I. INTRODUCTION

The study of the van der Waals forces is at present an active field of research. Despite their weak strength these forces are ubiquitous and play a significant role in a large class of phenomena as the packing of self-assembled monolayers or the conformation properties of biomolecules as DNA or proteins. From the theoretical point of view, describing the properties of a system of weakly bound atoms or molecules is a real challenge for the most sophisticated quantum methods since a detailed description of the electron correlations is needed. For this reason, the He-dimer system where only four electrons come into play is often adopted as a test for theoretical models.1–3 However, in spite of the simple electronic structure self-consistent calculations fail to describe the attraction between He atoms which is purely due to the electron correlation effects4 and predict no minimum in the He2 potential energy curve. Better accuracy than with ab initio calculations has been achieved by describing the He–He system with semiempirical potentials fitted to the scattering cross section and to the helium bulk properties. Recently, refinement of computational tools with microhar-tree precision are becoming available for the helium dimer.5 On the experimental side, accurate measurements are required to set constraints on the calculated values and the results obtained with different techniques are employed to gain an insight into the details of the He–He interaction. In the past years He beams have been widely used to this aim. Measurements of the helium scattering cross section described by means of a realistic two-parameter potential suggested for the first time the existence of a weakly bound He2 state.6,7 In order to detect the He dimer, further measurements were performed by Mester et al. with a He beam source working at temperatures of a few hundreds of milli-Kelvin.8 However, within the accuracy of this experiment no difference between the considered potentials was observed and the dimer presence was only indirectly proved. The He2 molecule was detected in a well expanded He beam with a mass spectrometer by Luo et al.9 but no discrimination, the LJ predictions mainly fit the data, in particular the skimmer interference is taken into account. As the considered potentials only partially describe the experiments, a phenomenological viscosity cross section is proposed which represents in a satisfactory way the He flow properties over the whole range of source temperatures. © 2003 American Institute of Physics. [DOI: 10.1063/1.1580801]
and good agreement is observed with the predictions of the TTY potential. In order to complete our previous study and to provide a further contribution to the knowledge of the He–He interatomic potential we present in this paper the whole set of measurements we have performed of the flow properties of helium during a free-jet expansion. The corresponding predictions of the LJ and of the TTY potential are reported. Moreover, the data are compared with the results of new calculations performed with a potential recently proposed by Hurly and Moldover (HM). This analytical potential is obtained by means of a fitting procedure to reproduce the best \textit{ab initio} potential curves and provides estimations of the He thermodynamic quantities in good agreement with the experiments. It seems therefore very promising in describing the He flow properties over a broad temperature range. To further check this point, in the last part of this paper, calculations of the LJ and of the TTY potential are reported. Moreover, the data are compared with the results of new calculations performed with a potential recently proposed by Hurly and Moldover (HM).

The outline of the paper is as follows: In Sec. II the experimental setup is described while the calculation procedure is reported in Sec. III. In Sec. IV the data are presented and compared with the results of the calculations. In Sec. V conclusions are finally singled out.

