that the Σ^- hyperon mass is 2343.3 m_e.[7] The error in the Σ^- hyperon energy includes uncertainties due to straggling, range-energy relationship, measurements in true range, and stopping power. Equating the momenta of the π^+ meson and the Σ^- hyperon, we obtain 82.8 ± 1.1 Mev for the kinetic energy of the π^+ meson. The Q_2 for reaction 2 is 95.3 ± 1.3 Mev. The mass of the Σ^- hyperon is found to be 2343.3 ± 3.1 m_e. The mass difference $M_{\Sigma^-}-M_{\Sigma^+}=Q_1-Q_2=15.9\pm2.9$ m_e. This determination of the mass difference is independent of an exact knowledge of the stopping power of the emulsion and independent of the absolute value of the mass of the K^- meson.

The above mass difference is in excellent agreement with the value $\geq 14\pm6$ m_e, given by Chupp *et al.*[8] and the value of 16 ± 5.4 m_e given by Chretien *et al.*[9]

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† On leave from the Naval Research Laboratory, Washington, D. C.

1 Out of 206 K^- stars, 14 consist of only a meson and a hyperon. The probability that the Σ hyperon and the π meson are collinear within 1 degree is 3.1×10^{-4}, if one assumes that the hyperon is distributed uniformly over a solid angle of π steradians.

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3 We are indebted to Dr. W. H. Barkas for sending us a prepublication copy of his latest range-energy relationship.

4 Throughout this work the masses of the π mesons used were $m_{\pi^+}=m_{\pi^-}=139.5$ Mev; Barkas, Birnbaum, and Smith, Phys. Rev. **101**, 778 (1956).

5 J. Hornbostel and E. O. Salant, Phys. Rev. **98**, 339 (1955) obtained 931 ± 24 m_e; Chupp, Goldhaber, Goldhaber, Iloff, and Webb reported $\geqslant 966\pm6$ m_e and $\geqslant 935\pm5$ m_e; Gilbert, Violet, and White, Phys. Rev. **103**, 248 (1956), give 966.2 ± 5 m_e.

6 See *Proceedings of the Sixth Annual Rochester Conference on High-Energy Physics, 1956* [Interscience Publishers, Inc., New York (to be published)] and the earlier report by Whitehead, Stork, Peterson, Perkins and Birge, University of California Radiation Laboratory Report UCRL 3295 (unpublished). Also Heckman, Smith, and Barkas, Nuovo cimento 4, 51 (1956).

7 A self-consistent procedure was followed whereby the mass assumed here for the Σ^- hyperon had to agree with the final result for the Σ^- hyperon mass.

8 Chupp, Goldhaber, Goldhaber, and Webb, University of California Radiation Laboratory Report UCRL 3044 (unpublished).

9 Chretien, Leitner, Samios, Schwartz, and Steinberger (to be published).

Nuclear Quadrupole Resonance in Metals*

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THE nuclear quadrupole interaction in solids is a sensitive indicator of structures[1] and of the structural changes[2] which accompany phase transitions. Previous reports of the observation of quadrupole interactions have been restricted to nonmetals, except for some results concerning the nuclear magnetic resonance in several metals and alloys,[3] and in beryllium.[4] In the former report[3] evidence is given for the effects of lattice imperfections and impurities; the quadrupole interaction here is inhomogeneous, and the experiments set a lower limit to the range of the interaction. The latter experiment[4] shows that the quadrupole interaction in pure Be metal, on the other hand, is homogeneous (i.e., approximately the same for all nuclei), since the quadrupole satellites of the central magnetic resonance are quite sharply resolved. Therefore, we thought it worthwhile to search for the nuclear quadrupole resonance (zero dc magnetic field) in those metals for which the size of the quadrupole interaction is large enough to prohibit observation of the nuclear magnetic resonance.

Gallium was chosen for the initial searches, which were made at 0°C. Two strong lines appear at 10.908 Mc/sec and 6.866 Mc/sec. These we attribute to Ga^{69} and Ga^{71}, respectively. The ratio of the frequencies gives the ratio of the nuclear quadrupole moments, $Q_{Ga^{69}}/Q_{Ga^{71}}=1.589\pm0.002$ which is in agreement with atomic beam measurement.[5] The line frequencies increase by about 3% when the sample is cooled to -196°C. The line widths at half the maximum intensity are approximately 8 kcps and 9 kcps for Ga^{69} and Ga^{71}, respectively. This is consistent with the assumption that the nuclear magnetic moments are primarily responsible for the broadening.

The sample was prepared by stirring molten Ga in mineral oil. Following this, the mixture was frozen. The apparatus is similar to that described in reference 2.

We believe that the nuclear quadrupole resonance is observable in a number of metals, alloys, and intermetallic compounds. The results of such observations should provide unique information regarding the crystalline electric fields and the role of conduction electrons in metallic structures.

