The Burgers vector of an edge dislocation in an $Al_{70}Co_{15}Ni_{15}$ decagonal quasicrystal determined by means of convergent-beam electron diffraction

1993 J. Phys.: Condens. Matter 5 L195

(http://iopscience.iop.org/0953-8984/5/14/001)

J. Phys.: Condens. Matter 5 (1993) L195–L200. Printed in the UK

LETTER TO THE EDITOR

The Burgers vector of an edge dislocation in an $Al_{70}Co_{15}Ni_{15}$ decagonal quasicrystal determined by means of convergent-beam electron diffraction

Yanfa Yan and Renhui Wang

China Centre of Advanced Science and Technology (World Laboratory), PO Box 8730, Beijing 100080, People's Republic of China, Department of Physics, Wuhan University, 430072 Wuhan, People's Republic of China† and Beijing Laboratory of Electron Microscopy, Chinese Academy of Sciences, PO Box 2724, 100080 Beijing, People's Republic of China

Received 5 December 1992, in final form 16 February 1993

Abstract. An edge dislocation in an $Al_{70}Co_{15}Ni_{15}$ decagonal quasicrystal was studied by means of a contrast experiment and a defocus convergent-beam electron diffraction technique. The Burgers vector of this edge dislocation in six-dimensional space was determined to be $[\frac{1}{2}00000]$. The magnitudes of this edge dislocation in six-dimensional space and physical space are both 0.4 nm.

Since the discovery of icosahedral quasicrystals (QCs) in rapidly quenched Al–Mn alloys (Shechtman *et al* 1984), studies of defects in QCs have attracted extensive attention because of their importance not only for structural studies, but also for understanding of many of their physical and mechanical properties. Dislocations with a Burgers vector parallel to a twofold axis have been observed in the $Al_{65}Cu_{20}Fe_{15}$ icosahedral QC (Devaud-Rzepski *et al* 1989, Zhang *et al* 1990). In Al–Cu–Co, Al–Cu–Co–Si, and Al–Ni–Fe decagonal QCs, two types of dislocation have been found by means of transmission electron microscopy. One has a Burgers vector parallel to the tenfold axis which is the periodic direction while the other has a Burgers vector lying in the two-dimensional quasilattice plane and is normally connected with some planar faults (Zhang and Urban 1989, Zhang and Zhuang 1992). Wang and co-workers (1991) observed a small dislocation loop in an $Al_{76}Si_4Mn_{20}$ icosahedral QC, and identified its Burgers vector to be parallel to one of the twofold axes of the icosahedral QC. Dai and co-workers (1991) and Yan and Wang (1992a) identified displacement vector directions and habit planes of stacking faults in an $Al_{70}Co_{15}Ni_{15}$ decagonal QC. Jiang and co-workers (1992) observed discommensuration in an octagonal QC. Yan and Wang (1992b) observed small-angle grain boundaries and dislocation networks in an Al–Co–Ni decagonal QC. To determine the magnitude and the sense of a dislocation is of fundamental importance for studying the model and the structure of the dislocation. Yu and co-workers (1992) determined the direction of the Burgers vector of a dislocation in an Al–Li–Cu icosahedral QC. Dai (1992) estimated the

---

† Mailing address.

0953-8984/93/140195+06$07.50

magnitude of the Burgers vector of a dislocation in an $Al_{62}Cu_{25.5}Fe_{12.5}$ icosahedral QC. Zhang and co-workers (1993) determined the magnitude of the Burgers vector in an icosahedral QC by means of high-resolution electron microscopy. Yan and co-workers (1992a) determined the magnitudes and senses of Burgers vectors of two screw dislocations in an Al–Co–Ni decagonal QC. In the present letter we report the results of the determination of the six-dimensional Burgers vector of an edge dislocation in an Al–Co–Ni decagonal QC by means of the defocus convergent-beam electron diffraction (CBED) technique.

Small ingots with the composition of $Al_{70}Co_{15}Ni_{15}$ were obtained by melting under Ar atmosphere and cooling to room temperature, and then annealed at 900 K for 24 h under Ar atmosphere. Thin foils for transmission electron microscopy were mechanically thinned to a thickness of nearly 30 μm and then ion milled. All observations were conducted by using a Philips CM12 electron microscope operated at 100 kV.