II. EXPERIMENTAL DETAILS

The measurements are performed using the scattering apparatus described in Ref. 23. Here, the setup is slightly modified and the time-of-flight (TOF) detector is mounted opposite the helium beam source, \( \sim 169 \, \text{cm} \) far from the skimmer. A schematic diagram of the beam line is shown in Fig. 1. To produce the supersonic beam, the helium gas stagnates at pressure \( P_0 \) and temperature \( T_0 \) within the source. Hence, it undergoes a free-jet expansion in the chamber C1 through a nozzle with a diameter of 10 \( \mu \text{m} \). A conical collimator, the skimmer Sk, having an inlet orifice diameter of 0.5 mm is located in front of the nozzle on the opposite side of C1. The stage C1 is pumped by two pumps followed by a mechanical blower and a rotary pump. In detail, a 7000 l/s diffusion pump with a water cooled baffle is used in parallel with a 1000 l/s turbomolecular pump. The pressure at the blower’s inlet is measured with a capacitance diaphragm gauge and this value is multiplied by the pumping speed of the blower itself to evaluate the nozzle He flow. The maximum flow at the roll off pressure of the diffusion pump is about 5 mbar l/s, corresponding to a pressure in C1 of \( \sim 2 \times 10^{-5} \) mbar. The nozzle source is cooled down to \( T_0 \sim 20 \, \text{K} \) by a two stage cold head and heated up well above room temperature by two resistive heaters. The source temperature is read by a platinum thermometer and kept stable within 0.02 K by means of a temperature controller. The nozzle can be carefully aligned with the skimmer by a source mount with two rotational degrees of freedom and three translations. One of them allows to change the nozzle-skimmer distance, \( d_{sk} \), in the range 12–22 mm. In the stage C2, the He beam is chopped in short pulses of width \( \tau = 4.3 \, \mu\text{s} \) by a slotted disk \( \sim 20 \, \text{cm} \) far from the skimmer tip. The disk rotational frequency is stable within 0.01% so that contributions to the time-of-flight beam distribution can be neglected. The stage C2 is pumped by a 600 l/s turbomolecular pump and the working pressure is about 2.5\( \times 10^{-7} \) mbar. The modulated beam goes through three differentially pumped stages C3, C4, and C5 with pressures in the low \( 10^{-10} \) mbar range. Hence, it is ionized in C6 and mass selected in C7 by a homemade detection system. In detail, the ionizer is carefully projected to minimize the detector contribution to the measured beam time spreading, \( \Delta t_D \). This requires that the length of the region where the incoming atoms are ionized is as short as possible. Trajectory simulations of the electrons emitted from the hot filament within the present geometry suggest a ionization length of about 4 mm. The quadrupole mass filter is projected to work on mass up to 20 amu and to have a transmission greater than 95% at mass resolution \( \sim 10 \). The mass selected ions are collected by an electron multiplier and the output signal is stored in a multichannel scaler with a time channel of 1 \( \mu\text{s} \) width and a negligible dead time between channels. The working pressure in the ionization stage is in the \( 10^{-11} \) mbar range and gives a background of a few counts/s at the He-ion mass.

III. CALCULATION DETAILS

In a free-jet expansion the random thermal energy of the gas in the source is converted into the beam translational kinetic energy by means of the interatomic collisions. Hence, the velocity distribution of the gas atoms, \( f(v) \), becomes narrower and the beam temperature is reduced. This process comes gradually to an end because of the decreasing collision frequency among the atoms. This is the so-called molecular flow regime where the beam temperature approaches a constant value. The evolution of \( f(v) \) during the expansion can be calculated by means of the Boltzmann equation which is solved using the approximated method discussed in Refs. 27 and 28 suitably adapted for the present case. Briefly, the first basic assumption is to treat the beam expansion beyond the nozzle as spherical symmetric so that the flow properties
depend only on the distance from the source. Moreover, to
take into account that the velocity components along and
across the streamlines behave differently during the expan-
sion an ellipsoidal velocity distribution is assumed. This is
the product of two Maxwellian peaks with two temperatures
(denoted with $T_1$ and $T_\perp$) as parameters, i.e.,
\[
f_{\text{eff}}(\mathbf{v}) = n \left( \frac{2 \pi k_b T_1}{m} \right)^{1/2} \left( \frac{2 \pi k_b T_\perp}{m} \right)^{1/2} \exp \left( - \frac{m}{2 k_b T_1} (v_\parallel - u)^2 - \frac{m}{2 k_b T_\perp} v_\perp^2 \right),
\]
where $m$ is the He mass, $k_b$ is the Boltzmann constant, $n$ is
the atom density, and $u$ is the most probable velocity of the
gas. The evolution of the parameters $n, u, T_1,$ and $T_\perp$
with the distance from the source, $x$, is obtained by solving nu-
merically the set of four coupled integro-differential equa-
tions derived from the Boltzmann equation with the method of
moments.\textsuperscript{19}

\[
\begin{align*}
\frac{d}{dr} (nu)^2 &= 0, \quad r = \frac{x}{d_n},
\int u dr + \frac{1}{m} \frac{d}{dr} \left[ \frac{n k_b T_1}{m} + 2nk_b \right] (T_1 - T_\perp) = 0,
\int \frac{d}{dr} \left[ u^2 + \left( \frac{3k_b T_1}{m} \right) + \frac{2nk_b}{m} \right] = 0,
\frac{d}{dr} k_b T_\perp + \frac{4nu}{m} k_b T_\perp^2 = (\Delta v_\perp^2).
\end{align*}
\]

