible to generate phase shifts and cross-sections very accurately for any energy, below 16.46 eV, for the helium atom. Bell et al. (1982) and O'Malley, Burke & Berrington (1979) adopted similar approximations.

**Figure 2.** Scaled He\(^+\) free-free absorption coefficients \( A_L(\lambda) \), calculated from equation (13) and the phases of Nesbet (1979). \( K_L \) is given in units of \( 10^{-26} \text{ cm}^4 \text{ dyne}^{-1} \) and \( \lambda \) is in \( \mu \text{m} \). Dashed line: the mean \( \langle q = 0.5 \rangle \); solid lines: results given by equations (13) and (14) \( 1, \lambda = 0.4; 2, \lambda = 0.5; 3, \lambda = 0.6 \).
They used the R-matrix method with target states (1S, 1P, 1D) constructed from 10 orbitals (the Hartree–Fock 1s orbital and nine pseudo-orbitals 2s to 4f), using similar configuration interaction techniques. O’Malley et al.’s phase shifts and scattering cross-sections were in excellent agreement with the results of Nesbet. Bell et al. (1982) used their wavefunctions to calculate He\(^+\) free–free absorption coefficients, and claimed good agreement with O’Malley et al.’s results, but they did not publish details of their scattering data. The most important differences between Bell et al.’s and O’Malley et al.’s continuum wavefunction computations were that the former required the Buttle correction method to overcome the slow convergence of wavefunctions at the R-matrix boundary, they did not include improvements ensuring the correct long-range behaviour of closed-channel wavefunctions, and they omitted 4f\(^-\) terms in the 1S and 1D states in order to speed computations. Phase-shift analysis of experimental data for the angular distribution of electrons scattered from helium offers an alternative and independent method of obtaining scattering results; Williams’ (1979) phases cover the widest energy range (0.5–20 eV) from this source published so far. Nesbet’s phase shifts and momentum-transfer cross-sections were in excellent agreement with the results of O’Malley et al.; similarly, the phases of Nesbet and of Williams were in good accord with each other. The consensus is that errors in Nesbet’s phases and cross-sections are at most 1 per cent, and hence they correspond to the case giving the most accurate scattering data for any atom or molecule currently available, and this explains their adoption in calibrating cross-sections for other systems. He\(^+\) free–free absorption coefficients based on Nesbet’s wavefunctions should be of comparable precision to the scattering results.

### 3 RESULTS AND DISCUSSION

Apart from the calculations of Bell et al. (1982), coefficients for the free–free absorption from He\(^+\) have been based on methods that reduce matrix elements to expressions involving phase shifts. The first estimates, by Sommerville (1965), used a method due to Ohmura & Ohmura (1960, 1961), in which s-states are given by their asymptotic form and p-states are represented by plane waves. This approach only allowed for s-p transitions of the system and is equivalent to the Dalgarno & Lane method (equation 10), with momentum-transfer cross-sections replaced by their elastic scattering counterparts. McDowell, Williamson & Myrskog (1966) and Bell et al. (1975) used similar methods to Ohmura & Ohmura and allowed for p-p transitions; Bell et al. also corrected matrix elements for long-range polariza-

#### Table 1. Contributions from the various transitions to He\(^+\)  

<table>
<thead>
<tr>
<th>(\lambda (\mu m))</th>
<th>Transition</th>
<th>(\theta = 0.5)</th>
<th>1.0</th>
<th>2.0</th>
<th>3.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-p</td>
<td>0.119</td>
<td>0.172</td>
<td>0.237</td>
<td>0.306</td>
<td></td>
</tr>
<tr>
<td>(\infty^+)</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.121</td>
<td>0.173</td>
<td>0.238</td>
<td>0.307</td>
<td></td>
</tr>
<tr>
<td>9.113</td>
<td>0.177</td>
<td>0.125</td>
<td>0.082</td>
<td>0.054</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>10.074</td>
<td>14.371</td>
<td>19.685</td>
<td>25.268</td>
<td></td>
</tr>
<tr>
<td>s-p</td>
<td>1.102</td>
<td>1.584</td>
<td>2.159</td>
<td>2.758</td>
<td></td>
</tr>
<tr>
<td>3.038</td>
<td>0.019</td>
<td>0.013</td>
<td>0.008</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1.121</td>
<td>1.597</td>
<td>2.167</td>
<td>2.765</td>
<td></td>
</tr>
<tr>
<td>s-p</td>
<td>0.398</td>
<td>0.571</td>
<td>0.778</td>
<td>1.025</td>
<td></td>
</tr>
<tr>
<td>1.823</td>
<td>0.007</td>
<td>0.005</td>
<td>0.004</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.405</td>
<td>0.576</td>
<td>0.782</td>
<td>1.030</td>
<td></td>
</tr>
<tr>
<td>s-p</td>
<td>0.101</td>
<td>0.145</td>
<td>0.208</td>
<td>0.301</td>
<td></td>
</tr>
<tr>
<td>0.911</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.102</td>
<td>0.146</td>
<td>0.210</td>
<td>0.305</td>
<td></td>
</tr>
</tbody>
</table>

†For this case, entries correspond to scaled absorption coefficients in the limit \(\lambda \to \infty\).

