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Nuclear Moment of Ni^{61}

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A re-examination of the electron spin resonance spectra of nickel in MgO and nickel in germanium is made. It is proposed that the previously estimated value of 0.3 nm for the nuclear moment of Ni^{61} is in error by a factor of three, and that the value of 0.9 nm is more consistent with the published spectra. The internal fields in nickel and nickel alloys are discussed on the basis of this new moment.

THE nuclear magnetic moment of Ni^{61} was estimated from an electron spin resonance experiment on Ni^{+2} in MgO by Orton, Auzins, and Wertz[1] to be (0.30 ± 0.02) nm. We believe this value of the moment is in error by a factor of three, and we propose a moment of 0.9 nm instead. This paper discusses how a re-examination of the electron spin resonance data leads to the higher value for the moment, and the consequences of this result in the understanding of the internal fields in ferromagnetic nickel and nickel alloys.

Using enriched nickel in an electron spin resonance experiment on Ni-doped germanium, Woodbury and Ludwig[2] found four hyperfine lines, giving $I=\frac{3}{2}$, for Ni^{61}. The lines were evenly spaced 10.4 gauss apart. Using unenriched nickel, Orton *et al.*[1] found no hyperfine structure at low powers due to the broad resonance line, but they did find two weak hyperfine lines separated by 23.9 gauss in the considerably narrower double quantum line[3] appearing at high power. They assume the weak lines to be the outer pair of a hyperfine quartet, the inner pair being lost in the central line. This conclusion leads to a separation between adjacent lines of 8 gauss and a nuclear moment of 0.30 nm. We propose that the weak lines are the *inner* pair of a hyperfine quartet, the outer pair being lost in the noise. An examination of their published spectrum does not favor one explanation over the other, but, as we will show, our interpretation is more consistent with the germanium data.[2] An experiment with enriched nickel would test our proposal. If we are right, spacing between *adjacent* lines would then be 23.9 gauss, leading to a Ni^{61} nuclear moment of 0.9 nm.

Since the nickel in the Ni-doped germanium is not isoelectronic with the nickel in the MgO, a direct comparison with Woodbury and Ludwig's experiment[2] is difficult. Two alternate cases arise:

First, if the nickel in the germanium is a single acceptor, the electron configuration would probably be $3d^8\,4s^2\,5s$. The contribution to the effective field at the nucleus from the two unpaired electrons in the $3d$ shell should be comparable to the Ni^{+2} result. The observed spacing is reduced, perhaps to one-half its value, by an oppositely directed contribution from the single $5s$ electron. Thus, we should multiply the 10.4-gauss spacing between adjacent levels by approximately two before comparing it with the Ni^{+2} result, in favorable agreement with our suggested interpretation of 23.9 gauss between *adjacent* lines.

On the other hand, if the nickel in the germanium is a double acceptor, the outer electrons would be something like $3d^8\,4s^2\,5s^2$. The two closed s shells will not affect the results appreciably and the spacings should be directly comparable to the $Ni^{+2}(3d^8)$. However, there is one difference. For an $S=1$ state, the double quantum transitions are spaced twice as far apart as for a single quantum transition. This is true because the $m_s=0$ state is not split. Hence, we must compare $10.4\times2=20.8$ with the Ni^{+2} case. This again compares favorably with 23.9 gauss between *adjacent* lines.

We make no conclusion concerning the procedure of Orton, Auzins, and Wertz comparing the hyperfine coupling constant in Ni^{+2} with Co^{+1} in MgO. In any case, any error in precision, due to this method, may be

[1] J. W. Orton, P. Auzins, and J. E. Wertz, Phys. Rev. **119**, 1691 (1960).
[2] H. H. Woodbury and G. W. Ludwig, Phys. Rev. Letters **1**, 16 (1958).
[3] J. W. Orton, P. Auzins, and J. E. Wertz, Phys. Rev. Letters **4**, 128 (1960).

expected to be no more than 20 or 30%[4] and does not affect any results here.

Using the previously accepted value of 0.30 nm, the internal field at Ni^{61} in nickel metal is found to be 170 koe,[5] which seems too high compared with iron or cobalt. If a plot of saturation magnetization vs internal field is made, a smooth curve through the iron and cobalt points and the origin leads to a prediction of about 50 koe for the internal field in nickel. Linear scaling from iron alone gives 90 koe, and from cobalt alone 70 koe. A nuclear moment of 0.9 nm yields an internal field of 57 koe, which is in much better agreement with any of these simple scaling procedures than the previously accepted field.

Furthermore, the field at Co^{59} in nickel is 112 koe.[6] Since cobalt is more "magnetic" (i.e., has more *d*-shell holes) than nickel, this field might have been expected to be higher than the nickel field, in disagreement with the old moment, but entirely consistent with the value proposed here.

Finally, the higher value of the moment leads to a more reasonable value of the field of nickel in cobalt.[7] The old moment would give a field at Ni^{61} in cobalt approximately twice that of Co^{59} in cobalt, whereas the moment of 0.9 nm yields a smaller value of the field at Ni^{61} than at Co^{59}. Since nickel is less "magnetic" than cobalt, the lower value of the field (i.e., the higher value of the moment) is again more appropriate.

There are a number of other consequences of the higher moment, such as a better understanding of line widths and signal-to-noise in the nuclear resonance of nickel, which we will not discuss here.

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[4] We acknowledge a discussion with Dr. A. J. Freeman on this point.

[5] L. J. Bruner, J. I. Budnick, and R. J. Blume, Phys. Rev. **121**, 83 (1961).

[6] L. H. Bennett and R. L. Streever, Jr., J. Appl. Phys. **33**, 1093 (1962).

[7] R. L. Streever, Jr., L. H. Bennett, R. La Force, and G. Day, (to be published).