The solution is calculated by means of the standard Runge–
Kutta computation procedure.\textsuperscript{29} The integration is started at
$r = 2.5$, where the spherically symmetric model is found to
be a good approximation to describe the expansion.\textsuperscript{30} The
starting parameters are obtained from the source conditions,
$T_0$ and $P_0$, using the analytical formula of Ref. 31 for
the isentropic expanding gas. To stop the integration the ratio
$b = T_\perp / T_1$ is assumed as the convenient parameter to check
the collisional coupling among the beam atoms. In detail, $b$
= 1 within the source where the gas is in equilibrium. In
the molecular flow regime $T_\perp$ monotonically decreases to zero
because of geometrical effects while $T_1$ levels off. Hence, $b \to 0$
for $r \to \infty$. In the present calculation negligible collisional
coupling is assumed at $b \leq 0.01$. Stopping the integration
at $b = 0.005$ the flow parameters change less than 0.1%.
At the end of the expansion, the speed ratio $S = \sqrt{\frac{m}{2k_b}}$
is estimated. The interatomic forces come into play in the evolution of the velocity distribution through
the collision integral,
\[
\Omega^{(2,1)}(T_{\text{eff}}) = \frac{k_b T_{\text{eff}}}{2\pi m} \int_0^\infty Q^{(2)}(E) \gamma^5 \exp(-\gamma^2) d\gamma,
\]
where $T_{\text{eff}}$ is an effective average temperature ranging be-
 tween $T_1$ and $T_\perp$, $Q^{(2)}$ is the viscosity cross section, and $E$
is the collision energy of two atoms in the center-of-mass sys-
tem. We have calculated the scattering cross section and the
associated collision integral taking into account quantum ef-
fects which are shown to be quite important for He at tem-
p eratures below 10 K.\textsuperscript{32} For collisions between Bose–
Einstein particles,
\[
Q^{(2)}(E) = \frac{8\pi \hbar^2}{m E} \sum_{l=0,1,2,3,\ldots} \frac{(l+1)(l+2)}{(2l+3)} \sin^2(\eta_{l+2} - \eta_l),
\]
where $\eta_l$ is the phase shift of the partial wave with orbital
angular momentum $l$. Phase shifts are estimated employing
the computation procedure described in detail in Ref. 33 and
the Numerov method\textsuperscript{34,35} for the numerical integration of the
Schro"{d}inger equation.

In order to describe the He–He interactions three poten-
tial curves have been considered. The well known LJ (12-6)
potential\textsuperscript{16} is expressed as
\[
V_{\text{LJ}}(R) = 4 \epsilon \left[ \left( \frac{R_0}{R} \right)^{12} - \left( \frac{R_0}{R} \right)^6 \right],
\]
where $R$ is the interatomic distance, $\epsilon = 0.94$ meV is the
well depth, and $R_0 = 2.64$ Å is the equilibrium position. The TTY
potential\textsuperscript{18} is obtained using the perturbation theory and can
be separated in a repulsive and an attractive contribution,
\[
V_{\text{TTY}}(R) = V_{\text{rep}}(R) + V_{\text{disp}}(R).
\]
The repulsive part is given by
\[
V_{\text{rep}}(R) = DR^{(\gamma/2)-1} \exp(-2\beta R),
\]
where $\beta = \sqrt{2} E_{\text{ion}}$ and $E_{\text{ion}} = 0.9036$ a.u. (Ref. 36) is the
He ionization energy. $D = 7.449$ a.u. depends on $\beta$ and on
the amplitude of asymptotic wave function. The attractive part
is given by
\[
V_{\text{disp}}(R) = - \sum_{n=3}^{12} g_{2n}(R) C_{2n} R^{-2n},
\]
where
\[
g_{2n}(R) = 1 - \exp(-b R) \sum_{k=0}^{2n} \frac{(b R)^k}{k!},
\]
and the dispersion coefficients are calculated with the recur-
rence relation
\[
C_{2n} = \left( \frac{C_{2n-2}}{C_{2n-4}} \right)^3 C_{2n-6}
\]
starting from $C_6 = 1.461$ a.u., $C_8 = 14.11$ a.u. and $C_{10}$
= 183.5 a.u.\textsuperscript{37,38} The HM potential is also expressed as
the sum of a repulsive and of an attractive contribution in the
range $R \geq 0.3$ a.u., i.e.,
\[
V_{\text{HM}}(R) = V_{\text{rep}}(R) + V_{\text{disp}}(R).
\]