Large-angle CBED (LACBED) has been well established as a powerful method in materials science to study defects such as dislocations and stacking faults (Carpenter and Spence 1982, Cherns and Preston 1986, Tanaka 1986, Tanaka *et al* 1988, Wen *et al* 1989, Wang and Wen 1989, Niu *et al* 1991, Chou *et al* 1992, Tanaka *et al* 1992). In the case of crystals, the Burgers vector $\boldsymbol{b}$, including its direction, sense and magnitude, may be determined by the defocus CBED method (see Wen *et al* 1989, Niu *et al* 1991, Cherns and Preston 1986 and Tanaka *et al* 1988). The principle of this method may be summarized as follows: when an incident probe illuminates the strain field region of a dislocation under a defocus mode, each higher-order reflection and corresponding deficient line with reciprocal vector $\boldsymbol{g}$ shifts and splits into $n + 1$ lines forming n nodes with $n = |\boldsymbol{g} \cdot \boldsymbol{b}|$. Thus one can determine the direction of the Burgers vector of a dislocation by finding two unsplit reflection fringes. When the finish–start/right-handed perfect crystal convention for the line direction $\boldsymbol{u}$ and the Burgers vector $\boldsymbol{b}$ of a dislocation is used and a vector $\boldsymbol{c}$ pointing from the dislocation to the crossover of the incident probe is defined, then we have the following rule for determining the sense of the Burgers vector $\boldsymbol{b}$: at the side of the shadow image of the dislocation pointed to by the vector $\boldsymbol{u} \times \boldsymbol{c}$, the higher-order reflection, and its corresponding deficient line, shift nearly along the direction of the Burgers vector $\boldsymbol{b}$. Previous studies (Wang and Cheng 1987, Yan *et al* 1992a, Dai 1992) show that the method of Burgers vector determination using the defocus CBED technique may be used for dislocations in QCs. They pointed out that one needs only to replace the terms $\boldsymbol{g} \cdot \boldsymbol{R}$ in the case of crystals, where $\boldsymbol{g}$ and $\boldsymbol{R}$ are three-dimensional (3D) reciprocal vectors and displacement vectors respectively, in the phase factors of the theory by the corresponding inner products $\tilde{\boldsymbol{g}} \cdot \tilde{\boldsymbol{R}} = \boldsymbol{g} \cdot \boldsymbol{R} + \boldsymbol{g}^{\perp} \cdot \boldsymbol{R}^{\perp}$ in six-dimensional (6D) space in the case of QCs, with $\tilde{\boldsymbol{g}}$, $\tilde{\boldsymbol{R}}$ being 6D reciprocal and displacement vectors and, $\boldsymbol{g}$, $\boldsymbol{R}$ their projections in 3D physical space and $\boldsymbol{g}^{\perp}$, $\boldsymbol{R}^{\perp}$ those in 3D complementary space respectively. Defocused CBED patterns in the present letter have been obtained by using the LACBED technique.

Figure 1 shows the selected-area electron diffraction patterns (SAEDPS) obtained from the $Al_{70}Co_{15}Ni_{15}$ decagonal QC. Figure 1(*a*) is the SAEDP taken along the tenfold axis A10. The diffraction spots are sharp and all of them are located at positions of the vertices of different sites of undistorted pentagons or decagons, implying that what we are examining is a decagonal quasicrystal rather than some crystalline approximant (Edagawa *et al* 1991). From the symmetry of this diffraction pattern it is clear that there are 20 twofold axes at 18° intervals in the plane normal to the tenfold rotational

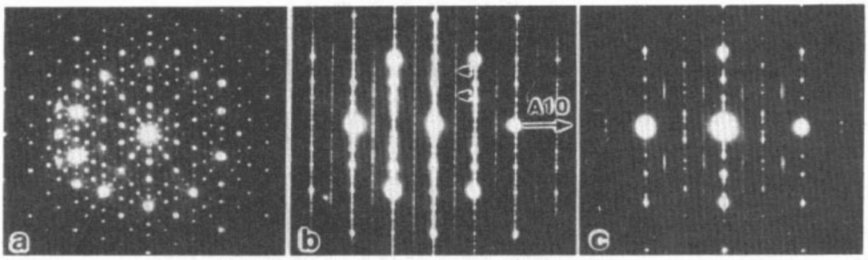

Figure 1. Selected-area diffraction patterns of a decagonal quasicrystal in the $Al_{70}Co_{15}Ni_{15}$ alloy with the electron beam parallel to (*a*) the A10, (*b*) the A2D and (*c*) the A2P axes.

axis. These twofold axes belong to two sets, which are denoted by A2D and A2P respectively (Fung *et al* 1986). Figure 1(*b*) and (*c*) shows the SAEDPs taken along the twofold axes A2D and A2P respectively. The extra spots (denoted by thick arrows) in figure 1(*b*) indicate that the periodicity of the $Al_{70}Co_{15}Ni_{15}$ decagonal QC along the tenfold axis is 0.8 nm. The quasiperiodic arrangement of the diffraction spots along the twofold axes and the periodic form of that along A10 (denoted by the thin arrow) show again the quasicrystal nature of the decagonal phase. The stereographic projection according to Yan *et al* (1992a,b,c) is shown in figure 2, covering two orientational triangles of the Al–Co–Ni decagonal QC.

