

that the  $\Sigma^-$  hyperon mass is  $2343.3 m_e$ .<sup>7</sup> The error in the  $\Sigma^-$  hyperon energy includes uncertainties due to straggling, range-energy relationship, measurements in true range, and stopping power. Equating the momenta of the  $\pi^+$  meson and the  $\Sigma^-$  hyperon, we obtain  $82.8 \pm 1.1$  Mev for the kinetic energy of the  $\pi^+$  meson. The  $Q_2$  for reaction 2 is  $95.3 \pm 1.3$  Mev. The mass of the  $\Sigma^-$  hyperon is found to be  $2343.3 \pm 3.1 m_e$ . The mass difference  $M_{\Sigma^-} - M_{\Sigma^+} = Q_1 - Q_2 = 15.9 \pm 2.9 m_e$ . 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  $\geq 14 \pm 6 m_e$ , given by Chupp *et al.*<sup>8</sup> and the value of  $16 \pm 5.4 m_e$  given by Chretien *et al.*<sup>9</sup>

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<sup>1</sup> Out of 206  $K^-$  stars, 14 consist of only a meson and a hyperon. The probability that the  $\Sigma$  hyperon and the  $\pi$  meson are collinear within 1 degree is  $3.1 \times 10^{-4}$ , if one assumes that the hyperon is distributed uniformly over a solid angle of  $\pi$  steradians.

<sup>2</sup> Fry, Schneps, Snow, and Swami, *Phys. Rev.* **103**, 226 (1956).

<sup>3</sup> We are indebted to Dr. W. H. Barkas for sending us a pre-publication copy of his latest range-energy relationship.

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

<sup>5</sup> J. Hornbostel and E. O. Salant, *Phys. Rev.* **98**, 339 (1955) obtained  $931 \pm 24 m_e$ ; Chupp, Goldhaber, Goldhaber, Iloff, and Webb reported  $\geq 966 \pm 6 m_e$  and  $\geq 935 \pm 5 m_e$ ; Gilbert, Violet, and White, *Phys. Rev.* **103**, 248 (1956), give  $966.2 \pm 5 m_e$ .

<sup>6</sup> 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by Whitehead, Stork, Peterson, Perkins and Birge, University of California Radiation Laboratory Report UCRL 3295 (unpublished).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).

<sup>7</sup> A self-consistent procedure was followed whereby the mass assumed here for the  $\Sigma^-$  hyperon had to agree with the final result for the  $\Sigma^-$  hyperon mass.

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 Chupp, Goldhaber, Goldhaber, and Webb, University of California Radiation Laboratory Report UCRL 3044 (unpublished).

<sup>9</sup> Chretien, Leitner, Samios, Schwartz, and Steinberger (to be published).

resonance in several metals and alloys,<sup>3</sup> and in beryllium.<sup>4</sup> In the former report<sup>3</sup> 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<sup>4</sup> 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  $\text{Ga}^{69}$  and  $\text{Ga}^{71}$ , respectively. The ratio of the frequencies gives the ratio of the nuclear quadrupole moments,  $Q_{\text{Ga}^{69}}/Q_{\text{Ga}^{71}} = 1.589 \pm 0.002$  which is in agreement with atomic beam measurement.<sup>5</sup> 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  $\text{Ga}^{69}$  and  $\text{Ga}^{71}$ , 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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<sup>1</sup> H. G. Dehmelt, *Am. J. Phys.* **22**, 110 (1954).

<sup>2</sup> R. M. Cotts and W. D. Knight, *Phys. Rev.* **96**, 1285 (1954).

<sup>3</sup> N. Bloembergen and T. J. Rowland, *Acta Metallurgica* **1**, 731 (1953).

<sup>4</sup> W. D. Knight, *Phys. Rev.* **92**, 539 (1953).

<sup>5</sup> R. T. Daly, Jr., and J. H. Holloway, *Phys. Rev.* **96**, 539 (1954).

## Nuclear Quadrupole Resonance in Metals\*

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THE nuclear quadrupole interaction in solids is a sensitive indicator of structures<sup>1</sup> and of the structural changes<sup>2</sup> 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

## 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