Here,
\[
V_{\text{rep}}(R) = A \exp(a_1 R + a_2 R^2 + a_3 R^{-1} + a_4 R^{-2}),
\]
where the parameters $A$ and $a_n$ are determined fitting the
potential curve to the $ab$ initio results.\textsuperscript{4,39–42} The attractive part is
The dipole–dipole term from account for relativistic effects and modify the behavior of the a.u. are assumed as starting values. The functions $h$ and $g$ are shown in detail.

![Image of graph showing interatomic potential comparison]

FIG. 2. In the upper panel the Lennard-Jones (LJ) interatomic potential for helium is compared with the potential curves proposed by Tang–Toennies–Yiu (TTY) in Ref. 18 and by Hurly–Moldover (HM) in Ref. 20. In the lower panel the corresponding viscosity cross sections $Q^{(1)}$ are plotted vs the relative energy $E$ of the colliding atoms. In the inset the oscillations of $Q^{(2)}$ are shown in detail.

$$V^{\text{HM disp}}(R) = -\sum_{n=3}^{8} \frac{g_{2n}(R)h_{2n}(R)C_{2n}}{R^{2n}};$$

$g_{2n}(R)$ is given by Eq. (3.1) but the corresponding parameter, $b$, is now obtained from the comparison with the \textit{ab initio} results. The dispersion coefficients are calculated with the recurrence relation

$$C_{2n} = \Omega_{n} \left( \frac{C_{2n-2}}{C_{2n-4}} \right)^3 C_{2n-6},$$

where the coefficients $\Omega_{n}$ are calculated in Ref. 43 and $C_{6} = 1.46097780$ a.u., $C_{8} = 14.117855$ a.u., $C_{10} = 183.691250$ a.u. are assumed as starting values.\textsuperscript{44} The functions $h_{2n}(R)$ account for relativistic effects and modify the behavior of the dipole–dipole term from $R^{-6}$ to $R^{-7}$ at large $R$. The expression of $h_{8}(R)$ is taken from Ref. 45 while for $n > 3$, $h_{2n}(R) = 1$ is assumed. The potential curves are compared in the upper panel of Fig. 2. Note that the TTY and the HM potentials behave very similarly over a wide range of interatomic distances. The LJ potential is slightly lower than the HM and the TTY ones at large $R$ while in the repulsive region the LJ curve is the steepest one. The well depth of the HM curve is intermediate between the LJ and the deepest TTY value. In the lower panel of Fig. 2 the corresponding viscosity cross sections are reported versus the collision energy. As expected, similar values are obtained for the HM and the TTY potentials especially above $10^{-3}$ meV. At lower energies the TTY cross section results only slightly higher than the HM. On the contrary, remarkably differences are observed in the LJ cross section behavior in particular in the low energy range. We remind that according to the effective range theory the asymptotic value of $Q^{(2)}$ at small $E$ is related to the energy of the bound state supported by the potential.\textsuperscript{46}

IV. RESULTS AND DISCUSSION

A. Characterization of the helium free-jet expansion

In order to investigate the helium flow properties during a free-jet expansion, more than 100 time-of-flight spectra have been collected at different nozzle-skimmer distances and source conditions. Source temperatures between 20 and 80 K and pressures in the range 2–16 bar have been considered.

