Pair interaction of metal atoms on a metal surface

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Pair interactions of tungsten and iridium adatoms on the W {110} plane are studied by measuring two-dimensional pair distributions with two adatoms on a plane. Each distribution contains from 600 to 950 field-ion-microscopy observations. Pair energies over a distance range of ~2.5 to ~50 Å are derived by comparing the experimentally measured pair distributions with the calculated pair distributions for two noninteracting atoms. It is found that Ir-Ir pair interaction exhibits an attractive region at ~5 Å and a repulsive region around 8 Å. If an oscillatory structure exists, its amplitudes decay already to less than ~10 meV beyond 10 Å. The plane edge seems to repel Ir adatoms with a weak long-range force. The W-Ir interaction at a short range is weaker than the Ir-Ir interaction. However, the interaction extends to larger distances. From ~950 observations at 330 K with two adatoms, we derive a pair energy which exhibits two attractive and two repulsive regions, thus strongly suggesting an oscillatory structure. The pair energies derived beyond 25 Å are erratic for both Ir-Ir and W-Ir interactions, most probably because of the limited amount of data available. However, this work represents the first time statistically reliable amounts of data have been obtained for two-dimensional pair distributions with only two adatoms on a plane. The nonmonotonic behaviors of adatom-adatom interaction on the smooth W {110} plane are clearly established.

I. INTRODUCTION

Some of the most fundamental information in surface physics includes the force laws governing the interaction of two atoms adsorbed on a metal surface. Several possible effects have been considered.[1] They include a dipole interaction between two adatoms,[2] a weak van der Waals interaction,[3] an interaction due to a mutual elastic distortion of the substrate lattice by the adatoms,[4] an interaction arising from the substrate phonon field,[5] and an indirect interaction.[1,6-9] The last interaction arises from the fact that the wave functions of both adatoms can tunnel through narrow potential barriers to the metal and couple with propagating metal wave functions. The asymptotic form of the indirect interaction, as expected from the wave nature of electron propagation, is oscillatory.

Direct experimental evidence of a nonmonotonic and long-range behavior of the adatom-adatom interaction was reported in 1972 from a field-ion microscopic observation.[10] The interaction between two Re atoms on the W {110} plane were found qualitatively to have at least two attractive regions and a repulsive region, suggesting a possible oscillatory structure. To quantify such an observation, radial distributions were measured with five Re atoms on a W {110} plane.[11] A potential of mean force derived exhibited an oscillatory structure. The result, however, was questioned for the following reasons. (1) A potential of mean force is not a pair potential, although in the low particle-density limit of the experiment, the two should agree quite well. (2) Statistical fluctuations of the data are large.[12] (3) The data analysis does not account for discrete adsorption sites. (4) Experiments on Re-Re interaction on the W {112} shows that the interaction is less than $\frac{1}{2}kT$, ~15 meV, beyond 9 Å.[13] Despite these uncertainties, the result has attracted considerable interest.[1,8,9]

Ever since we started a field-ion microscopy (FIM) study of the long-range adatom-adatom interaction, we have been continuing the study with various adatom pairs on the W {110} planes often with thousands of heating periods with now only two adatoms on a plane. We report here an investigation of the adatom-adatom interaction on the W {110} plane for Ir-Ir and W-Ir pairs. There are three major reasons for choosing the W {110} plane for such a study. (1) The W {110} plane is the smoothest plane available on a W field-ion-emitter surface. Since theories on indirect interaction assume an idealized flat surface, the W {110} should be as good an idealized plane as any other plane available on a W filed-ion-emitter surface. (2) The W {110} plane is known to be chemically least active of all planes, thus contamination problems can be minimized. (3) As the plane size is comparatively large on a field-ion-emmiter surface, the range of the adatom-adatom interaction which can be studied is also much larger. Since a two-dimensional plane of large size also contains a large area and a large number of adsorption sites, a very large number of observations have to be made for the data to be statistically significant. We report here pair distributions; each of these contains 600 to nearly 1000 observations. These data are further sub-

jected to statistical smoothings. The smoothing procedures will dampen the energy of sharply localized energy states. Our method of analysis is thus deliberately conservative to avoid misinterpreting statistical fluctuations as existence of sharply localized energy states.[14]

We should also mention the choice of adatoms. To derive a meaningful pair distribution with less than 1000 observations with two adatoms, the interaction energy must not be significantly larger than kT, the average thermal energy at the temperature where adatoms diffuse sufficiently but do not often overcome the reflectory plane boundary; thus loss of adatoms from falling down the plane edge usually does not occur. The Ir-Ir and W-Ir pairs satisfy these criteria quite well. In addition, Ir adatoms on the W{110} plane have undetectably small dipole moment.[15] Thus the effect of surface-induced dipole-dipole interaction of the adatoms can be eliminated.