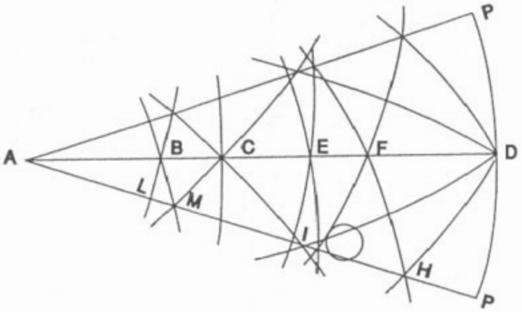

Figure 2. Stereographic projection covering two orientational triangles of the Al–Co–Ni decagonal quasicrystal.

Figure 3(*a*) shows the bright-field (BF) image of an edge dislocation obtained in an annealed Al–Co–Ni decagonal QC under the $g = (4\ 0\ 0\ 0\ 0\ 0)$ two-beam condition. Two contaminations were made at the ends of the dislocation to help one find the position of this dislocation under defocus diffraction mode. In the present work, an index system for the decagonal QC given by Yan *et al* (1992b) is used, where the first number corresponds to the tenfold axis A10 with a period of 0.8 nm. From figure 3(*a*) it can be seen that the dislocation line is perpendicular to the tenfold axis. The contrast vanished if a diffraction vector parallel to an A2P axis was employed as shown in figure 3(*b*). The contrast also vanished when reflection vectors parallel to

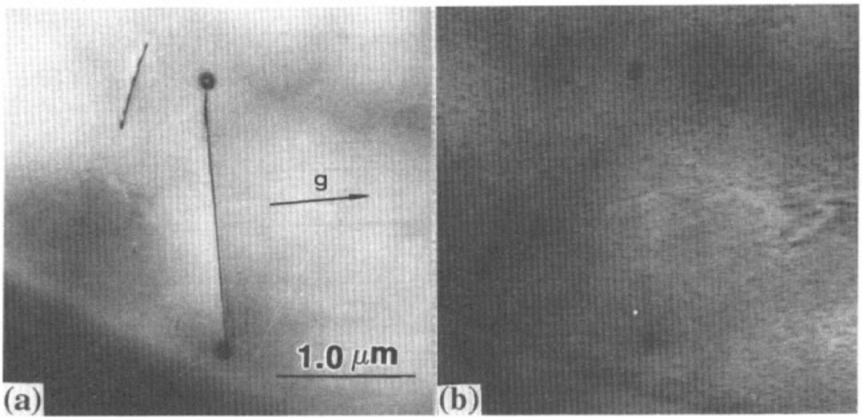

Figure 3. (*a*) Bright-field image of an edge dislocation in an Al–Co–Ni decagonal quasicrystal; (*b*) the contrast vanished when a reflection parallel to any one of the A2 axes was employed.

other A2P or A2D axes, which lie in the plane perpendicular to the tenfold axis, were used. This suggests that the Burgers vector of this dislocation lies along the direction parallel to the tenfold axis. That the Burgers vector is parallel to A10 means that this dislocation is of edge type. Therefore the indices of the Burgers vector of this edge dislocation in 6D space may be expressed as $\tilde{b} = [b_1\ 0\ 0\ 0\ 0\ 0]$.

