Ferromagnetism in the Manganese-Indium System

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WE recently undertook an investigation of the phase equilibria in the previously unreported manganese-indium system. About twenty-five alloys, varying in manganese content from 3 to 91 weight percent in steps of about 4 weight percent, have been prepared, and over half of these specimens have been found to be ferromagnetic.

The alloys were prepared by melting 40-gram to 70-gram mixtures of the metals under argon in an induction furnace, using a Westinghouse 10-kw rf generator as a source of power. "Triangle RR recrystallized alumina" crucibles (Morgan, England) and alumina-silica thermocouple protective tubes, sealed off at one end with packed magnesia, were used. Indium of 99.97 percent purity was obtained from the Indium Corporation of America and electrolytic manganese of purity greater than 99.9 percent was obtained from the U. S. Bureau of Mines. Chemical analysis showed both materials to be at least 99.9 percent pure. A chromel-alumel thermocouple, calibrated at the freezing points of tin, zinc, silver, copper, and copper-silver eutectic alloy, was used in conjunction with a Brown recording potentiometer to obtain the cooling curves of the alloys. All specimens were chemically analyzed to make sure that they were homogeneous and to determine their exact composition.

The existence of ferromagnetism in this system was suggested by Hames and Eppelsheimer, but no data were given.[1] While we have made only qualitative magnetic measurements with a small Alnico magnet, the intensity of magnetization appears to increase regularly from 3 to about 50 weight percent manganese, and then to die out completely. An alloy containing 53.2 percent manganese is strongly ferromagnetic, while one containing 59.4 percent manganese is unaffected by the magnet, as are the subsequent alloys of increasing manganese content. The same range of ferromagnetism holds for alloys annealed and quenched from temperatures between 850 and 950°C. On the basis of these, plus incomplete thermal and metallographic data, we believe the ferromagnetism is due to a single phase, the compound Mn_2In. The alloys containing up to 49 percent manganese appear to be composed of indium plus Mn_2In, no eutectic mixture being formed (the solidus is at the freezing point of indium, 157.5°C).

In a private communication, Dr. R. M. Bozorth has pointed out to us that there are now definitely known about sixteen binary systems, containing no ferromagnetic elements, which show ferromagnetism. Of these binary systems, both components are metals in eight cases. The manganese-indium system described here provides a new additional case.

Thermal and metallographic measurements are being continued, as a thorough knowledge of the phase relations is needed before proceeding to further measurements of magnetic and other properties.

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[1] F. A. Hames and D. S. Eppelsheimer, Nature **162**, 968 (1948). See also R. R. Grinstead and D. M. Yost, Phys. Rev. **75**, 984 (1949) on ferromagnetism in the Mn-Cu-In system.

Erratum: The $Li^6(n,\alpha)H^3$ Reaction Spectrum

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THE sentence on lines 10 and 11 of the right-hand side of page 476 in the above article should read, "Deviations from ideal behavior of the whole apparatus are in any case less than 0.3 percent."

Least-Squares Adjusted Values of the Atomic Constants as of December, 1950

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AS part of the work of the National Research Council Committee on Constants and Conversion Factors of Physics and at the request of its chairman, E. U. Condon, we have prepared a report,[1] dated December, 1950, giving a complete re-evaluation of the atomic constants in the light of the wealth of important new and very accurate data obtained since our previous study of January, 1948. As input data we have used the most recent results of Kusch and Prodell[2] on the hydrogen hyperfine shift; of Hipple and his N.B.S. associates[3] and also of Bloch and Jefferies of Stanford[4] on the proton cyclotron frequency; of Gardner and Purcell[5] on the electron cyclotron frequency; of Craig and Hoffman[6] (N.B.S.) on the faraday by electrolysis of sodium oxalate; of Bearden and associates[7] on h/e (which latter have recently also been verified at 25 kv at this Institute by the work[8] of Gaelen Felt and John Harris); of Birge[9] on λ_0/λ_s and on N obtained in 1945 from a study of all experimental evidence; of the four independent sources, Hansen and Bol,[10] Bergstrand,[11] Aslakson,[12] and Essen,[13] on the velocity of light; and of Cohen[14] on a re-evaluation of R_∞ in the light of the Lamb shift.

