It is seen that, in accordance with the earlier data,[2] annealing for 125 min. at 400°C produces a grain size equal to that produced by a 5 min. anneal at 450°C (specimens 1 and 3). The data also show (specimens 2 and 4) that the final grain size obtained by an anneal of 125 min. at 400°C and a subsequent anneal of 120 min. at 450°C was equal to that produced by a single anneal of 125 min. at 450°C. The period of annealing at 450°C necessary for increasing the grain size from 0.23 mm to 0.34 mm was, therefore, the same (120 min.) regardless of whether the initial grain size of 0.23 mm had been obtained by a prior 125-min. anneal at 400°C or by annealing for 5 min. at 450°C.

Since the rate of growth is determined by the instantaneous grain size and the temperature, it is desirable to express dD/dt as a function of these variables. From (1)

$$t=(D/K)^{1/n}.$$

By substituting this into (2) one obtains:

$$dD/dt=n\cdot K^{1/n}\cdot D^{1-1/n}, \tag{3}$$

or in logarithmic form:

$$\log(dD/dt)=\log n+1/n\,\log K+(1-1/n)\log D. \tag{4}$$

If $\log(dD/dt)$ is plotted *vs.* $\log D$, a straight line is obtained for each temperature with a slope of $1-1/n$. Figure 1 gives this plot for high purity aluminum at 350° to 600°C, from data previously published.[2] The slight initial deviations from the $D=K\cdot t^n$ relationship at the lowest temperatures are here neglected. It is seen that the rate of decay of dD/dt increases considerably with decreasing temperature.

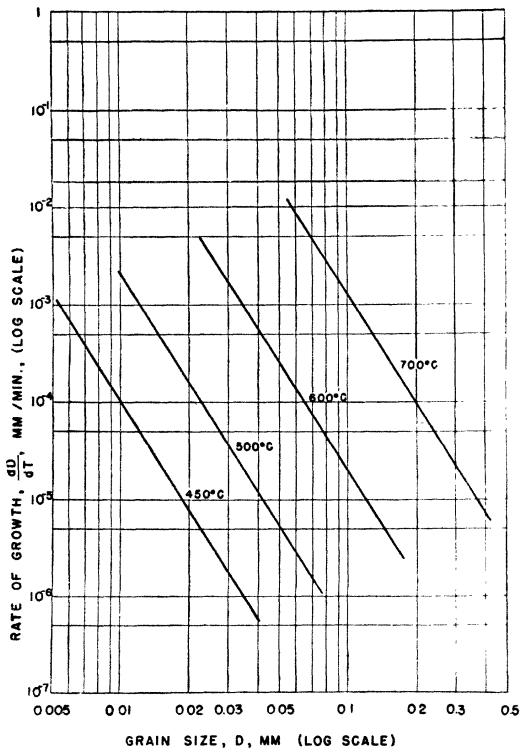

FIG. 2. Rate of grain growth as a function of grain size for 70-30 brass.

As shown in Fig. 1 by the variation of slope with temperature, the ratio of the instantaneous rates of growth at two different temperatures depends on the grain size. Since the temperature dependence of dD/dt varies with the grain size, the "heat of activation" which might be calculated from instantaneous rates will also be grain size dependent. For instance, the "heat of activation" calculated for dD/dt at $D=0.15$ mm is about 38 K cal./g atom, but at $D=0.5$ mm it is roughly 60 K cal./g atom. It has been shown previously[1] that for high purity aluminum, strictly speaking, no heat of activation value can be derived from the temperature dependence of the total time of growth to a certain grain size (average rate of growth), because the value obtained depends on the grain size. The above results show that the same difficulty is also encountered if, in accordance with a recent suggestion by Hollomon,[3] instantaneous rates of growth are used instead of average rates.

For 70-30 brass, where the exponent n is independent of temperature,[4] it is possible to derive a heat of activation value from *either* the total time for a certain grain size, *or* from the instantaneous rate dD/dt, as given in Fig. 2. It can be easily shown that both methods give the *same* numerical value of $Q=61.8$ K cal./g atom, which is independent of the grain size.

This work was supported by the Office of Naval Research, U. S. Navy.

[1] P. A. Beck, J. C. Kremer, and L. J. Demer, Phys. Rev. 71, 555 (1947).
[2] P. A. Beck, J. C. Kremer, L. J. Demer, and M. L. Holzworth, "Grain growth in high purity aluminum and in an aluminum-magnesium alloy," AIME Tech. Pub. No. 2280 Metals Technology, September 1947.
[3] Discussion of reference 2 by J. J. Hollomon.
[4] P. A. Beck, J. Towers, Jr., and W. D. Manly, "Grain growth in 70-30 brass," AIME Annual Meeting, February 1948.

Laue Photography of Neutron Diffraction

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THE photographic technique has played so important a role in the field of x-ray diffraction that it is of interest to develop this technique for use in neutron diffraction problems. With this idea in mind, we have obtained the Laue photograph, shown in Fig. 1, of the diffraction of neutrons by a NaCl crystal.

The experimental arrangement used in obtaining this and other Laue photographs with neutrons is shown schematically in Fig. 2. A collimated beam of thermal neutrons possessing a continuous wave-length distribution in the region from 0.5 to 3.0 angstroms was taken from the Clinton pile. The collimating system consisted of a hole through a 2½-foot shield block. The exit aperture of this hole was ¼ inch in diameter, and in order to increase the intensity it was successively stepped to larger diameters (up to ⅝ inch) toward the inside of the shield block. The final two inches of the collimating shield consisted of boron carbide impregnated plastic for strong neutron absorption.