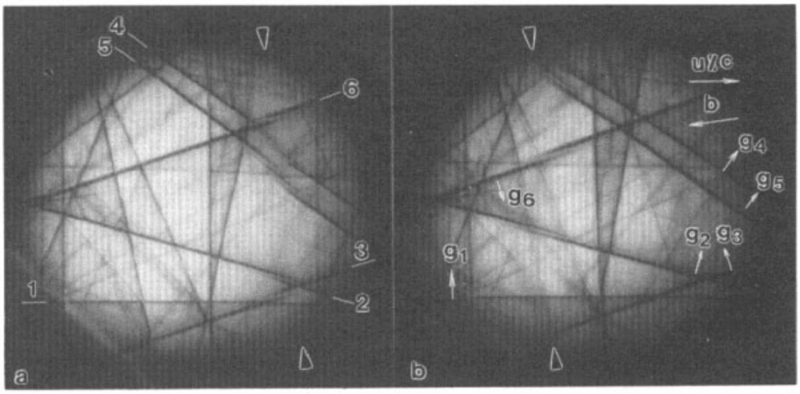

Figure 4. LACBED patterns showing the splitting of the HOLZ lines induced by the edge dislocation. The incident beam was along the direction shown by a circle in figure 2.

Figure 4 shows LACBED patterns produced when the electron beam illuminated the edge dislocation shown in figure 3(*a*). The incident beam was along the direction shown by a circle in figure 2. For this pattern, the crossover of the incident beam lies at the upper side of the foil and hence the vector *c* points to the upper side. Two arrows mark the position of the dislocation line in the LACBED patterns. The main HOLZ lines in the LACBED patterns were indexed according to our previous work (Yan *et al* 1992a,b,c). The reciprocal indices N_1^*, N_2^*, ..., N_6^*, the magnitudes $|g^{\|}|$ in physical space and the Bragg angles θ of the reciprocal vectors corresponding to these HOLZ lines are listed in table 1. From figure 4, it can be seen that the dislocation crosses the HOLZ lines 1, 2, 3, 4, 5 and 6. The deficient line with diffraction vector $g_1 = (0\ 1\ 1\ -1\ -1\ 0)$ is not affected by the dislocation because $b = [b_1\ 0\ 0\ 0\ 0\ 0]$. The deficient lines with diffraction vectors $g = g_2, g_3, g_6$ split into one node. The reflection line with diffraction vector $g = g_4$ splits into two nodes; the deficient line with diffraction vector $g = g_3$ splits into three nodes. The split nodes $n = |\tilde{g} \cdot \tilde{b}|$ of the deficient lines are also listed in the table.

Table 1. Split nodes n and corresponding diffraction vectors analysed in the experiment.

No	N_i^*						$\lvert g^{\parallel}\rvert$	θ	$\lvert g \cdot b\rvert$
1	0	1	1	−1	−1	0	1.27	1.35	0
2	−2	0	−1	1	1	0	0.92	0.98	1
3	2	−1	−1	1	1	0	1.29	1.37	1
4	−6	−1	−1	0	1	0	1.30	1.38	3
5	−4	−1	−1	0	0	0	0.83	0.88	2
6	−2	1	1	−1	−1	0	1.29	1.37	1

As mentioned above the n split nodes appear in a defocus CBED pattern in the crystal when $|g \cdot b| = n$. By substituting $\tilde{g} \cdot \tilde{b}$ by $\tilde{g} \cdot \tilde{b}$ this rule may be extended to the case of QCs, which means that for a QC, a deficient or reflection line will split into n nodes when $|g \cdot b| = n$. Therefore we can obtain that $|g_1 \cdot b| = 0$, $|g_2 \cdot b| = 1$, $|g_3 \cdot b| = 1$, $|g_4 \cdot b| = 3$, $|g_5 \cdot b| = 2$, $|g_6 \cdot b| = 1$. In this case the vector $u \times c$ and the directions of the reciprocal vectors g_1, g_2, g_3, g_4, g_5, and g_6 are shown in figure 4(*b*). From the $u \times c$ rule proposed by Wen *et al* (1989) and Niu *et al* (1991) the signs of the numbers $n = |g_i \cdot b|$ can be deduced to be

$$\tilde{g}_1 \cdot \tilde{b} = 0 \qquad \tilde{g}_2 \cdot \tilde{b} = -1 \qquad \tilde{g}_3 \cdot \tilde{b} = 1 \qquad \tilde{g}_4 \cdot \tilde{b} = -3 \qquad \tilde{g}_5 \cdot \tilde{b} = -2 \qquad \tilde{g}_6 \cdot \tilde{b} = -1. \tag{1}$$

This equation set can be expressed in matrix form:

$$\begin{vmatrix} 0 & 1 & 1 & -1 & -1 & 0 \\ -2 & 0 & -1 & 1 & 1 & 0 \\ 2 & -1 & -1 & 1 & 1 & 0 \\ -6 & -1 & -1 & 0 & 1 & 0 \\ -4 & -1 & -1 & 0 & 0 & 0 \\ -2 & 1 & 1 & -1 & -1 & 0 \end{vmatrix} \cdot \begin{vmatrix} b_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{vmatrix} = \begin{vmatrix} 0 \\ -1 \\ 1 \\ -3 \\ -2 \\ -1 \end{vmatrix}. \tag{2}$$

By solving the equation set (2) we obtain the following indices of the six-dimensional Burgers vector $\tilde{b}$ to be $\tilde{b} = \frac{1}{2}[1\ 0\ 0\ 0\ 0\ 0]$. It is a positive edge dislocation.

