

FIG. 3. Revealing the **B** in Fig. 2. Double diagram consisting of Fig. 2 and the reference pattern from a nonmagnetic gold foil. It is seen from ring eccentricity that the **B** lies perpendicular to the face of the sample holder. **Z**: magnetic displacement of Fig. 2. $Z \perp 100$. $B \parallel 100$.

Fig. 3. Stronger field than this weak field was not suitable for aligning the specimen particles with their easy axes.

The easy axis of Fe_3S_4 of spinel type revealed here $[100]$ is different from that of Fe_3O_4 of the same structure $[111]$.

- ¹ S. Yamaguchi and H. Wada, *Naturwiss.* **36**, 138 (1969).
- ² S. Yamaguchi, *Rev. Sci. Instrum.* **59**, 1224 (1968).

Superconducting Properties of bcc Alloys in the Nb-Ti-Mo System

V. SADAGOPAN,* H. C. GATOS, AND G. OLSON

Center for Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02159

(Received 19 September 1969)

The superconducting transition temperature (T_c), the (resistive) critical field (H_c) and the current-carrying capacity (J_c) were determined on a few selected alloys, with the bcc structure, of the ternary Nb-Ti-Mo system. This brief study was part of a broader investigation on ternary superconducting systems. The number of detailed investigations on ternary super-

TABLE I. Superconducting properties of bcc Nb-Ti-Mo alloys.

Composition atomic percent			Average valence electron concentration (n)	T_c of annealed samples ($^{\circ}K$)	\bar{H}_c (kilogauss)
Nb	Ti	Mo			
47.5	47.5	5	4.58	8.3	80
40.0	55.0	5	4.50	8.3	84
30.3	64.7	5	4.40	8.2	82
45.0	45.0	10	4.65	6.7	45
30.0	60.0	10	4.50	5.8	...
42.5	42.5	15 ^a	4.73	5.5	...
20.0	65.0	15 ^a	4.50
40.0	40.0	20 ^a	4.80	4.2	0

^a Brittle samples.

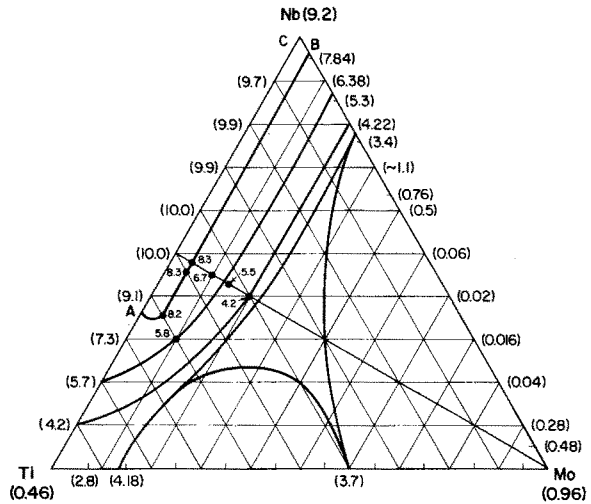


FIG. 1. Superconducting transition temperatures and iso- T_c lines for some compositions in the Nb-Ti-Mo systems. The T_c values in parenthesis were taken from the literature.^{2,4-7}

conducting alloys is extremely limited.¹ In fact, our study of the Ti-Nb-V system² represents the only extensive study. Yet ternary systems offer distinct possibilities for superconducting materials with mechanical or superconducting properties superior to those presently in use. They also lend themselves to the study of certain fundamental or theoretical aspects of type II superconductors.

The alloys employed in the present study were prepared by arc melting in argon atmosphere. The resulting buttons were remelted a number of times to achieve homogeneity. The alloys were further homogenized by annealing at 1300°C for 24 h and then furnace cooling to room temperature. The buttons were subsequently cold rolled. Ribbon samples were sheared with dimensions of 0.4 mm × 0.4 mm × 2.5 cm.

The values of T_c were obtained by a self-inductance technique with an accuracy of $\pm 0.1^{\circ}K$. All superconducting transitions were very sharp. H_c and J_c values were determined by the standard four-probe technique at 4.2°K. The results are summarized in Table I. The J_c values (not included in the table) were determined by fixing the magnetic field at the desired value and increasing the current until a potential drop of 1×10^{-6} V could be detected. At 70 kG the values ranged from 5 to 8×10^8 A/cm². No attempt was made to optimize J_c by heat treatment or other processing.

