In any crystal lattice there are certain lattice planes which are most densely packed with atoms, and normal to which the lattice planes are more widely separated. In a situation in which interstitial atoms are able to aggregate, they will take up the minimum energy configuration which is in the form of a platelet one atom thick lying between the adjacent close-packed planes. The form of such a cluster is illustrated in Fig. 18, and for clusters containing more than about 100 atoms this may be considered as a ring of edge dislocation with Burgers vector normal to the close-

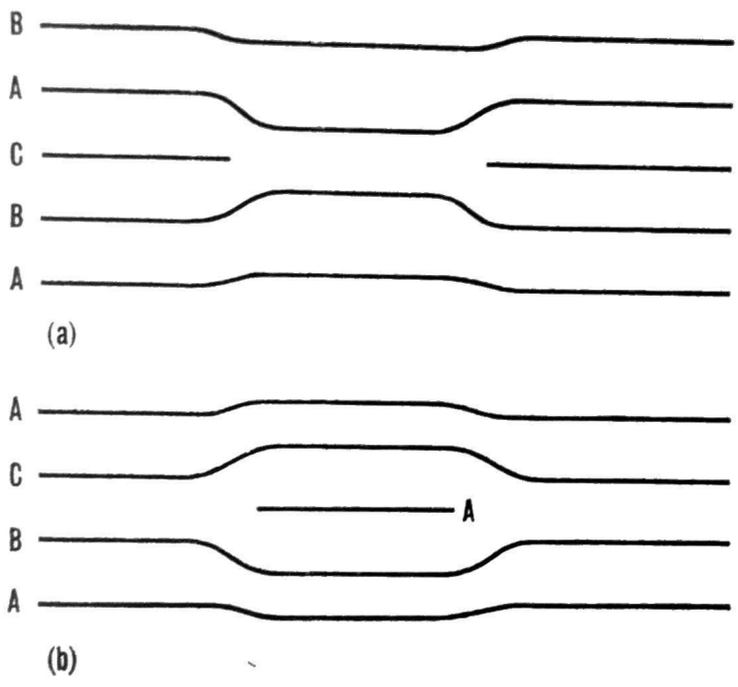

FIG. 18. (*a*) Vacancy, and (*b*) interstitial condensation in f.c.c. crystals.

packed plane, the actual nature of the loop depending upon the crystal lattice.

In the f.c.c. lattice the interstitial loop [44] has a Burgers vector $a/3$ (111) and constitutes a stacking fault. The stacking fault can be removed if two partial dislocations sweep across the loop, one on the glide plane above the loop plane, and the other in the plane below the loop. Figure 18 shows the condensation of interstitials and vacancies in the f.c.c. lattice.

The stacking fault is removed if the energy E_p of the perfect loop is smaller than that of the faulted one E_f. The energies of the

loops, considered as discs of radius R, are given by:

(*a*) Faulted loop:

$$E_f = \frac{2}{3}\frac{1}{(1-\nu)} . Gb^2R\left[\ln\frac{4R}{r_0} - 2\right] + \pi R^2\gamma \tag{2.4}$$

(*b*) Perfect loop:

$$E_p = \left[\frac{2}{3}\frac{1}{(1-\nu)} + \frac{1}{3}\left(\frac{2-\nu}{2(1-\nu)}\right)\right] Gb^2R\left[\ln\frac{4R}{r_0} - 2\right] \tag{2.5}$$

In these expressions G is the shear modulus, b the Burgers vector of the loop, γ the stacking fault energy and ν the Poissons ratio. It is found that the stability criterion is

$$\gamma \geqq \frac{Gb^2}{3\pi}\left[\frac{2-\nu}{2(1-\nu)}\right]\frac{1}{R}\left[\ln\frac{4R}{r_0} - 2\right] \tag{2.6}$$

This kind of reaction may be expected to happen in the case of hexagonal materials, where the interstitial loop is once more in a stacking fault location, taking up a *c*-position between the usual layer positions which may be denoted by *ABAB* [45], if the loop grows to sufficient size.