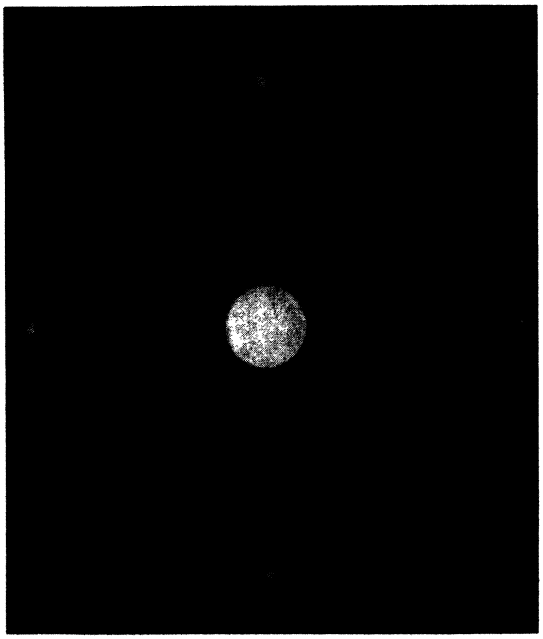

FIG. 1. Laue photograph showing neutron diffraction by NaCl.

Since photographic film (in our case x-ray double emulsion film) is quite insensitive to neutrons, it is necessary to use some type of sensitive screen in conjunction with the film. For this purpose, a sheet of indium 0.5 mm thick has been placed in contact with the film, and the beta-particles resulting from neutron capture in the indium produce the photographic effect. A $1\frac{1}{2}$-inch hole was cut in the center of the indium sheet to reduce the darkening in the vicinity of the primary beam, and the outline of this hole can be seen in Fig. 1. The film was backed by a $\frac{1}{4}$-inch boron carbide plastic shield through which a $\frac{3}{4}$-inch hole was cut for the primary beam. The white area in the center of the photograph arises from neutrons and gamma-rays backscattered from the film cassette into the region not covered by the boron carbide shield.

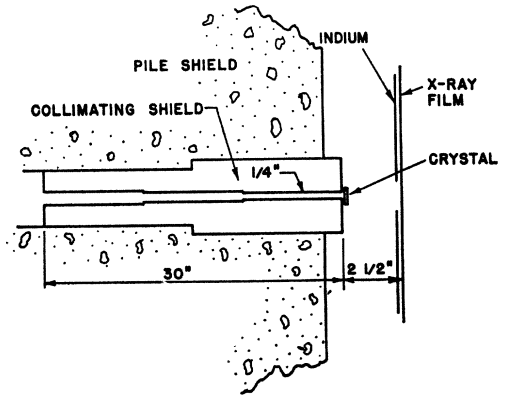

FIG. 2. Schematic diagram of Laue camera for obtaining neutron diffraction patterns.

The photograph in Fig. 1 was obtained with a NaCl crystal 0.35 cm thick, with the incident beam parallel to one of the cube axes and with a crystal to film distance of 6.40 cm. An exposure time of 10 hours was used. By the usual gnomonic projection the Laue spots have been identified as (402), (422), and their permutations for the outer series, and (311) and permutations for the inner series. Other spots such as the (442) and (513) are visible on the original negative but are too weak to show on the reproduction. The relative intensities of the spots on the pattern are in agreement with those expected from the distribution of intensity in the neutron spectrum of the incident beam.

Patterns have also been obtained for a variety of other crystals, including quartz, calcite, LiF, and $NaNO_3$, and several activating materials other than indium have been tried. Details on these and related studies will be published later.

Note on Angular Distributions in Nuclear Reactions

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IN a recent paper[1] of the same title a proof is given of the general theorem that in a nuclear reaction produced with an unpolarized beam of given orbital angular momentum incident on an unpolarized target, the angular distribution of the outgoing intensity cannot be more complicated than that of the incoming intensity. In the last two paragraphs of that paper, an error is made in the application of the treatment to reactions which lead to an arbitrary number of particles of arbitrary spin.

The theorem may be applied to the angular distribution of one of the outgoing particles provided no other independent outgoing particle direction and no state of polarization of any of the particles is specified. This distribution is obtained by summing the absolute square of the wave function describing outgoing particles over all of the unspecified variables. It is shown in the original paper that the absolute square of the wave function may be analyzed into products of the form $\psi_j{}^{\mu'}\psi_l{}^{M}\psi_{l'}{}^{-M'}\psi_s{}^{M''}\psi_s{}^{-M'''}\cdots$, where the first factor describes the angular distribution of the particle under observation and the remaining factors describe the orbital and spin distributions over which the integration is to be performed. Because of the orthogonality relations for the $\psi_l{}^{M}\psi_s{}^{M''}$, the integration eliminates all terms except those for which $\mu'=m-m'$ with $-L\leq m\leq L$, $-L\leq m'\leq L$, where L is the orbital angular momentum of the incident particle. At this point the basic argument of reference 1 may be applied, with the consequence that only terms with $j'\leq 2L$ remain in the intensity expression after integration (rather than before integration as originally stated).

[1] E. Eisner and R. G. Sachs, Phys. Rev. 72, 680 (1947).

FIG. 1. Laue photograph showing neutron diffraction by NaCl.