Low Temperature Polymorphic Transformation in WO_3

B. T. Matthias and Elizabeth A. Wood
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received October 24, 1951)

Tungsten trioxide has been described as having a triclinic structure of corner-linked WO_6 octahedra at room temperature[1] and a tetragonal structure at 740°C.[2] We have found a polymorphic transformation near −50°C below which the symmetry is again higher. The temperature of the transition varies widely with small variations in the composition of the crystals. The transformation has been repeatedly observed with the polarizing microscope and confirmed by x-ray diffraction photographs, both Laue type and powder.

Kehl, Hay, and Wahl find that the structure of the high temperature tetragonal form is that suggested by Kittel for an antiferroelectric crystal.[3] When WO_3 is placed in an alternating electric field at −198°C, a hysteresis loop is observed, indicating that it is ferroelectric at this temperature.[4] An x-ray diffraction pattern taken by Matthias[5] near this temperature is closely similar to that taken at −60°C and the structure is probably the same.

These observations suggest that WO_3 has a high temperature, antiferroelectric tetragonal form and a low temperature, ferroelectric form. The form at intermediate temperatures[1] may or may not be ferroelectric.[6]

[1] Haakon Bräkken, Z. Krist. **78**, 484 (1931).
[2] Kehl, Hay, and Wahl, Phys. Rev. **82**, 774 (1951).
[3] Private communication, to be published soon in J. Appl. Phys.
[4] B. T. Matthias, Phys. Rev. **76**, 430 (1949).
[5] At the University of Chicago, Chicago, Illinois.
[6] Sawada, Ando, and Nomura, Phys. Rev. **82**, 952 (1951).

"Anomalous" $\pi-\mu$ Decay*

H. Primakoff
Washington University, St. Louis, Missouri
(Received October 26, 1951)

The process of $\pi-\mu$ decay of a slow π-meson $\pi\rightarrow\mu+\nu$, involving as it does the sudden creation of a rapidly moving charged particle (the μ-meson with velocity $\approx(3/10)c$), is necessarily accompanied by the simultaneous production of a spectrum of "soft" photons.[1] Such soft photons have been theoretically predicted[2] and experimentally observed[3] in the analogous situation of nuclear β-decay, while Feer[4] and Schiff[5] have given theoretical discussions of the expected soft photon intensity accompanying, respectively, the β-decay of a μ-meson[6] and the creation of a π-meson in a nucleon-nucleon collision. In the present note we wish to report the theoretically expected result for the soft photon intensity produced in $\pi-\mu$ decay; we find that occasionally—probability per decay $\approx10^{-3}$ to 10^{-4}—the soft photon spectrum accompanying the emitted μ-meson carries away so much energy that the μ-meson appears with an "anomalously" small energy, and therefore an anomalously short range in, for example, a photographic emulsion.

More specifically, application of the energy and momentum conservation laws to the $\pi-\mu$ decay with accompanying soft photon emission gives, to a rough but sufficient approximation,

$$E_\mu=E_\mu^{(0)}(1-\epsilon/\epsilon_{\max}). \tag{1}$$

In Eq. (1) E_μ is the kinetic energy of the emitted μ-meson, and $E_\mu^{(0)}=(m_\pi-m_\mu)^2/2m_\pi=4.15$ Mev is the maximum value of this kinetic energy; ϵ is the total energy carried off by the soft photon spectrum accompanying the μ-meson, and $\epsilon_{\max}=\frac{1}{2}(m_\pi-m_\mu)=17.1$ Mev is the maximum value of this total energy; m_π, m_μ are the π-meson and μ-meson rest energies; the angular distribution of the soft photons relative to the μ-meson velocity direction has been taken, as is true to lowest order in 1/137, as following the $\sin^2$ law. Further, the probability that any particular $\pi-\mu$ decay is accompanied by a soft photon spectrum carrying off a total energy between ϵ and $\epsilon+d\epsilon$ is[7]

$$P(\epsilon)d\epsilon=A(\epsilon/\epsilon_{\max})^A d\epsilon/\epsilon;\ \int_0^\infty P(\epsilon)d\epsilon=1 \tag{2}$$