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Inelastic Scattering of Low-Energy Neutrons by Lattice Vibrations of Vanadium*

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VERY low-energy neutrons are inelastically scattered by the lattice vibrations of materials, usually gaining energy, by absorption of one or more phonons, in the scattering process. A recent discussion

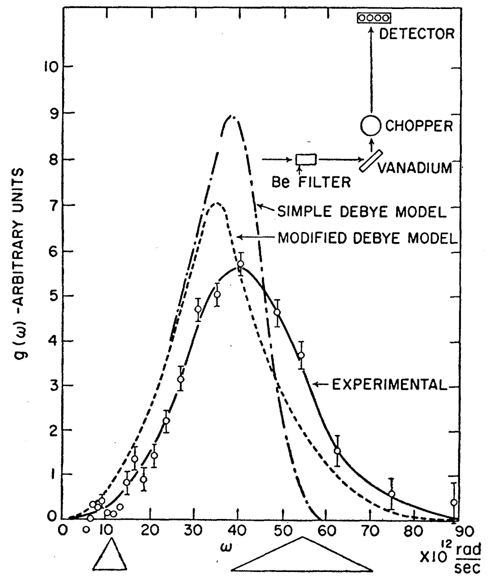

FIG. 1. Experimental frequency distribution of the normal modes of elastic vibrations in vanadium, compared with theoretical distributions based on the simple Debye model and a modified model, which includes the different modes of polarization and the geometrical effects of the Brillouin zone.

of this phenomenon by Placzek and Van Hove[1] gives the relationship between the properties of the lattice vibrations and the energy distribution of the scattered neutrons. If the scattering cross section of the material is coherent, the energy distribution of the inelastically scattered neutrons exhibits discrete peaks, whose energies are related to the wavelengths and energies of the lattice vibrations. If the cross section is incoherent, however, the energy distribution of the scattered neutrons is continuous and is related in a simple manner to the frequency distribution of the lattice vibrations.

For the incoherent case, the energy distribution of the neutrons scattered from a polycrystalline sample of a material with a cubic lattice structure is

$$\frac{d(mv)}{dk} \approx \frac{1}{k_0} e^{-2W} \frac{(\mathbf{k}-\mathbf{k}_0)^2}{k^2-k_0^2} \frac{1}{e^{\hbar\omega/kT}-1} g(\omega). \quad (1)$$

Here nv is the flux of scattered neutrons, e^{-2W} is the Debye-Waller factor, $1/(e^{\hbar\omega/kT}-1)$ is the Boltzmann factor for the population of the normal modes of the lattice vibrations, $\mathbf{k}$ is the wave vector of the scattered neutron, $\mathbf{k}_0$ is the wave vector of the incident neutrons, and $g(\omega)$ is the frequency distribution of the normal modes. The measurement of $g(\omega)$, one of the fundamental properties of the lattice vibrations, is the object of the present experiment. Fortunately an element exists, namely vanadium, whose cross section is almost entirely incoherent and which has a cubic lattice structure, thus satisfying the conditions for the validity of Eq. (1).

A beam of low-energy neutrons with small energy spread was obtained by filtering pile neutrons through beryllium. (See sketch in Fig. 1.) The mean wavelength of the filtered neutrons was 4.5 A. The energy distribution of the neutrons scattered at 90° to the incident beam from a polycrystalline sample of vanadium was determined by standard chopper time-of-flight techniques. The frequency distribution, $g(\omega)$, can be obtained directly from the measured distribution $d(nv)/dk$ by use of Eq. (1). The angular frequency, ω, of the phonon absorbed is known because the phonon's energy, $\hbar\omega$, must equal the change in energy of the neutron. The Debye-Waller factor is computed, $\mathbf{k}_0$ is obtained from the incident wavelength, and $\mathbf{k}$ is given by the measured time of flight of the scattered neutrons. Hence all the quantities except $g(\omega)$ are known and so $g(\omega)$ is determined.

The experimental result for $g(\omega)$ of vanadium is shown by the solid curve in Fig. 1. Obviously, a simple ω^2 Debye distribution, shown by the broken line as modified by instrumental resolution, does not fit the experimental data. Also, a more realistic distribution (dotted curve), still based on the Debye model but modified to include the geometrical effects of the Brillouin zone and the presence of both transverse and longitudinal modes of vibration, fails to fit the data. A Debye temperature of 338°K, obtained from specific heat measurements,[2] was used in the calculations. In order to compare the computed and experimental frequency distributions, the area under the measured and computed curves have been made equal and the computed curves were modified by the instrumental resolution shown by the triangles in Fig. 1.

A general discussion by Van Hove[3] shows that the frequency distribution of the normal modes will exhibit discontinuities and cusps at certain critical frequencies. The resolution is not yet good enough to allow observation of these effects, but with better resolution it should be possible to observe the details of the distribution. Improvements now being made in the apparatus will increase the resolution about threefold.

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