In Fig. 3 some spectra measured at $d_{ns} = 20$ mm are reported. The upper panel shows that at $T_0 = 22.5K$ a narrow TOF distribution with high intensity is obtained at $P_0 = 2$ bar. On increasing the source pressure up to 4 bar the distribution broadens, the most probable beam velocity decreases and the peak intensity is dramatically reduced. At $T_0 = 79.0 K$ the peak shape evolution with pressure is different. In fact, (see lower panel) on increasing $P_0$ from 2 to 13 bar the TOF distribution becomes narrower and the intensity becomes higher. Moreover, the peak position shifts toward lower times-of-flight by about 20 $\mu$s.

To provide a quantitative estimation of the beam properties, each spectrum is fitted as the sum of a constant, taking into account for the He background in the detector stage, and a peak function $f$ describing the time distribution of the beam. Here $f(t) = A(t_0/t)^\alpha \exp\{-[t(t/t_0-1)]^\beta/\sigma^2\}$ is the Maxwellian distribution function, converted into a time scale and $A$, $t_0$, and $\sigma$ are the fitting parameters. The best fit peak is integrated to obtain the beam intensity, $I$, while the peak maximum provides the most probable beam energy $E$. The intrinsic time spreading of the beam, $\Delta t_B$, is estimated from the peak full width at half maximum (FWHM), $\Delta t_{exp}$. In detail, we assume that the measured time spreading is due to
three independent contributions, namely the chopper opening time, the detector arrival time spreading and $\Delta t_B$. Hence,

$$\Delta t_B = \sqrt{\Delta t_{\exp}^2 - \tau^2} - \Delta t_D.$$  \hfill (4.1)

$\Delta t_B$ is used to estimate the FWHM beam energy width $\Delta E = 2 E \Delta t_B / t_0$. \cite{46} Other useful parameters which describe the beam distribution are the speed ratio $S_{\exp} = 1.65 t_0 / \Delta t_B$ and the beam parallel temperature $k_B T_{\parallel, \exp} = E / S_{\exp}^2$.

The evolution of $\Delta E$ with the nozzle-skimmer distance is reported in Fig. 4 at different source pressures and temperatures. In the range 12–20 mm the beam width is observed to essentially remain constant independently from the source parameters. At 22 mm a slight broadening appears at the lowest temperature, $T_0 = 22.5$ K. This result suggests $d_{ns} \sim 20$ mm as the right tradeoff to exclude spurious contributions to $\Delta E$ which can be mainly ascribed to collisions among the beam atoms and the background gas in C1. The beam energy width and the beam intensity measured at $d_{ns} = 20$ mm are reported versus $T_0$ at different source pressures in the upper and in the lower panel of Fig. 5. It can be noted that $\Delta E$ and $I$ follow a nonmonotonic behavior. In particular, at given $P_0$ the maximum of the intensity corresponds almost to the same temperature where a minimum of the beam width is observed. The highest beam intensity is obtained at $P_0 = 16$ bar and $T_0 \sim 60$ K, corresponding to $\Delta E \sim 200$ $\mu$eV. On the other hand, an energy width lower than 100 $\mu$eV is achieved at temperatures below 35 K and $P_0 \leq 4$ bar with $I$ greater than 30% of the maximum value.

The behavior of the beam intensity is further investigated in Fig. 6, where $I$ is reported versus the ratio $P_0 / T_0$. It can be noted that the data obtained at different source pressures overlap in the low $P_0 / T_0$ region where a linear trend is followed in good agreement with theoretical predictions. \cite{49} However, on increasing $P_0 / T_0$ deviations from theory appear. The intensity curves have a maximum, hence they start to decrease suggesting that the beam loses some He atoms. Further information on this point is provided in Fig. 7, where the evolution of the beam parallel temperature with $T_0$ is shown at different source pressures and at $d_{ns} = 20$ mm. On decreasing $T_0$ the beam temperature attains a minimum value of the order of a few mK which is roughly independent from $P_0$. On further cooling the source the beam heats up and a strong increase of the signal associated with the helium dimer ion is detected. These results suggest that helium cluster condensation during the expansion causes the heating of the beam and the ob-

