Table 1. Crystal data for the basic ferric phosphates (*5*).

| Basic ferric phosphate | *a* (Å) | *b* (Å) | *c* (Å) | *β* | Space group | Specific gravity | No. of formula units per cell (Z) |
|---|---|---|---|---|---|---|---|
| Dufrenite | 25.59 | 5.14 | 13.78 | 111°24′ | *C*2/*c* | 3.34 | 8 |
| Rockbridgeite | 13.85 | 16.82 | 5.18 | | *Bbmm* | 3.49 | 4 |
| Laubmannite | 13.91 | 30.60 | 5.15 | | *Pbma* | 3.33 | 4 |
| Beraunite | 20.646 | 5.129 | 19.213 | 93°37′ | *C*2/*c* | 3.08 | 4 |
| Cacoxenite | 27.66 | | 10.65 | | *P*6/*mmm*(?) | 2.26 | 12 |

octahedral face-sharing triplet, linked by corner-sharing to four other octahedra. The cluster of seven octahedra is knit together by phosphate tetrahedra. In fact, all the phosphate tetrahedra in these minerals are linked to the polyatomic complex.

This complex appears to occur in the other basic ferric phosphates as well. Inspection of the cell data (Table 1) reveals that all members have a common fiber axis of ~ 5.1 Å as well as another crystal axis of ~ 13.8 Å. Preliminary Patterson synthesis on the *hk*0 data of laubmannite reveals the same polyatomic complex in projection as that found for the three other species studied.

The family of basic ferric phosphates arises from the variety of ways in which the complex can be linked along the third "variable" crystallographic axis. The linking units are corner-sharing octahedral chain segments, extending along the directions of the four arrows shown in Fig. 2. In beraunite, the chain segments are one and two octahedra in length; in rockbridgeite, two octahedra; in dufrenite, three octahedra; and, tentatively, in laubmannite, four octahedra.

Once these data have been refined so that accurate interatomic distances can be obtained, the oxidation states of the iron atoms over the independent sites can be determined. It appears likely that the deep greenish-black color and pronounced pleochroism of these minerals arise from mixed valences in the face-sharing triplet, and this cluster may also result in peculiar magnetic and electric properties for these substances. Since their crystal chemistry can be placed on an absolute basis, perhaps even a direct link can be established between their paragenesis and their crystallochemical interrelations.

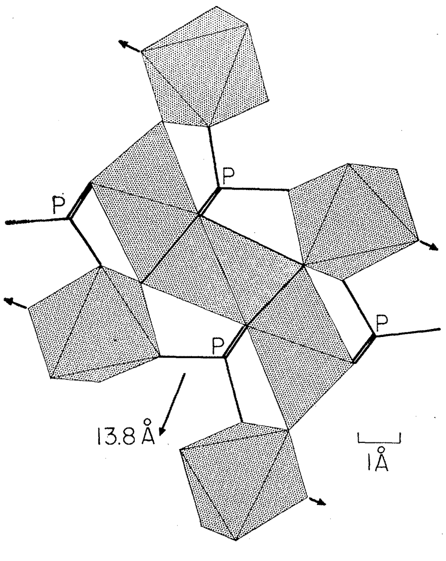

Fig. 2. The polyatomic complex common to the crystal structure of the basic ferric phosphates projected down the fiber axis. The seven octahedra are stippled; shared faces in the octahedral triplet are drawn bold. The phosphate tetrahedra are centered on phosphorus and the P-O distances are drawn bold. The direction of the ~ 13.8-Å cell repeat is designated; the directions of the octahedral corner-sharing chain segments are shown by four short arrows. The locations of the phosphorus atoms in Fig. 1, A and B, can be found by superimposing Fig. 2 upon them.

PAUL B. MOORE

*Department of Geophysical Sciences,*
*University of Chicago,*
*Chicago, Illinois 60637*

### References and Notes

1. C. Frondel, *Amer. Mineral.* **34**, 513 (1949).
2. L. Fanfani and P. F. Zanazzi, *Acta Crystallogr.* **22**, 173 (1967).
3. Since the valence states of the iron are not known, compositions are quoted as the ferric end-members.
4. C. R. Stern assisted in the solution of the dufrenite structure. Specimens were donated by A. Kidwell and J. K. Nelson. Computation expenses were provided by the Advanced Research Projects Agency contract awarded to the University of Chicago.
5. The crystal data for beraunite are from Fanfani and Zanazzi (*2*). The cacoxenite data were reported by D. J. Fisher, *Amer. Mineral.* **51**, 1811 (1966). Approximate specific gravities are from Frondel (*1*). I am responsible for the remaining data and the crystallochemical interpretations. In cacoxenite $a/2$ = 13.83 Å and $c/2$ = 5.32 Å. In beraunite, one-half the obtuse diagonal for $a$ and $c$ = 13.65 Å, in agreement with the orientation of the polyatomic complex in that structure.