We should mention here that pair distributions have been reported earlier for a "one-dimensional" plane. Tsong[10] reported that out of 38 observations of two W adatoms forming a cluster with the two atoms in the adjacent channels of the W{112} plane, 29 of them were found to have a bond separation of ~ 4.47 Å, whereas nine of them had a bond separation of ~ 5.24 Å. Thus a difference in the bond energy at the two separations was estimated to be $[U(4.47\ \text{Å}) - U(5.24\ \text{Å})] \approx -30$ meV. A subsequent measurement[16] with a much larger number of observations and a more detailed analysis gave essentially a similar result of ~ 41.6 ± 6.4 meV. A similar study, but with a rigorous stochastic analysis, for two Re adatoms on the same plane by Stolt *et al.*[17] found that the 5.24-Å bond was more heavily populated. They found that $U(4.47\ \text{Å}) - U(5.24\ \text{Å}) \approx +35 \pm 11$ meV. Graham and Ehrlich found that two Re adatoms on the W{112} plane, separated by two surface channels, gave essentially a random distribution.[13] Thus the interaction beyond 9 Å was less than $\frac{1}{2}kT$, or less than ~ 15 meV. The {112} plane is of course a very rough plane. It is doubtful that any small oscillatory tails based on calculations with flat surface can be observed on the {112} with deep atomic channel structure. Thus the lack of oscillatory structure observed for adatom-adatom interactions on the W{112} plane should not be interpreted as contradictory to the earlier results on the W{110} plane.[10,11]

II. EXPERIMENTAL METHOD

Detail procedures of single-adatom field-ion-microscope experiments are well established and can be found elsewhere.[10,17-19] We took extreme care in vacuum processing since any contamination of the surface would affect the reliability of the data derived. After a specimen replacement, the system was subjected to several cycles of baking and degassing procedures. Each cycle consisted of ~ 20 h of baking at 250 °C, ion bombardments of the channel plate by pure-helium field ions for several hours, degassing of deposition-source coil close to the melting point, and extensive degassings of the ion gauge, the sublimation pump, and the Vyco glass bulb at ~ 500 °C. The vacuum after these rigorous procedures, as read by an ionization gauge, was always ~ 2×10^{-11} Torr, the x-ray limit of the gauge even before cooling of the getter and the cold finger. We use exclusively Vyco-glass-diffused helium for imaging. The diffusion temperature was ~ 350 °C.

A desired number of adatoms were deposited on a well developed plane by repeated depositions and controlled field evaporations, a procedure we have been practicing.[10] A field-ion micrograph was taken after each heating period of 60 sec at the specified temperatures, 330 ± 5 K or 300 ± 5 K. During heatings, no image voltage was applied. The adatom positions were mapped out using a greatly enlarged field-ion image by using lattice-atom images as fiducial marks, a procedure with a comparable precision to a color-comparison technique; both of them have been practiced by us.[10] Distance calibration was based on the displacements observed in single-W-adatom diffusion at low temperatures, which was taken to be 2.74 Å, the nearest-neighbor distance of the lattice. This is based on all our available evidence that a W adatom sits on a lattice site. Since our data analysis is based on the average frequencies of observation within a distance interval of 3 Å, the effect of adsorption site is minimal. Pair distributions are plotted with distance intervals of 1 Å each. Distances between two adatoms cannot be determined with an accuracy of 1 Å for large atomic separations due to an intrinsic nonuniform image magnification existing in field-ion images; such a distance interval is only a convenient starting point for further statistical data smoothings. This will be discussed in greater detail in the next section.

III. METHOD OF ANALYSIS

All observations indicate that the interaction between two metal adatoms on a metal surface is very much weaker than the interaction between an adatom and the substrate surface. It is therefore reasonable to assume that the adsorption site of an adatom is not changed by the presence of

another adatom on the plane. The distances allowed for adatom-adatom separations are partly limited by the adsorption sites available. The adatom-adatom pair interaction will be defined as the difference in the potential energy of an adatom on a plane with and without the presence of another adatom on the plane.