The case of vacancy condensation is a little different for small numbers of vacancies; the form of an aggregate with least energy is the spherical void. If the surface energy of the solid is σ, the energy of the spherical void of radius r is

$$E_S = 4\pi r^2\sigma \tag{2.7}$$

As the number of vacancies in the cavity increases, the least energy configuration is that of the planar dislocation loop. In this case, the energy is the same as that for the interstitial loop (2.4). In order to achieve this planar configuration, however, the sphere has to pass through the form of a disc-shaped cavity for which the energy is

$$E_C = 2\pi a^2\sigma \tag{2.8}$$

where a is the radius. If Ω^3 is the atomic volume then the number

of vacancies in the void is

$$n_V = \frac{4}{3}\frac{\pi r^3}{\Omega^3} \tag{2.9}$$

For the same number of vacancies, $E_c > E_s$, and therefore an activation energy is required for the transformation.

The disc-shaped configuration collapses to the closed ring of dislocation loop if it grows to sufficient size. The energy of the loop is approximately given by

$$E_L = Gb^2\pi r_0 + \pi r_0^2\gamma \tag{2.10}$$

(The last term applies only if there is a stacking fault.) It is obvious that $E_C > E_L$ if

$$r_0 > \frac{Gb^2}{(2\sigma - \gamma)} \tag{2.11}$$

It is thus reasoned that the vacancy agglomerate is spherical for a small number of vacancies, and then if the activation energy is available becomes a planar cluster. When the number of vacancies is increased the planar cluster becomes a closed ring of vacancy loop. It is easily seen that in substances with a large surface energy small voids may remain.

One further type of defect formed by vacancies is the tetrahedral void, which has been observed by Silcox and Hirsch [46] in quenched gold; this is referred to again later.

In the f.c.c. lattice the vacancies precipitate in planar sheets on the (111) plane, the close-packed planes; the cavity formed collapses as discussed above. Once more there is a stacking fault which can only be eliminated by the passage of a partial dislocation with Burgers vector $a/6$ (111). The resulting dislocation loop is then a perfect prismatic dislocation with Burgers vector

$$a/3[111] + a/6[11\bar{2}] \rightarrow a/2[110]$$

which is inclined with respect to the original loop plane. It is interesting to observe that the interstitial and vacancy loop cases are not equivalent. The motion of a single partial dislocation removes the stacking fault from the vacancy loop, whereas two

partial dislocations are required in the case of the interstitial loop. It is possible that there is insufficient energy available in some substances to nucleate the two partial dislocations required for the interstitial case and then it would be expected that the stacking faults would be removed from the vacancy but not the interstitial loop [47].

The observed formation of tetrahedral voids by vacancies in gold is believed to occur when vacancies condense into triangular sessile loops on a (111) plane, with the edges parallel to the $[1\bar{1}0]$, $[10\bar{1}]$, $[01\bar{1}]$ directions. The partial dislocations around the loop limits are able to split on the different (111) planes intersecting the edges of the loop with a gain in energy. A sequence of dislocation reactions then leads to the formation of the tetrahedron [46]. An alternative formation process has been proposed by De Jong and Koehler [47] in which the tetrahedral trivacancy acts as a nucleus which grows by accretion of vacancies into a tetrahedron. The interested reader is referred to these papers for further details of tetrahedra, which have been observed in silver [48] and nickel–cobalt alloys [49] as well as gold.

There do not as yet seem to be any observations of defect clusters in b.c.c. metals.

In hexagonal materials such as magnesium, zinc and graphite it is to be expected that vacancies would condense into loops in the basal plane. The normal stacking in hexagonal crystals is *ABAB*. If part of a layer is removed, the stacking of the adjacent layers is *AA*. The collapse of layers when the loop reaches sufficient size must therefore require the slip of one layer with respect to the other to reduce the stacking fault energy. A more detailed discussion is given in the book by Read [45].

We pass now to the kinds of damage produced by various bombarding particles.

2.2. DEFECT FORMATION DURING BOMBARDMENT

The simplest type of irradiation damage is expected to be produced when those atoms which interact directly with the