with

$$A\approx(2/3\pi)(1/137)(2E_\mu^{(0)}/m_\mu).$$

Equation (2) yields, as a numerical example, a probability of 1/5000 for emission of a soft photon spectrum with total energy between $\frac{1}{6}\epsilon_{\max}$ and $\frac{3}{4}\epsilon_{\max}$; this corresponds, from Eq. (1), to a μ-meson energy E_μ between $\frac{5}{6}E_\mu^{(0)}$ and $\frac{1}{4}E_\mu^{(0)}$, i.e., to a μ-meson range R between $(5/6)^{1.7}$ and $(1/4)^{1.7}$ times the "normal" range,[8] or to 450 microns $\geqq R\geqq 60$ microns. Experimentally, first Smith, and then Gross, working in Sagane's group at Berkeley have found several "anomalously" short tracks in an examination of some 1000 $\pi-\mu$ decays,[9] Branson, Seifert, and Havens[10] report one such anomalously short μ-meson track, with length less than 450 microns (235 microns), in a study of 1500 $\pi-\mu$ decays, while Fry[11] finds four μ-meson tracks which can be definitely considered as anomalously short (260, 258, 185, 120 microns) in 3018 decays. The longer two of Fry's four anomalous tracks can conceivably be interpreted as originating in $\pi-\mu$ decay in flight with backward emission of the μ in the π's rest frame; in the case of his two shorter tracks, however, such an assumption leads to calculated π-meson velocities and so to estimated grain densities which do not correspond to observation.[11]

The above discussion makes it obvious that much more experimental $\pi-\mu$ decay data are necessary before any agreement or disagreement with the present theory can be considered as at all statistically significant; if a disagreement is eventually indicated, as, for example, would be the case if a greater prevalence of anomalously short tracks were found than is predicted by Eqs. (2) and (1), other possibilities of interpretation of a majority of the short tracks will have to be entertained. One such, already suggested by Fry,[11] involves the assumption of a relatively rare alternative mode of decay of the π-meson; another interpretation would postulate the possession by the μ-meson of a relatively improbable (more or less catastrophic) energy loss mechanism operating in addition to the usual atomic excitation and ionization. The implied μ-meson nucleus interaction cross section, assuming this last explanation, would, however, be too large by many orders of magnitude to reconcile with the otherwise known properties of the μ-meson.

We wish to thank Dr. R. W. Williams and Dr. W. B. Cheston for helpful discussion of the possible interpretation of the anomalously short tracks.

* Assisted by the joint program of the ONR and AEC.
[1] See the discussion of the basic theory of soft photons in F. Bloch and A. Nordsieck, Phys. Rev. **52**, 54 (1937), and in W. Pauli and M. Fierz, Nuovo cimento **15**, 167 (1938). An application to soft photon emission in hard photon radiation processes is given in H. Primakoff and F. Villars, Phys. Rev. **83**, 686 (1951).
[2] J. K. Knipp and G. E. Uhlenbeck, Physica **3**, 425 (1936); F. Bloch, Phys. Rev. **50**, 272 (1936); C. S. W. Chang and D. Falkoff, Phys. Rev. **76**, 365 (1949).
[3] L. Madansky and F. Rasetti, Phys. Rev. **83**, 187 (1951) and earlier references there given; T. B. Novey, Phys. Rev. **84**, 145 (1951).
[4] D. Feer, Phys. Rev. **75**, 931 (1949).
[5] L. I. Schiff, Phys. Rev. **76**, 89 (1949).
[6] Feer (reference 4) assumes however a two-particle decay scheme: $\mu\rightarrow e+\nu$.
[7] Equation (2) is obtained by a field theoretic extension to the case where a (nonrelativistic) charged particle is created or destroyed, of the argument required to obtain the probability of soft photon emission in the case of an atomic electron transition with emission or absorption of a hard photon. The expressions for the soft photon emission probabilities are actually essentially identical in the two cases, as may be seen by comparing Eq. (2) with Eqs. (1), (2) of the last reference of footnote 1. It may also be remarked that the general argument of the references of footnote 1 may be used to show that, in the overwhelming majority of individual instances of emission (e.g., during $\pi-\mu$ decay) of a soft photon spectrum carrying a total energy between ϵ and $\epsilon+d\epsilon$, this spectrum consists of a single fairly energetic soft photon with energy $\eta\approx\epsilon$, and of an associated indefinite (infinite) number of very soft photons with total energy $\epsilon-\eta\ll\epsilon$.
[8] The "normal" $\pi-\mu$ decay μ-meson range in C2 emulsions is about 600 microns; in these emulsions, $R=\text{const}(E_\mu)^{1.7}$. See C. F. Powell, Reports on Progress in Physics, **13**, 350 (1950).
[9] Private communication.
[10] Bramson, Seifert, and Havens, Bull. Am. Phys. Soc. **26**, No. 6, 23 (1951).
[11] W. C. Fry, Phys. Rev. **83**, 1268 (1951).