![FIG. 4. The beam energy width $\Delta E$ is reported vs the nozzle-skimmer distance. Open symbols are obtained at $T_0 = 22.5$ K, $P_0 = 2$ bar (◊) and 4 bar (⊙); filled symbols are obtained at $T_0 = 44$ K, $P_0 = 6$ bar (▲) and 13 bar (▼). Lines are guides for the eyes.](image)

![FIG. 5. Symbols report the He-beam intensity (lower panel) and energy width $\Delta E$ (upper panel) vs the nozzle temperature at different source pressures: □ 2 bar, △ +4 bar, ▽ 9 bar, ◇ 16 bar. Lines are guides for the eyes. Here, $d_{ns} = 20$ mm.](image)

![FIG. 6. The He-beam intensity measured at $d_{ns} = 20$ mm is reported here versus the ratio $P_0 / T_0$. Symbols correspond to different source pressures. The dotted lines are guides for the eyes. The dashed line represent the best fit of the data in the range where a linear increase is observed.](image)

![FIG. 7. Symbols show the evolution of the He-beam temperature $T_{\parallel, \exp}$ with $T_0$ at different source pressures and at $d_{ns} = 20$ mm. Lines are guides for the eyes.](image)
served increase of the beam energy width.\textsuperscript{21,50} We remark that scattering with residual gas in the source chamber can also contribute to heat the beam during a free-jet expansion. This effect is investigated in Fig. 8, where the beam energy width at $T_0 = 33$ K is compared with the results of measurements performed with the turbomolecular pump in C1 switched off. Because of the reduced pumping speed the background in the chamber increases by a factor which depends on the helium flow through the nozzle, $\Phi$, and attains the maximum value of about 1.3 at $P_0 = 16$ bar, $\Phi = 4.2$ mbar l/s. In Fig. 8 a residual gas contribution to $\Delta E$ of about 5\%, i.e., comparable with the accuracy of the data, is detected up to $P_0 = 6$ bar corresponding to $\Phi \sim 2$ mbar l/s. At higher flux the peak broadening becomes more pronounced. This result confirms that scattering with the residual gas in C1 provides only a secondary contribution to the beam heating close to the minima of Fig. 6, where $\Phi$ ranges between 1.3 and 2.8 mbar l/s.

B. Comparison of experimental and theoretical results

The flow properties of the beam are compared with the results of the calculations in Figs. 9, 10, and 11. Here, $S_{\exp}$ and $S$ calculated for LJ, TTY, and HM potentials are reported versus $T_0$ at fixed source pressure. First of all, it can be noted that the HM and the TTY curves are almost indistinguishable over the whole range of source parameters we explored. On the contrary, distinct predictions are obtained with the LJ potential especially in the low $T_0$ and high $P_0$ range where an overcooling of the TTY and the HM beams with respect to the LJ is expected. These results are easily traced back to the cross section behavior. In fact, a correlation exists between the temperature $T_i$ the beam reaches at the end of the supersonic expansion and $Q_{mp}^{(2)}$ estimated at the most probable final beam energy $E = \frac{1}{2}k_B T_i$.\textsuperscript{17} In particular, our calculations demonstrate that the TTY and HM speed ratios overcome the LJ ones whenever the energy range below $\sim 5 \cdot 10^{-3}$ meV is exploited during the last stage of the expansion. Here, the HM and the TTY cross sections are remarkably higher than the LJ curve (see Fig. 2). It is worth noting, that our description of the free jet expansion does not include cluster condensation processes. Hence, calculations predict a monotonic increase of the speed ratio with reducing $T_0$ in...
log–log straight line the tangent line to the log-
lected in order to produce a smooth cross section curve, i.e.,