When two adatoms are present on a circular plane of radius R, the range of possible adatom separations is from r_0 to $2R$, where r_0 is the closest possible bond length between the two atoms and R is the radius of the plane. In an experimental measurement, the exact distance between two adatoms cannot be determined. The best one can achieve is to determine the separation within an accuracy of, say, Δr. Let us divide the entire distance range, i.e., from r_0 to $2R$ into n intervals of Δr each. In a total of N observations, and therefore a total of N atomic separations derived for a pair distribution, the number of distances falling into the range of the mth interval as represented by n_m is determined not only by the pair interaction at that separation, $\sim r_m$, but also the number density of adsorption sites available within the distance range. In our experiment, both adatoms can change their position nearly randomly on the plane; the number n_m is really an average over all possible adatoms' positions on the plane.[11] To derive the pair interaction, the experimental values have to be compared to the expected values for two noninteracting particles on a plane of the same size and structure.

The expected relative probability of observing atomic separations falling within r and $r+\Delta r$, for two noninteracting atoms can be derived by multiplying the number of adsorption sites per unit area falling in a circular strip of inner and outer radii of r and $r+\Delta r$, and the relative probability of having an atomic separation falling within the same range on a "flat" plane of radius R. A flat plane here means that the plane does not have any structure and an atom can sit anywhere on the plane.

The number of adsorption sites within an area enclosed by circles of radii r and $r+\Delta r$ can be easily calculated. Since a metallic adatom on the W{110} sits most probably on a lattice site, we have calculated this number as a function of r based on a lattice site adsorption. Figure 1 shows the result with a Δr of 1 Å for the W{110} plane.

The probability of having an atomic separation falling within a range from r to $r+\Delta r$ on a flat circular plane of R has been discussed previously although no details were given.[11] In fact the treatment given was slightly more general by considering N atoms on a surface. We now present

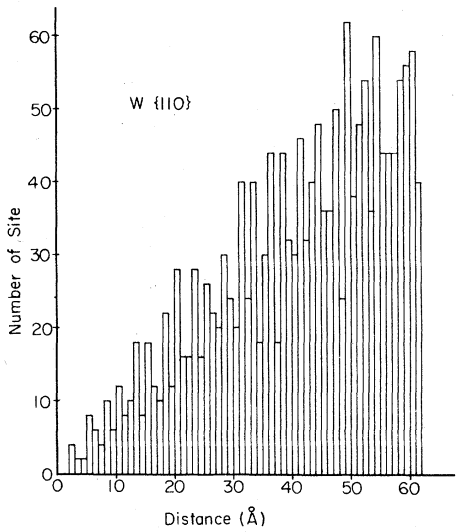

FIG. 1. Number of adsorption sites available in a circular zone of 1-Å width as a function of radius on the W{110} plane.

the calculation in some detail for the case with two atoms on a plane. Referring to Fig. 2, the probability that either of the two atoms is sitting inside the surface element dS shown is given by

$$2\frac{dS}{\pi R^2}=\frac{2}{\pi R^2}r\,d\theta\,dr. \tag{1}$$

The probability that the other atom is separated by a distance within lR and $lR+d(lR)$ from the atom in dS is given by

$$\frac{2\phi\, lR\, d(lR)}{\pi R^2}. \tag{2}$$

The pair distribution function $p(lR)$ for two noninteracting atoms on a flat plane is therefore given by

$$p(lR)\,d(lR)=\tfrac{1}{2}\oint\frac{4lR}{\pi^2R^4}\phi r\,dr\,d\theta\,d(lR). \tag{3}$$

l is a number ranging from 0 to 2. The factor $\frac{1}{2}$ in the last equation is introduced to avoid double counting. From Fig. 2 one has

$$\phi=\begin{cases}\cos^{-1}\left(\dfrac{r^2+l^2R^2-R^2}{2rlR}\right) & \text{for } r>(R-lR)\\ \pi & \text{for } r\leq(R-lR).\end{cases} \tag{4}$$