#### Table 2. He\(^+\) free–free absorption coefficients from all transitions (coefficients are given in units of \(10^{-20}\) cm\(^4\) dyne\(^{-1}\)).

<table>
<thead>
<tr>
<th>(\lambda (\mu m))</th>
<th>(\theta)</th>
<th>0.5</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
<th>1.8</th>
<th>2.0</th>
<th>2.8</th>
<th>3.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.1878</td>
<td>0.121</td>
<td>0.134</td>
<td>0.155</td>
<td>0.173</td>
<td>0.189</td>
<td>0.202</td>
<td>0.215</td>
<td>0.227</td>
<td>0.236</td>
<td>0.275</td>
<td>0.307</td>
<td></td>
</tr>
<tr>
<td>3.6451</td>
<td>1.614</td>
<td>1.783</td>
<td>2.065</td>
<td>2.229</td>
<td>2.502</td>
<td>2.861</td>
<td>2.842</td>
<td>2.990</td>
<td>3.126</td>
<td>3.592</td>
<td>3.979</td>
<td></td>
</tr>
<tr>
<td>3.0376</td>
<td>1.121</td>
<td>1.239</td>
<td>1.435</td>
<td>1.597</td>
<td>1.737</td>
<td>1.860</td>
<td>1.971</td>
<td>2.073</td>
<td>2.167</td>
<td>2.452</td>
<td>2.765</td>
<td></td>
</tr>
<tr>
<td>2.2732</td>
<td>0.632</td>
<td>0.698</td>
<td>0.808</td>
<td>0.899</td>
<td>0.977</td>
<td>1.045</td>
<td>1.108</td>
<td>1.165</td>
<td>1.218</td>
<td>1.405</td>
<td>1.574</td>
<td></td>
</tr>
<tr>
<td>1.8225</td>
<td>0.405</td>
<td>0.447</td>
<td>0.518</td>
<td>0.567</td>
<td>0.625</td>
<td>0.670</td>
<td>0.710</td>
<td>0.747</td>
<td>0.782</td>
<td>0.910</td>
<td>1.030</td>
<td></td>
</tr>
<tr>
<td>1.5188</td>
<td>0.282</td>
<td>0.311</td>
<td>0.360</td>
<td>0.400</td>
<td>0.435</td>
<td>0.466</td>
<td>0.495</td>
<td>0.522</td>
<td>0.547</td>
<td>0.643</td>
<td>0.737</td>
<td></td>
</tr>
<tr>
<td>1.1391</td>
<td>0.159</td>
<td>0.176</td>
<td>0.204</td>
<td>0.227</td>
<td>0.247</td>
<td>0.266</td>
<td>0.283</td>
<td>0.300</td>
<td>0.316</td>
<td>0.380</td>
<td>0.444</td>
<td></td>
</tr>
<tr>
<td>0.9113</td>
<td>0.102</td>
<td>0.113</td>
<td>0.131</td>
<td>0.147</td>
<td>0.160</td>
<td>0.173</td>
<td>0.186</td>
<td>0.198</td>
<td>0.210</td>
<td>0.258</td>
<td>0.305</td>
<td></td>
</tr>
<tr>
<td>0.7594</td>
<td>0.072</td>
<td>0.079</td>
<td>0.092</td>
<td>0.103</td>
<td>0.114</td>
<td>0.124</td>
<td>0.133</td>
<td>0.143</td>
<td>0.152</td>
<td>0.190</td>
<td>0.227</td>
<td></td>
</tr>
<tr>
<td>0.6509</td>
<td>0.053</td>
<td>0.059</td>
<td>0.069</td>
<td>0.077</td>
<td>0.086</td>
<td>0.094</td>
<td>0.102</td>
<td>0.109</td>
<td>0.117</td>
<td>0.148</td>
<td>0.178</td>
<td></td>
</tr>
<tr>
<td>0.5695</td>
<td>0.041</td>
<td>0.045</td>
<td>0.053</td>
<td>0.061</td>
<td>0.067</td>
<td>0.074</td>
<td>0.081</td>
<td>0.087</td>
<td>0.094</td>
<td>0.120</td>
<td>0.145</td>
<td></td>
</tr>
<tr>
<td>0.5083</td>
<td>0.033</td>
<td>0.036</td>
<td>0.043</td>
<td>0.049</td>
<td>0.055</td>
<td>0.061</td>
<td>0.066</td>
<td>0.072</td>
<td>0.078</td>
<td>0.100</td>
<td>0.121</td>
<td></td>
</tr>
</tbody>
</table>

†Absorption coefficients for \(\lambda > 15.1878\) \(\mu\)m can be estimated by multiplying entries from this line by \(\lambda^2\).
John (1994a) showed that, at low photon energies, the coefficients of Bell et al. (1982) were incompatible with computations based on the scattering data of O'Malley et al. (1979) and Nesbet (1979).