$$\log$$

perature until the source temperature where the TTY and HM
range where cluster condensation can be neglected. Small
2 bar are now reproduced over the whole source parameter
pared in Figs. 9, 10, and 11 with the experiment. The data at

$$P$$

speed ratios calculated using the LH cross section are com-
pared to the corresponding calculated values. This suggests
that within our experimental conditions the beam velocity
distribution is not completely frozen at $$d_{ns}$$ and the super-
sonic expansion partly continues beyond the skimmer inlet.
However, at $$P_0$$=3 bar the agreement with the data becomes
very good over the whole source parameter range where he-
lium clustering does not significantly contribute to heat the
beam. This result further suggests that although the model
we adopt only provide a rough description of the skimmer
interference the scattering processes with the skimmer wall
can play a key role in determining the asymptotic beam
properties.

To further confirm this picture other experimental speed
ratios of the literature are compared in Fig. 12 with the cor-
responding calculations. In the upper panel measurements
from Ref. 21 are reported. This experiment has been per-
formed with a nozzle source with a nominal diameter of 5
$$\mu$$m and at $$d_{ns}=7$$ mm. Final beam temperatures between
0.64 and 1.91 mK are reached, corresponding to most prob-
able beam energies between 1.3 and 4.1 $$\times$$ 10$$^{-4}$$ meV. In good
agreement with our results we observe that the LJ potential
cannot describe the supersonic expansion in this energy
range. On the contrary, the data are quite well reproduced by
the LH curve if the expansion is stopped at the nozzle–
skimmer distance where Knudsen numbers below units are
estimated. In the lower panel measurements obtained from
Ref. 22 are shown. Here, the beam expands from a pulsed
nozzle source held at room temperature and with a nozzle
skimmer distance of 125 mm. Within this experiment the speed
ratio is observed to decrease below its maximum value at low
source temperatures and high source pressures because of
helium clustering. In this source parameter range strong dev-
ations from theory appear.

To further compare the measured speed ratio with the
calculations the data at $$P_0$$=2 bar are first considered. It can
be noted that on decreasing $$T_0$$ from the liquid nitrogen tem-
perature until the source temperature where the TTY and HM
curves cross the LJ curve the results are well described by
the LJ potential. Therefore, any further $$T_0$$ decrease makes
our data follow the TTY or HM predictions, thus overhang-
ing the expected LJ values, until they collapse because of
cluster condensation. A similar behavior is observed if the
source pressure is raised although the critical source tem-
perature for potential crossing shifts towards higher values.
This result suggests that the He–He cross section follows the
LJ behavior down to the critical energy of about $$\sim$$5 $$\times$$ 10$$^{-3}$$
meV and increases at lower energies as predicted by the TTY
and HM potentials.

To further check this point we have introduced a phe-
nomenological $$Q^{(2)}(E)$$ curve (hereafter referred to as LH)
which coincides with the HM one for $$E$$<$$E_1$$=4.3 $$\times$$ 10$$^{-5}$$
meV and with the LJ one for $$E$$>$$E_2$$=1.2 $$\times$$ 10$$^{-2}$$ meV. In the
energy range $$E_1$$–$$E_2$$ a linear dependence of log($$Q^{(2)}$$) with
log $$E$$ is assumed. The values of $$E_1$$ and $$E_2$$ have been se-
lected in order to produce a smooth cross section curve, i.e.,
to make the log–log straight line the tangent line to the loga-
thrithmic HM and LJ curves in $$E_1$$ and $$E_2$$, respectively. The
speed ratios calculated using the LH cross section are com-
pared in Figs. 9, 10, and 11 with the experiment. The data at
2 bar are now reproduced over the whole source parameter
range where cluster condensation can be neglected. Small
deviations are observed in the region where the LJ and the
HM curves cross each other which are probably to ascribe to
the arbitrariness of the linear behavior assumed between $$E_1$$
and $$E_2$$.