With a few more steps, one obtains

$$p(lR)=\begin{cases}\frac{2l}{R}\left[(1-l)^2+\frac{2}{\pi}\int_{1-l}^{1}\cos^{-1}\left(\frac{x^2+l^2-1}{2xl}\right)x\,dx\right] & \text{for } 0\leq l\leq 1\\ \frac{2l}{R}\,\frac{2}{\pi}\int_{l-1}^{1}\cos^{-1}\left(\frac{x^2+l^2-1}{2xl}\right)x\,dx & \text{for } 1<l\leq 2.\end{cases} \tag{5}$$

Usually it is much more convenient to define a slightly different function which when plotted or tabulated can be easily adapted to planes of various sizes. Let us define $F(l)$ by

$$F(l)=Rp(lR). \tag{6}$$

Thus

$$p(lR)\,d(lR)=F(l)\,dl. \tag{7}$$

As one can see from Eq. (5) $F(l)$ is a reduced function which does not depend on the radius of the plane. In Fig. 3 $F(l)$ as a function of l is plotted.

Now the probability of observing a pair separation falling within a small distance interval of Δr about r is simply given by

$$p_0(r)=Cn_mF(r/R)/r, \tag{8}$$

where C is a normalization constant which can be easily evaluated by summing over the entire range of possible distance separations. Thus

$$C=\left[\sum_{i=0}^{2R/\Delta r} n_i F\left(\frac{r_i}{R}\right)\Big/ r_i\right]^{-1}, \tag{9}$$

where $r_i=(i+\frac{1}{2})\,\Delta r$, and n_i is the number of adsorption sites within a circular area of inner and outer radii of $(i-1)\,\Delta r$ and $i\,\Delta r$.

The experimentally observed frequencies at various distance ranges $p_e(r)$ are related to each other by both the pair energies $U(r)$ and the statistical weight $p_0(r)$.

$$\frac{p_e(r_i)}{p_e(r_j)}=\frac{p_0(r_i)e^{-U(r_i)/kT}}{p_0(r_j)e^{-U(r_j)/kT}}, \tag{10}$$

where $p_e(r_i)$ represents the experimentally measured probability of observing the pair separation falling into the range of width Δr about r_i. Thus

$$\frac{p_e(r_i)}{p_0(r_i)}=C'e^{-U(r_i)/kT}, \tag{11}$$

where C' is an undetermined constant. Using this method only the relative values of a pair interaction at various distances can be determined. The zero level of the pair interaction can in principle be derived from the asymptotic value of the pair potential at large distances. In practice this is rather difficult since the largest distance available is only twice the radius of the plane. The amount of experimental data available is also too small to determine the asymptotic value with sufficient accuracy. The difficulty is further enhanced by the slightly noncircular shape of the field-emitter surface planes. These difficulties make the derived pair energies beyond 25 Å erratic, as will be obvious in the next section.

IV. EXPERIMENTAL RESULT AND DISCUSSION

A. Ir-Ir Interaction

Iridium adatoms on the W{110} plane exhibit high evaporation field,[15] thus accidental field evaporation of adatoms does not occur. The surface-induced dipole moment is undetectably small.[15] The surface-induced dipole-dipole interaction between two Ir adatoms can be neglected from consideration.

Two iridium adatoms on the W{110} tend to combine into a cluster which is unstable near

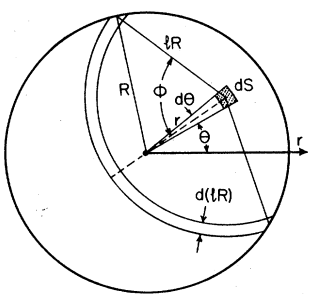

FIG. 2. Geometrical relationships as discussed in the text.

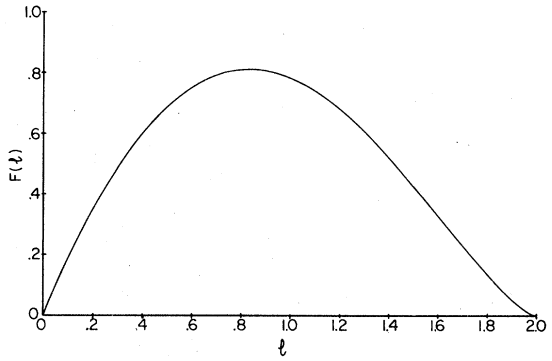

FIG. 3. Reduced probability density function $F(l)$ as a function of l.