As a result of making a number of trial adjustments, we soon discovered that the new data are likely to lead to observational equations whose observed numerics are not independent but are observationally correlated. If such correlations are ignored, a serious error of method is committed and wrong results[15] are obtained, because the error (or the weight) to attach to each equation cannot then be described by a single number. Instead an error matrix must be used to describe the error situation with all the intercorrelations between equations. The classical procedure for forming the normal equations of least squares no longer applies, but one of us has shown[16] how a generalization in matrix algebra can be used.

A simpler method may be, as we have shown in our report, to recast the equations so as to diagonalize the error and weight matrices,[17] thus removing the correlations between equations. To do this completely, it may be (and in this case was) necessary to transfer some of the observational data from the category of fixed auxiliary constants to that of the unknowns to be adjusted. For this and other more involved reasons discussed in the above report we finally concluded that a solution in the following six unknowns was required: N, e, m, h, c, and λ_0/λ_s. The present data permit of setting up, with a diagonalized error matrix, nine observational equations in these six unknowns (including equations for the direct observations on c and λ_0/λ_s) so that the overdetermination is sufficient to yield an index of the presence or absence of systematic errors in the data from a study of the residues. The consistency of the data, so adjusted, is excellent. The somewhat abridged Table I gives the resulting adjusted values of the six primary unknowns and of other useful quantities which can be computed from them, the probable errors being all computed by the ellipsoid method. The adjusted value of λ_0/λ_s turns out to be a little lower than our input value, while that for c is a little higher.

These values must still be regarded as tentative, partly because not all of the input data are as yet quite finally settled, and also because the theoretical formula,[18] connecting the hydrogen fine structure shift with Sommerfeld's α, is not yet known, as regards certain correction terms,[18,19] with the accuracy which the observational data warrant. The Bethe-Longmire correction terms give only "orders of magnitude" and *may*, according to H. Bethe, have to be modified by many parts in 10^5. (See Γ-coefficients in Table I). We are also suspicious regarding the magnitude of the higher order corrections[19] giving the electron moment in Bohr magnetons for hydrogen. This ratio is probably Z-dependent, and we are informed

TABLE I. Least-squares adjusted values of atomic constants and conversion factors, December, 1950. (Each quantity is accompanied with a Γ-coefficient giving the change in ppm which may later be made in that quantity for each ppm change in the constant G^2 of the equation $\Delta\nu_H = \alpha^2(\mu_p/\mu_0)R_\infty G^{-2}$ as later advances in our theoretical knowledge may require. The present values are based on $G^2 = 0.004751364$. The physical scale of atomic weights is used here exclusively, since Nier has shown that the definition of the chemical scale in terms of "natural abundance ratios" is ambiguous to presently accessible accuracy).