We find it more convenient to work with the scaled absorption coefficient $A_k(T)$, which is a much more slowly varying function of wavelength,

$$A_k(T) = \lambda^{-2} K_k(T). \tag{16}$$

Applying the phase-shift and Dalgarno & Lane methods, we calculated scaled absorption coefficients of He$^-$ from the scattering data of Nesbet (1979), as defined by equation (16).

Figure 3. Scaled He$^-$ free–free absorption coefficients $A_k(T)$, calculated from equations (13) and (14), with $\alpha = 0.5$. $K_k$ is given in units of $10^{-26}$ cm$^4$ dyne$^{-1}$ and $\lambda$ is in $\mu$m. Solid line: the phases of Nesbet (1979); $\circ$: phases of O'Malley et al. (1979) (corrected values); $\times$: phases of Williams (1979).
In common with other researchers, we find it sufficient to include just the first two terms \((L=0, 1)\) in the summation of equation (3). Details of contributions from higher transitions are given in John (1994a). Our scaled absorption coefficients for selected temperatures are given in Fig. 1. These coefficients are similar to those obtained for \(H^-\) (John 1993, 1994b), in that the phase-shift method gives results in excess of values by the Dalgarno & Lane method; these differences grow as wavelengths and temperatures are lowered. It is difficult to gauge precisely the accuracy of these results, but errors are likely to exceed 10 per cent for \(\lambda < 1 \mu m\), and to exceed 20 per cent for \(\lambda < 0.5 \mu m\). The effect of corrections

\[
\begin{align*}
\text{(i) 10080 K} & \\
\text{(ii) 5040 K} & \\
\text{(iii) 2520 K} & \\
\text{(iv) 1400 K}
\end{align*}
\]

Figure 4. Comparison of scaled \(He^-\) free-free absorption coefficients \(A_\lambda(T)\) of Bell et al. (1982, 1975) and John (1968) with the current best estimates calculated from equations (13) and (14), with \(\alpha = 0.5\), using the phases of Nesbet (1979). \(K_s\) is given in units of \(10^{-25}\) cm\(^4\) dyne\(^{-1}\) and \(\lambda\) is in \(\mu m\). Solid line: present results based on Nesbet's phases; broken line: results of Bell et al. (1982); \(\times\): results of Bell et al. (1975); \(\circ\): results of John (1968).
to the phase-shift method, given by equations (13) and (14),
are shown in Fig. 2. These results correspond to the same
temperatures and atomic data as in Fig. 1. Our experience
with $H^-$ was that coefficients were relatively insensitive to
the choice of $a$. The same seems to be true for $He^-$ (see Fig.
2), where results for $a = 0.4$, $0.5$ and $0.6$ are all in good
agreement with each other and with the corresponding com-
putations with $q = 0.5$. In these circumstances, we shall
assume that $a = 0.5$ will give the most reliable $He^-$ coeffi-
cients by the corrected phase-shift method (equations 13
and 14) using Nesbet's phases. Contributions from the various
transitions at representative temperatures $[\theta = 5040/\text{K}]$
and wavelengths for this case are given in Table 1; we can
confirm that absorption is dominated by $s\rightarrow p$ transition terms.
A full set of total absorption coefficients, covering a wide
range of wavelengths and temperatures, is given in Table 2.
Scaled absorption coefficients determined by the corrected
phase-shift method ($a = 0.5$) and alternative phase-shift data
sets, the corrected results of O'Malley et al. (1979) and
values derived from a phase-shift analysis of experiments
(Williams 1979) are compared with our 'best estimates' in
Fig. 3. Values of $A_x$ from O'Malley et al.'s data hardly differ
from those obtained from Nesbet's phases. There is very
good agreement between these results and the corresponding
coefficients obtained from Williams' data. A comparison
of our 'best estimate' with some of the earlier computations is
given in Fig. 4. Major differences from the results of Bell et
al. (1982) appear at low temperatures, where Bell et al.'s
values consistently overestimate absorption. The results of
Bell et al. (1975) are in closest agreement with our 'best
estimate'. This is because the dynamic-exchange polarized
orbital phases of LaBahn & Callaway (1966), used in their
work, coincide closely with the values of Nesbet (see John
1994a). The same holds for the coefficients of John (1968)
at low frequencies. These were calculated by the original phase-
shift method (equation 9), using LaBahn & Callaway's scat-
ttering data.

4 CONCLUSIONS

The free–free absorption coefficients given in Table 2 are
expected to be the most accurate $He^-$ values currently avail-
able for the IR spectrum. Further developments are unlikely
to change results, for $\lambda > 1 \mu m$, by more than about 2 per
cent. The situation at smaller wavelengths is less certain and
requires a full wavefunction treatment with direct evaluation
of dipole radiation integrals; however, errors in Table 2 are
expected to be well below 10 per cent for the range
$0.506 \leq \lambda (\mu m) \leq 1$, and adequate for most applications.

REFERENCES

Brennan M. J., Alle D. T., Euripides P., Buckman S. J., Brunger
Phys. B, 24, 1435
144, 827
O'Malley T. F., Burke P. G., Berrington K. A., 1979, J. Phys. B, 12,
953
2659
Williams J. F., 1979, J. Phys. B, 12, 265

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