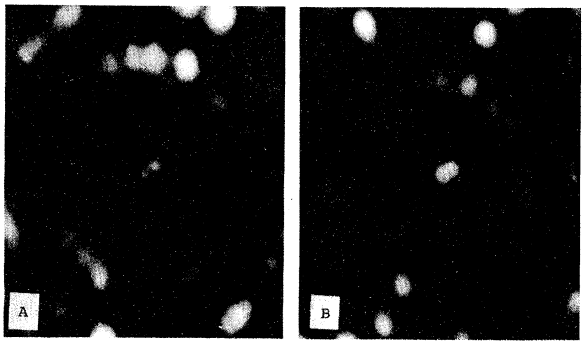

FIG. 4. (a) Field-ion image of a closest bond Ir-Ir cluster on the W {110}. (b) Field-ion image of a closest bond W-Ir cluster on the W {110}.

room temperature. Our experiment was carried out with two Ir adatoms on a plane of about 60 Å average diameter. The shape of a plane is often not exactly circular, but often slightly elliptical. Since plane-edge atoms are much more magnified than other parts of the plane, the exact size of the plane is difficult to determine. We take the average diameter of the plane as determined by the shortest jumping distance (2.74 Å), and reduced this value by a diameter of the image size of an atom when the atom is at the edge of the plane. The difficulties of determining the plane size accurately, and the slightly noncircular shape of the planes, make our data analysis unreliable for distance ranges close to $2R$, the diameter of the plane. This uncertainty shows up in every set of our data, as will be clear from further discussion.

The closest bond length observed for two Ir adatoms is not 2.74 Å, the nearest-neighbor distance of the substrate.[20] In field-ion images, the two adatoms in a cluster are fully resolved. It has been assumed that the bond distance is twice

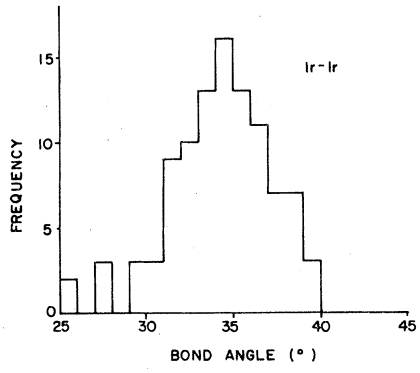

FIG. 5. Experimentally determined orientations of Ir-Ir diatomic clusters with respect to the [1$\bar{1}$0] direction.

the nearest-neighbor distance of the substrate surface. As the determination of bond distance is most difficult in this range of atomic separation because of the slight overlap of the image spots, the bond length cannot be directly determined from a distance measurement with much accuracy. An alternative method is to determine the bond orientation from the images. Figure 4(a) shows a field-ion (FI) image of the closest-bond Ir diatomic cluster. The angular distribution of the bond orientations of the 100 clusters observed are shown in Fig. 5. The average angle of clusters with respect to the [1$\bar{1}$0] axis is found to be $33.7° \pm 4.1°$ which agrees within the statistical uncertainty with the 35.3° angle we expect from a bond if the two atoms are separated by two nearest-neighbor distances. Thus both the distance calibration and the bond-orientation measurement are consistent with the assumption of a bond length of ~5.48 Å. The difficulty of determining the exact atomic separation further strengthens our view that the statistical smoothing method we use for our data analysis is a sensible approach to avoid misinterpretations of the data.

The cluster is not stable at 330 K. Of the 57 times a cluster was formed, 37 times the cluster disassociated within one heating period, 12 times within two heating periods, 2 times within 3 heating periods, 3 times within 5 heating periods, and 3 times within 6 heating periods. The average lifetime at 330 K is thus about $(37 \times 0.5 + 12 \times 1.5 + 2 \times 2.5 + 3 \times 4.5 + 3 \times 5.5) \times 60/57 = 75$ sec.