N	Avogadro's number $(6.02544 \pm 0.00011) \times 10^{23}$ g-mole^{-1} (phys.)	(-1.241Γ)
c	Velocity of light (299790.2 ± 0.9) km sec^{-1}	(0.023Γ)
e	Electronic charge $(4.80223 \pm 0.00007) \times 10^{-10}$ esu	(1.291Γ)
m	Electron rest mass $(9.10721 \pm 0.00025) \times 10^{-28}$ g	(1.077Γ)
h	Planck's constant $(6.62377 \pm 0.00018) \times 10^{-27}$ erg sec	(2.073Γ)
λ_g/λ_s	Conversion factor from Siegbahn x-units to milliangstroms (1.002020 ± 0.000011)	(0.349Γ)
$F' = Ne/c$	Faraday constant (9651.94 ± 0.07) emu g-mole^{-1} (phys.)	(0.027Γ)
h/e	$(1.379311 \pm 0.000018) \times 10^{-17}$ erg sec esu^{-1}	(0.782Γ)
e/mc	Specific charge of the electron $(1.758897 \pm 0.000032) \times 10^{7}$ emu g^{-1}	(0.191Γ)
h/m	(7.27311 ± 0.00009) cm^2 sec^{-1} or erg sec g^{-1}	(0.966Γ)
$\alpha = 2\pi e^2 h^{-1} c^{-1}$	Fine structure constant $(7.29698 \pm 0.00005) \times 10^{-3}$	(0.486Γ)
α^{-1}	137.0429 ± 0.0009	(-0.486Γ)
$\lambda_{ce} = hm^{-1}c^{-1}$	Compton wavelength of the electron $(2.426067 \pm 0.000032) \times 10^{-10}$ cm	(0.973Γ)
Nm	Atomic wt. (electron) $(5.48749 \pm 0.00010) \times 10^{-4}$ (phys.)	(-0.164Γ)
$a_0 = h^2(4\pi^2 me^2)^{-1}$	First Bohr radius $(5.29151 \pm 0.00003) \times 10^{-9}$ cm	(0.487Γ)
$r_0 = e^2 m^{-1} c^{-2}$	Classical radius of the electron $(2.81751 \pm 0.00006) \times 10^{-13}$ cm	(1.459Γ)
H	Atomic wt. of hydrogen 1.0081284 ± 0.0000030 (phys.)	
$H^+ = H - Nm$	Atomic wt. of proton 1.0075797 ± 0.0000030 (phys.)	$(8.94 \times 10^{-5}\Gamma)$
H^+/Nm	Ratio proton mass to electron mass 1836.139 ± 0.034	(0.164Γ)
R_∞	Rydberg for infinite mass (109737.323 ± 0.010) cm^{-1}	
$R_H = (1 - Nm/H)R_\infty$	Rydberg for hydrogen (109677.591 ± 0.010) cm^{-1}	$(8.94 \times 10^{-5}\Gamma)$
$\mu = mH^+/H$	Reduced mass of electron in hydrogen atom $(9.10225 \pm 0.00024) \times 10^{-28}$ g	(1.077Γ)
$\sigma = 2\pi^5 R_0^4/(15c^2h^3N^4)$	Stefan-Boltzmann constant $(5.6699 \pm 0.0009) \times 10^{-5}$ erg cm^{-2} deg^{-4} sec^{-1}	(-1.301Γ)
$c_1 = 8\pi hc$	First radiation constant $(4.99071 \pm 0.00014) \times 10^{-15}$ erg cm	(2.096Γ)
$c_2 = hcNR_0^{-1}$	Second radiation constant (1.43868 ± 0.00006) cm deg	(0.855Γ)
c_2/c	Atomic specific heat constant $(4.79894 \pm 0.00021) \times 10^{-11}$ sec deg	(0.832Γ)
$k = R_0 N^{-1}$	Boltzmann's constant $(1.38026 \pm 0.00006) \times 10^{-16}$ erg deg^{-1}	(1.241Γ)
$\lambda_{max} T = chN/(4.965114R_0) = 0.2014052c_2$	Wien's displacement law constant (0.289757 ± 0.000012) cm deg	(0.855Γ)

TABLE I.—*Continued.*

$\mu_0 = he'/(4\pi m)$	Bohr magneton $(0.927120 \pm 0.000022) \times 10^{-20}$ erg gauss^{-1}	(2.264Γ)
$(3k/N)^{\frac{1}{2}} = (3R_0/N^2)^{\frac{1}{2}}$	Multiplier of (Curie const.)$^{\frac{1}{2}}$ to give magnetic moment per molecule $(2.62148 \pm 0.00007) \times 10^{-20}$ (erg mole deg^{-1})$^{\frac{1}{2}}$ (phys.)	(1.241Γ)
$E_0 = c^2 F'^{-1} 10^{-14}$	Conversion factor from atomic mass units to Mev (931.152 ± 0.008) Mev (amu)$^{-1}$ (phys.)	(0.019Γ)
$E_g = c^2 e'^{-1} 10^{-14}$	Conversion factor from grams to Mev $(5.61060 \pm 0.00009) \times 10^{26}$ Mev g^{-1}	(-1.222Γ)
$E_e = c^2(e'/m)^{-1} 10^{-14}$	Energy equiv. of electron mass in Mev (0.510969 ± 0.000010) Mev electron-mass^{-1}	(-0.145Γ)
$E_p = E_e H^+/Nm$	Energy equiv. of proton mass in Mev (938.210 ± 0.008) Mev proton^{-1}	(0.019Γ)
$\lambda_{cp} = \lambda_{ce} Nm/H^+$	Compton wavelength of the proton $(1.321287 \pm 0.000017) \times 10^{-13}$ cm	(0.809Γ)
$\lambda_0 = (hc^2 e^{-1}) 10^{-8}$	Wavelength associated with 1 ev $(12396.44 \pm 0.17) \times 10^{-8}$ cm	(0.828Γ)
$\tilde{\nu}_0 = 10^8 eh^{-1}c^{-2}$	Wave number associated with 1 ev (8066.83 ± 0.11) cm^{-1}	(-0.828Γ)
$e10^8/c$	Energy associated with 1 ev $(1.601864 \pm 0.000024) \times 10^{-12}$ erg	(1.268Γ)
$(F'/R_0)10^8$	"Temperature" associated with 1 ev (11605.6 ± 0.5) deg Kelvin	(0.027Γ)
$n_0 = N/V_0$	Loschmidt's number $(2.68744 \pm 0.00007) \times 10^{19}$ cm^{-3}	(-1.241Γ)
$S_0/R_0 = \ln\{(2\pi k)^{\frac{3}{2}}(2.71828)^{5/2}h^{-3}N^{-5/2}\}$	Sakur-Tetrode constant (-5.57305 ± 0.00007)	(0.225Γ)
S_0	$(-4.634907 \pm 0.000036) \times 10^8$ erg mole^{-1} deg^{-1} (phys.)	(0.225Γ)