6 January 1969

## Cuprous Complexes Formed with Isonicotinic Hydrazide

Abstract. *Chelate formation by Cu(II) and isonicotinic acid hydrazide has been postulated as an important step in the antitubercular activity of isonicotinic hydrazide (Isoniazid). Reevaluation of the copper–isonicotinic hydrazide system gives evidence for the formation of a Cu(I) species rather than a Cu(II) species. The reduction of Cu(II) to Cu(I) and the subsequent formation of an isonicotinic hydrazide complex with the latter ion, therefore, may be the critical reaction responsible for the efficacy of isonicotinic hydrazide against* Mycobacterium tuberculosis.

Isonicotinic acid hydrazide serves as a fundamental drug in the treatment of tuberculosis. Cupric ion enhances the in vitro activity of isonicotinic acid hydrazide against *Mycobacterium tuberculosis* (*1*). Studies of the cupric ion–isonicotinic hydrazide system (*1–3*) have indicated that cupric ion forms 1:1 and 2:1 bidentate complexes (chelates) with isonicotinic hydrazide. These reports point to a copper–isonicotinic hydrazide complex as the curative agent (*3*) or as a critical agent in the antitubercular activity.

Early reports on the existence of cupric–isonicotinic hydrazide chelates (*1, 2*) were based on spectrophotometric measurements (according to Job's method) and an observed drop in *p*H on mixing the metal ion and hydrazide. An equilibrium constant for the overall formation of the 2:1 chelate was calculated from the data ($K = 1.7 \times 10^5$); the constant was dependent on *p*H, however. The same system was studied (*3, 4*) by a potentiometric *p*H method, and the stability constant for the charged 1:1 complex ($1 \times 10^8$) was obtained. Three other metal ions also were studied, Ni(II), Co(II), and Zn(II); the stability constants for all three ions were several orders of magnitude smaller than that for copper.

All of the reports cited thus far indicate that isonicotinic hydrazide complexes by a chelation mechanism; that is, the anion is the complexing species and protons are released in the overall complexation reaction

$$2RH + M^{2+} \rightleftarrows R_2M + 2H^+ \qquad (1)$$

where RH is isonicotinic hydrazide and M represents metal ions such as Cu(II), Ni(II), Co(II), and Zn(II). However, complexation of Cd(II) by several classes of hydrazides including isonicotinic hydrazide (*5*) occurred through a totally different route. No protons were released in the overall reaction; at least three or four soluble complexes were observed; and a symmetrically disubstituted hydrazide, diacetyl hydrazine, showed no evidence of complexation. These data indicate that complexation must occur through a neutral hydrazide moiety and cannot involve chelation; the cadmium complex must be of a monodentate form. This is unusual since the zinc complex was reported to be a chelate (*3*) and one would expect, in general, similar behavior from both cadmium and zinc. Accordingly, a critical reevaluation of metal-hydrazide complexes was undertaken, particularly the Cu(II)-hydrazide systems.

Titration of solutions of various salts of Cu(II) with solutions of various hydrazides, including isonicotinic hydrazide, does produce a significant drop in *p*H below that observed for either metal ion or hydrazide alone. In addition, precipitation during titration was observed with isonicotinic hydrazide and nicotinic hydrazide, and effervescence was noted during the Cu(II)–isonicotinic hydrazide titration. Examination by gas chromatography indicated that the evolved gas was nitrogen. From a solution containing 2 mmole of isonicotinic hydrazide and 1 mmole of $CuCl_2$, 0.3 mmole of $N_2$ gas were collected, although no attempt was made to capture all the nitrogen. The quantity of evolved nitrogen thus indicates that a major reaction occurred.

Another solution containing 10 mmole of isonicotinic hydrazide and 5 mmole of $CuCl_2$ was prepared, and the brown precipitate which was produced was filtered, washed, and dried. The solid had a melting point of 265°C and was insoluble in water, alcohol, acetone, carbon tetrachloride, and benzene, but it could be dissolved in 5 percent hydrochloric acid. Infrared spectra of the precipitate indicated the presence of both carbonyl and N-H groups. These data and elemental analyses are consistent with a material containing equimolar quantities of copper, isonicotinic hydrazide, and chlorine, that is, $Cu \cdot RH \cdot Cl$. The presence of one chloride demonstrates that the copper–isonicotinic hydrazide fragment is a positively charged (+1) species.