To gain a further insight into the He free jet expansion
the evolution of the beam properties with the nozzle-
skimmer distance has been finally investigated. Now, it is
well known that collisions with the skimmer walls can limit
the terminal He speed distribution whenever the skimmer is
reached during the final stages of the expansion. An empiri-
cal criterion to rule out the skimmer interference is to have a
local Knudsen number $$K_n$$=$$\lambda/d$$>1 at the skimmer entrance.
Here, $$\lambda$$ is the mean free path of a helium beam atom and $$d$$
is the skimmer diameter. The Knudsen number at $$d_{ns}$$=20
mm is calculated within the geometry of the present experi-
ment at different source parameters assuming $$\lambda$$=1$$/nQ_{mp}$$.
$$Q_{mp}^{(2)}$$ is the local most probable LH cross section. As in the
low $$T_0$$ and high $$P_0$$ range local Knudsen numbers below
units are obtained, calculations are repeated taking into ac-
count the skimmer contribution. In detail, the LH speed ratio
is estimated under the assumption that the He free jet expa-
ansion stops at the skimmer entrance (sudden freeze model).

The results are compared with the data in Figs. 9, 10,
and 11. First, it can be noted that at $$P_0$$=2 bar the speed
ratios measured at source temperatures of about 30 K over-
whelm the corresponding calculated values. This suggests
that within our experimental conditions the beam velocity
distribution is not completely frozen at $$d_{ns}$$ and the super-
sonic expansion partly continues beyond the skimmer inlet.
However, at $$P_0$$=3 bar the agreement with the data becomes
very good over the whole source parameter range where he-
lium clustering does not significantly contribute to heat the
beam. This result further suggests that although the model
we adopt only provide a rough description of the skimmer
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In order to confirm this picture other experimental speed
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able beam energies between 1.3 and 4.1 $$\times$$ 10$$^{-4}$$ meV. In good
agreement with our results we observe that the LJ potential
cannot describe the supersonic expansion in this energy
range. On the contrary, the data are quite well reproduced by
the LH curve if the expansion is stopped at the nozzle–
skimmer distance where Knudsen numbers below units are
estimated. In the lower panel measurements obtained from
Ref. 22 are shown. Here, the beam expands from a pulsed
nozzle source held at room temperature and with a nozzle
diameter of 125 $$\mu$$m. The nozzle–skimmer distance is about
1120 mm. Within this experiment the speed ratio is observed
to depend on $$d_{ns}$$ at source pressures above 70 bar where the
interference with the skimmer wall is claimed as the limiting
factor for the terminal helium speed distribution. To compare
the data with calculations we remark that the final tempera-

FIG. 11. The same as in Fig. 9 but for $$P_0$$=11, 13, and 16 bar.
**V. CONCLUSIONS**

In the previous section a study of the He flow properties during a free jet expansion is presented. Measurements at source temperatures between 20 and 80 K and source pressures in the range 2–16 bar are reported. Through a detailed analysis of several TOF spectra the parameters describing the beam energy distribution are estimated. Experimental effects which could limit the performances of the expanding beam, such as scattering with the background gas or helium condensation, are discussed. In particular, clusters are observed to form whenever the beam temperature decreases down to about $10^{-3}$ K during the final stages of the expansion. The experimental results are compared with calculations performed using the LJ, TTY, and HM He–He interatomic potentials. Since none of them fully describes the data a phenomenological viscosity cross section curve is introduced matching the HM behavior with the LJ behavior in the low and high energy range, respectively. Calculations based on this cross section are performed including the skimmer interference in an approximate way. A better agreement is obtained with our data and with other measurements in the extended source temperature range between 6 and 300 K.

We hope that these results will stimulate new theoretical calculations to improve the knowledge of the He–He interatomic potential curve.

**ACKNOWLEDGMENTS**

We gratefully acknowledge Professor R. Tatarek for his useful contribution to the design and the setup of the apparatus. We are very grateful to Mr. A. Gussoni for technical support. This work was supported by the Italian MIUR through Grant No. 2001021128 and by the Surfaces and Interfaces section (F) of the Istituto Nazionale di Fisica della Materia.

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1 a.u. = 27.2111 eV for energies and 1 a.u. = 0.52917 Å for lengths.