Besides the 100 times a cluster was observed, the rest of the 610 times the two adatoms were observed at various separations ranging from ~7 to ~60 Å. A histogram of the pair distribution measured is shown in Fig. 6(b). As can be seen the frequencies fluctuate considerably from one distance interval to the next. For example, in the range from 18 to 19 Å, the frequency of observation is 26. The frequency drops to 9 in the next range, and raises again to 25 in the next range. To interpret such rapid changes, which are most probably simple statistical fluctuations, as due to a pair-potential-energy change is dangerous. Such large fluctuations are present in the entire range of the distribution. In Fig. 6(c) we show a normalized pair distribution by taking the average of each range with two nearest-neighbor ranges. The excessive fluctuations of the data are greatly reduced. This statistical smoothing method can dampen the amplitudes of the pair energies as much as $kT \ln 3 = 1.1kT$ for sharply defined energy states. Our method of analysis is thus a realistic but deliberately conservative way to avoid misinterpreting statistical

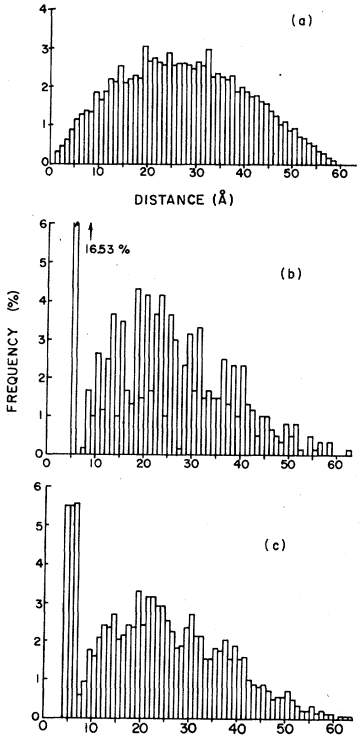

FIG. 6. (a) Calculated normalized pair distribution, averaged over 3-Å range, for two noninteracting atoms on a circular W{110} plane of 60 Å in diameter. (b) An experimental pair distribution from 610 observations at 330 K for two Ir adatoms on nearly circular W{110} planes of comparable diameters. (c) The same pair distribution as shown in (b) but now has been averaged over 3-Å range to reduce the statistical fluctuations.

fluctuations as existence of localized bound states. However, this method also reduces the chance of identifying sharply defined (in space) but very weakly bound states. The method also reduces chances of observing oscillatory structure in the pair potential if the wavelength is ~3 Å or less. In Fig. 6(a) a normalized pair distribution for two noninteracting particles, also averaged over a 3-Å range, is shown.

The pair-potential energy derived, as well as the statistical errors calculated by taking the uncertainty in frequency N to be $\sqrt{N}$, is shown in Fig. 7. Before any further discussions, we have to recognize that the method gives only the relative values of pair-potential energy as a function of distance. A reference level of the energy scale can in principle be determined from the asymptotic value of the pair energy at large distances. Unfortunately, because of the limited amount of data, the slightly noncircular shape of the plane, and the effect of the plane boundary, the asymptotic value cannot be derived with any accuracy. The zero-energy line shown in Fig. 7 results from setting C' in Eq. (11) to be one. The reference line is not taken to be the true zero-energy level.

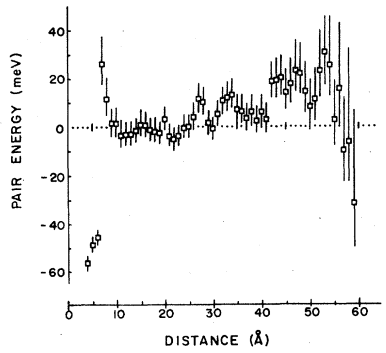

FIG. 7. Pair energy of the Ir-Ir interaction derived from Figs. 6(a) and 6(c).

A few features of the pair-energy curve can be noticed. A sharp bound state exists around 5 Å, followed by a repulsive region near 7 Å, then followed by a very gently attractive region extending to about 35 Å. Data points beyond 35 Å are perhaps unreliable. Although there may be oscillations of amplitude of about 10 meV or less, they cannot be established with any certainty because of statistical fluctuations. The gently attractive potential beyond 10 Å may not be due directly to the pair interaction, but rather a repulsive interaction of the adatoms with the plane edges. It is noticed that Ir adatoms tend to stay away from the plane edge. This behavior is not seen for W adatoms on the W{110} plane. In summary, the Ir-Ir pair energy clearly shows an attractive and a repulsive region. Small oscillations may be present, but not established. There is a gently attractive potential beyond 10 Å in the pair potential derived. However, this may be an effect of Ir adatom–plane-edge interaction rather than adatom-adatom interaction.