Thus it appears that an oxidation-reduction reaction occurs between $CuCl_2$ and isonicotinic hydrazide to produce nitrogen and a reduced form of copper. The reaction of hydrazides with metal ions [such as Cu(II)] to produce nitrogen is well documented and has been used for the analysis of hydrazides for many years (*6, 7*).

As a further step toward elucidating the overall reaction, we may postulate that the reduced form of copper can react with another mole of hydrazide to give the very insoluble brown precipitate. Samples of the precipitate were treated with *p*-dimethylaminobenzalrhodanine (*8*) and 2,2′-biquinoline (*9*). In both cases, a strong positive test for Cu(I) was obtained. Electron paramagnetic resonance spectra, however, disclosed the presence of some Cu(II) in the precipitate. An iodometric determination of the Cu(II) content disclosed the presence of 2.1 percent Cu(II) (by weight) out of a total copper content of 25.2 percent. Therefore, approximately 92 percent of the copper which was precipitated as the copper–isonicotinic hydrazide complex existed in the Cu(I) form. Whether the 8 percent Cu(II) is due to occluded material, a reoxidation of the cuprous ion, or an equilibrium between Cu(I) and Cu(II) species is not known. Other analyses showed, however, that exposure of the precipitate to an oxygen atmosphere increased the Cu(II) assay. Furthermore, a precipitate with essentially the same characteristics as those described above was produced by reaction of CuCl and isonicotinic hydrazide.

These findings, therefore, point toward an initial reaction of Cu(II) with isonicotinic hydrazide to give Cu(I), followed by the formation of an insoluble Cu(I)–isonicotinic hydrazide–chloride complex.

The presence of copper enhances the antitubercular activity of isonicotinic hydrazide. This enhancement was postulated to be due to a neutral 2 : 1 Cu(II) complex which might penetrate the bacterial cell wall more readily than the hydrazide alone. However, the results of this investigation indicate that the copper is reduced to Cu(I) ion, and that a charged 1:1 hydrazide complex is then formed. Therefore, it seems more reasonable to ascribe the synergistic effect of copper to the initial oxidation-reduction reaction that yields Cu(I), or alternatively, to the greater toxicity of the cuprous hydrazide complex against *Mycobacterium tuberculosis*. The same mechanism might account for a similar synergistic effect of copper when used with another antitubercular drug, *p*-acetamidobenzaldehyde thiosemicarbazone (thiacetazone) (*10*).

ALAN F. KRIVIS
JOHN M. RABB

*Department of Chemistry,*
*University of Akron,*
*Akron, Ohio 44304*

**References and Notes**

1. E. Sorkin, W. Roth, H. Erlenmeyer, *Helv. Chim. Acta* **35**, 1736 (1952).
2. S. Fallab and H. Erlenmeyer, *Experientia* **8**, 298 (1952); *Helv. Chim. Acta* **36**, 6 (1953).
3. A. Albert, *Experientia* **9**, 370 (1953).
4. ———, *Nature* **177**, 525 (1956).
5. A. F. Krivis, G. R. Supp, R. L. Doerr, *Anal. Chem.* **37**, 52 (1965); *ibid.* **38**, 936 (1966); G. R. Supp, *ibid.* **40**, 981 (1968).
6. H. Strache, *Monatsh. Chem.* **12**, 524 (1891); H. Harting, *J. Amer. Pharm. Ass.* **42**, 323 (1953).
7. S. Siggia, *Quantitative Organic Analysis via Functional Groups* (Wiley, New York, ed. 3, 1965).
8. F. Feigl, *Spot Tests in Inorganic Analysis* (Elsevier, Amsterdam, ed. 5, 1958).
9. I. M. Kolthoff and P. J. Elving, Eds., *Treatise on Analytical Chemistry* (Interscience, New York, 1961), part 2, vol. 3.
10. K. Liebermeister, *Z. Naturforsch.* **5b**, 79 (1950).

12 March 1969

---

# Maser Amplification of 9.5-Gigahertz Elastic Waves in Sapphire Doped with Divalent Nickel Impurity Ions

Abstract. *The three spin energy levels of divalent nickel impurity ions in sapphire interact strongly with ultrasonic waves whose frequency corresponds to certain allowed transitions between the levels. Under population inversion of the levels it is possible to achieve significant amplification of very high frequency ultrasonic waves by stimulated emission from the spin system.*

This report describes a successful attempt to achieve the amplification of 9.5-Ghz longitudinal elastic waves in sapphire by stimulated emission from the inverted spin population of $Ni^{2+}$ impurity ions. Phonon maser action by impurity spin systems has been reported by Tucker (*1*), who worked with ruby, and by Shiren (*2*), who employed adiabatic fast passage to invert the spin population of $Fe^{2+}$ in MgO.

The choice of $Ni^{2+}$ as a phonon