For dislocations in decagonal QCs with a Burgers vector b parallel to the tenfold axis (i.e. the periodic direction) the corresponding perpendicular component $b_\perp$ is equal to zero. Hence the magnitude of the Burgers vector of these dislocations in six-dimensional space is equal to that in physical space. The periodicity of the Al–Co–Ni decagonal QC along the A10 axis is 0.8 nm. Therefore the magnitudes of this edge dislocation in 6D and in physical space are both 0.4 nm. The ordered

Al–Co–Ni decagonal QC may be described as stacked by atomic planes according to the sequence ABA′B′ with a plane distance of 0.2 nm. The extra half atomic plane of this edge dislocation with the Burgers vector $b = \frac{1}{2}[1\ 0\ 0\ 0\ 0\ 0]$ consists of two basic atomic layers.

This project was supported by the National Natural Science Fundation of China.

References

Carpenter R W and Spence J C H 1982 *Acta Crystallogr.* A **38** 55

Cherns D and Preston A R 1986 *Proc. XIth Int. Congr. on Electron Microscopy (Kyoto)* p 721

Chou C T, Preston A R and Steeds J W 1992 *Phil. Mag.* A **65** 863

Dai M X 1992 *Phil. Mag. Lett.* **66** 235

Dai M X, Wang R, Gui J and Yan Y F 1991 *Phil. Mag. Lett.* **64** 21

Devaud-Rzepski J, Quivy A, Calvayrac Y, Cornier-Quiquandon M and Gratias D 1989 *Phil. Mag.* B **60** 855

Edagawa K, Suzuki K, Ichihara M and Takeuchi S 1991 *Phil. Mag.* B **64** 629

Fung K K, Yang C Y, Zhou Y Q, Zhao J G, Zhan W S and Shen B G 1986 *Phys. Rev. Lett.* **56** 2060

Jiang J C, Fung K K and Kuo K H 1992 *Phys. Rev. Lett.* **68** 616

Niu F, Wang R and Lu G 1991 *Acta Crystallogr.* A **47** 36

Shechtman D, Blech I, Gratias D and Cahn J W 1984 *Phys. Rev. Lett.* **53** 1951

Tanaka M 1986 *J. Electron Microsc.* **35** 314

Tanaka M, Terauchi M and Kaneyama T 1988 *Convergent-beam Electron Diffraction II (Tokyo: Jeol–Maruzen)* pp 160–85

Tanaka M, Yamada S and Terauchi M 1992 *5th Asia–Pacific Electron Microscropy Conf. (Beijing)* pp 154–8

Wang R and Cheng Y F 1987 *Mater. Sci. Forum* **22–4** 409

Wang R and Wen J G 1989 *Acta Crystallogr.* A **45** 428

Wang Z G, Wang R and Deng W F 1991 *Phys. Rev. Lett.* **66** 2124

Wen J G, Wang R and Lu G 1989 *Acta Crystallogr.* A **45** 422

Yan Y F and Wang R 1992a *Phil. Mag. Lett.* at press; 1992b *J. Mater. Res.* at press; 1992c *Phil. Mag. Lett.* **66** 253

Yan Y F, Wang R and Feng J L 1992a *Phil. Mag. Lett.* **66** 197

Yan Y F, Wang R, Gui J and Dai M X 1992b *Acta Crystallogr.* at press

Yan Y F, Wang R, Gui J, Dai M X and He L X 1992c *Phil. Mag. Lett.* **65** 33

Yu D, Staiger W and Kleman M 1992 *Phil. Mag. Lett.* **65** 189

Zhang H, Zhang Z and Urban K 1993 to be published

Zhang Z and Urban K 1989 *Phil. Mag. Lett.* **60** 97

Zhang Z, Wollgarten M and Urban K 1990 *Phil. Mag. Lett.* **61** 125

Zhang Z and Zhuang Y 1992 *Phil. Mag. Lett.* **65** 203