that it may soon be settled (for hydrogen) by direct measurements now in progress at Columbia University.

[1] For costs of printing of this report the N.R.C. was assisted by the Office of Naval Research. A limited number of copies are still available upon request from R. C. Gibbs of the NRC, Washington, D. C., or from the authors.

[2] P. Kusch and Prodell, Phys. Rev. **79**, 1009 (1950).
[3] Hipple, Sommer, and Thomas, Phys. Rev. **80**, 487 (1950); Thomas, Driscoll, and Hipple, N.B.S., R.P. 2104, Vol. 44, June, 1950; Phys. Rev. **78**, 787 (1950).
[4] F. Bloch and C. D. Jefferies, Phys. Rev. **80**, 487 (1950).
[5] J. H. Gardner and E. M. Purcell, Phys. Rev. **76**, 1262 (1949).
[6] D. N. Craig and J. I. Hoffman, Phys. Rev. **80**, 487 (1950).
[7] J. A. Bearden and G. Schwarz, Phys. Rev. **79**, 674 (1950); Bearden, Johnson, and Watts, NORD 8036, July 31, 1950; Phys. Rev. **81**, 70 (1951).
[8] G. Felt and J. Harris. As yet unpublished, this constituted G. Felt's doctorate thesis. Available on library loan.
[9] R. T. Birge, Am. J. Phys. **13**, 63 (1945).
[10] Kees Bol, Phys. Rev. **80**, 298 (1950).
[11] L. E. Bergstrand, Arkiv. Mat. Astron. Fysik, A **36**, paper 20 (1949); Nature **165**, 405 (1950).
[12] Aslakson, Nature **164**, 711 (1949).
[13] L. Essen and Gordon-Smith, Proc. Roy. Soc. (London) **A194**, 348 (1948); L. Essen, Nature **165**, 582 (1950).
[14] E. R. Cohen, as yet unpublished. May be obtained from author upon request.
[15] This is illustrated in certain earlier versions of Bearden and Watts' recent adjustments of the atomic constants. They have since corrected their error of method in part, but have nevertheless still overlooked (Phys. Rev. **81**, 73 (1951)) an important correlation entering, because they have used λ_g/λ_s (which they still treat as a fixed auxiliary constant) in computing the numerics for two of their observational equations (their Eqs. (1) and (6), Table V).
[16] E. R. Cohen, Phys. Rev. **81**, 162 (1951). Appendix III of the December, 1950 DuMond and Cohen report gives the theory of the matrix method of least squares, and Part IV illustrates its application.
[17] This obvious alternative, which we have been using since June, 1950, has recently also been applied by Bearden and Watts, Phys. Rev. **81**, 160 (1951), but they avoid the difficulty (which we met by increasing the number of our variables) by the simple device of ignoring two important basic equations, (i) the equation (reference 9) relating Avogadro's number N with λ_g/λ_s and the x-ray and other physical constants of crystals, (ii) the equation (reference 6) relating the new N.B.S. results on the faraday with N, e, and c.
[18] H. A. Bethe and C. Longmire, Phys. Rev. **75**, 306 (1949).
[19] R. Karplus and N. M. Kroll, Phys. Rev. **77**, 536 (1950).