B. W-Ir Interaction

A W and an Ir adatom on the W{110} plane can form a closely packed diatomic cluster as shown in Fig. 4(b). Although the exact bond length cannot be determined from the FI images, judging from the marginally resolved images and the bond directions, we believe that the bond distance is one nearest-neighbor distance of the substrate lattice. The bond length is then ~2.74 Å. The closely packed W-Ir diatomic cluster is much less stable with regard to migration than the Ir-Ir cluster.

Two sets of data on the W-Ir interaction have

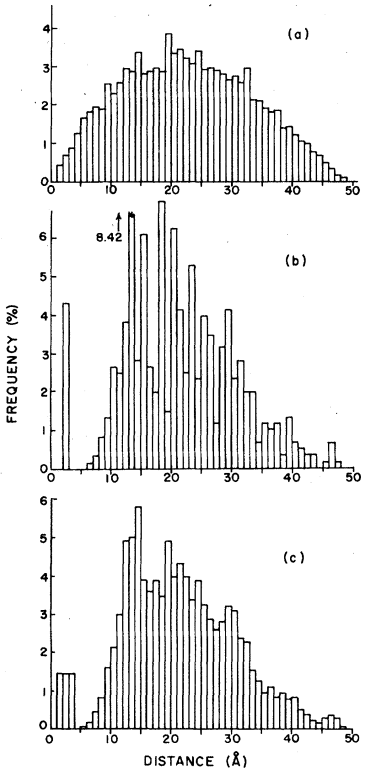

FIG. 8. (a) Calculated normalized pair distribution function, averaged over a 3-Å range, for two noninteracting atoms on a circular W {110} plane of 50 Å in diameter. (b) An experimental pair distribution from 604 observations at 300 K for one W and one Ir adatom on nearly circular W {110} planes of comparable diameters. (c) The same pair distribution as shown in Fig. 8(b) but now averaged over 3-Å range.

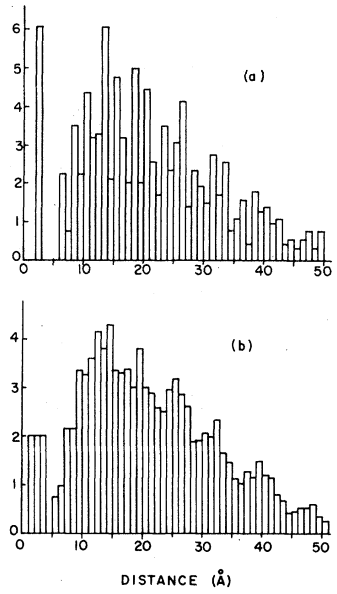

FIG. 9. (a) An experimental pair distribution from 947 observations at 330 K for one W and one Ir adatom on nearly circular W {110} planes of comparable diameters. (b) The same pair distribution which has now been averaged over a 3-Å range.

been taken, one at 300 ± 5 K with 604 observations, and one at 330 ± 5 K with 947 observations. Histograms of the pair distributions plotted with 1-Å intervals are shown in Figs. 8(b) and 9(a). In Figs. 8(c) and 9(b) normalized pair distributions obtained by taking averages over three distance intervals are shown. A pair distribution of two noninteracting atoms on a plane of the same size is shown in Fig. 8(a). Figures 10 and 11 show the pair energies derived from Eq. (11) by taking $C' = 1$. The two derived pair energies exhibit essentially the same features: an attractive region at ~3 Å, followed by a repulsive region around 5 Å, followed by another attractive region around 12 Å. The 300-K set of data becomes erratic beyond ~25 Å, perhaps because of the more limited amount of data available, and perhaps at 300 K the adatoms are not sufficiently mobile, especially since the amount of data is still small. The 330-K set of data shows very "clean" features up to about 25 Å. The pair energy clearly suggests an oscillatory structure. This set of data contains 947 observations, almost 60% more than the other set. The temperature 330 K is also high enough for the adatoms to move quite freely on the surface and distribute quite evenly over the entire plane. These may have contributed to the "cleanliness" of the data. The pair energies derived beyond 25 Å again are erratic. We believe this to be caused by not only the insufficient amount of data, but also the slightly noncircular shape of the plane. The nonuniform magnification of the field-ion image may have also caused the determination of atomic distances at large sepa-

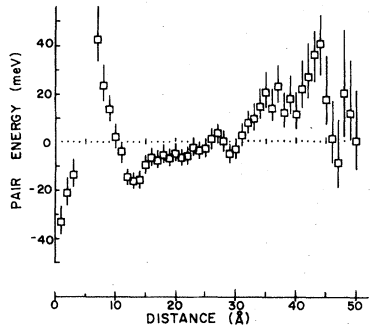

FIG. 10. Pair energy of the W-Ir interaction derived from Figs. 8(c) and 8(a).

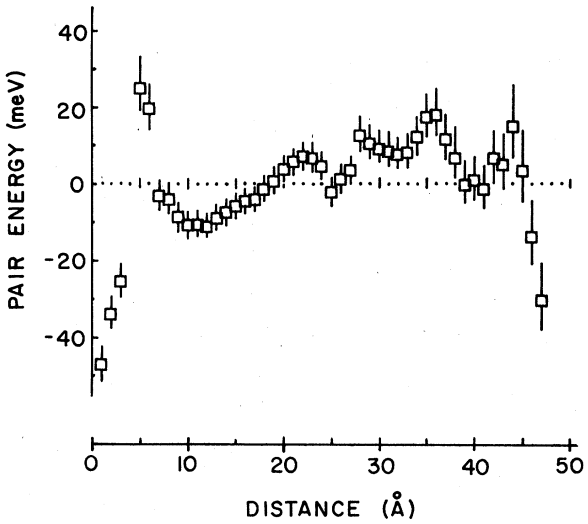

FIG. 11. Pair energy of the W-Ir interaction derived from Figs. 9(b) and 8(a).

ration to be rather inaccurate. This difficulty is intrinsic to the technique, and we do not yet have a solution.

V. SUMMARIES

The pair interactions of Ir-Ir and Ir-W on the W{110} plane are studied by measuring the pair distributions with two adatoms on a nearly circular plane of diameters 50 to 60 Å. The W{110} as developed by field evaporation is atomically perfect, and the atomic structure is as smooth as can be expected from a solid surface; thus a wave-mechanical interference effect of the atomic interaction can be expected to be detectable on this plane.

The pair interactions are derived by a measurement of the pair distributions. The Ir-Ir interaction shows an attractive region around 5 Å, and a repulsive region around 8 Å. If an oscillatory structure exists, then it decays already to less than 10 meV, comparable to the statistical uncertainty of the measurement, beyond ~10 Å.

The W-Ir interaction is weaker, but it extends to a larger distance. From ~950 observations, two attractive and two repulsive regions are clearly established. This observation strongly suggests that the W-Ir interaction is oscillatory, with the range of the interaction extending to 20 Å or beyond. The interaction is very weak, but is significantly larger than the statistical uncertainty of the data.

The amount of data available is still too small to be used for quantitatively establishing the precise form of the force laws governing the adatom-adatom interactions on metal surfaces. But the magnitude of the force, as well as the nonmonotonic nature of the interaction, is clearly established. It is difficult to collect a greater amount of data using the present method of tip heating. Tip heating can be more rapidly done by a pulsed-laser heating technique.[21] It can also be done by a pulsed electron beam.[22] However, the temperature calibration in both cases will be much more difficult. We intend to pursue this study using these new techniques with various adatom pairs in the near future. The interaction between an adatom and the plane edge can in principle be studied by measuring the position distribution function for a single adatom on the plane. Thus the effect of the plane edge can be eliminated from the pair distribution of two interacting atoms. This point will also be investigated in the near future.

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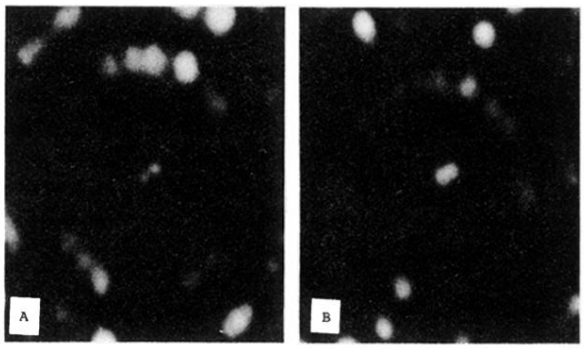

FIG. 4. (a) Field-ion image of a closest bond Ir-Ir cluster on the W {110}. (b) Field-ion image of a closest bond W-Ir cluster on the W {110}.