As can be seen from the table the highest T_c values were observed for an average valence electron concentration of 4.4-4.6. The corresponding n_{eff} range as defined by DeSorbo and co-workers³ is 4.44-4.56. It is thus apparent that T_c and H_c vary smoothly with composition in this ternary system just as they do in the ternary Nb-Ti-V.²

The variation of T_c as a function of composition is shown in Fig. 1. Clearly the addition of Mo in the Nb-Ti binary depresses T_c ; however, the mechanical properties are improved with Mo additions, thus the ternary alloys are far more refractory and less susceptible to hydrogen embrittlement than the binary Nb-Ti alloys. In the light of these advantages the alloys in range ABC of the figure appear technologically attractive. Although the Ti-Nb-V ternary was found better suited for extensive studies of superconducting behavior, it was felt that the limited results on the Nb-Ti-Mo system might be of some general interest.

The authors are grateful to the National Aeronautics and Space Administration for financial support.

* Present address: Thomas J. Watson Research Center, IBM Corporation, Yorktown Heights, New York 10598.

¹ M. I. Bychkova, V. V. Baron, and E. M. Savitskii, Akad. Nauk. SSSR Inst. Metallurg. **2-3**, 79 (1967).

² P. H. Bellin, Ph.D. thesis, M.I.T., 1969; also P. H. Bellin, V. Sadagopan, and H. C. Gatos, J. Appl. Phys. **40**, 3982 (1969).

³ W. DeSorbo, P. E. Lawrence, and W. A. Healey, J. Appl. Phys. **38**, 903 (1966).

⁴ R. A. Hein, J. W. Gibson, and R. D. Blaugher, Rev. Mod. Phys. **36**, 149 (1964), and references cited therein.

⁵ R. A. French, J. Lowell, and K. Mendelsshon, Cryogenics **7**, 83 (1967).

⁶ E. Bucher, F. Heininger, and J. Muller, Proc. Int. Conf. Low Temp. Phys. 9th, Columbus, Ohio, 1964, 482 (1965).

⁷ U. Zwicker, Z. Metallk. **54**, 477 (1963).

Broadband Gain with Naturally Inverted Stable to Continuum Molecular Transitions*

C. V. HEER

Department of Physics, Ohio State University, Columbus, Ohio 43210

(Received 3 November 1969)

The transition from the stable $1s2s\sigma^2\ ^3\Sigma_g$ state to the repulsive $1s2p\sigma^2\ ^3\Sigma_u$ state of the H_2 molecule provides an example of a system which has gain from 0.16 to $0.5\ \mu$. This transition appears with great intensity in an electrical discharge in H_2 and is a widely used source of ultraviolet. Since the repulsive state dissociates into two neutral H atoms in a time of the order of 10^{-14} sec and the lifetime of the upper state is 10^{-8} sec, the system is naturally inverted. This is just one example of molecules with a stable upper state and a continuous lower state. Other immediate examples are D_2 , Hg_2 with an emission continuum near $0.33\ \mu$,¹ and He_2 with a continuous spectrum between 0.06 and $0.1\ \mu$.² The remaining rare gas atoms form molecules Ne_2 , Ar_2 , Kr_2 , and Xe_2 which decay to an unstable level and emit into a continuum in the ultraviolet.³ Each of these stable to continuum transitions are inverted and may provide broad band amplification in the ultraviolet. Other molecules may provide amplification in other spectral regions.

Potential curves for the stable $^3\Sigma_g$ and repulsive $^3\Sigma_u$ states for H_2 are shown in Fig. 1. The upper $^3\Sigma_g$ state forms a stable molecule with a number of vibrational levels and these levels can decay only to the repulsive $^3\Sigma_u$ state. This lower state dissociates into two hydrogen atoms with a relative velocity which is given by $\frac{1}{2}\mu V^2 = U(r)$. An average relative velocity is of the order of 3×10^4 m/sec and therefore the lifetime of the lower state is of the order of 3×10^{-16} sec. The transition rate from state b to state a for the emission of a photon into $d\Omega d\nu$ with polarization \hat{u} is given by

$$W(ba; \nu) d\Omega d\nu = (2\pi^3 \nu^2 / hc^3 \epsilon_0) |(a | P \cdot \hat{u} | b)|^2 (n+1) g(\nu) d\Omega d\nu, \quad (1)$$

where P is the electric dipole moment. $g(\nu)$ is the normalized line shape and for an upper state with a lifetime γ_b^{-1} and a lower

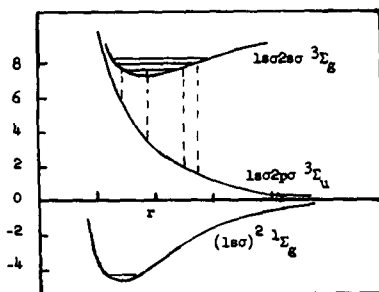


FIG. 1. Potential energy curves for the $(1s\sigma)^2\ ^1\Sigma_g$ ground state, $1s2s\sigma^2\ ^3\Sigma_g$ stable excited state, and the repulsive $1s2p\sigma^2\ ^3\Sigma_u$ state of the H_2 molecule.

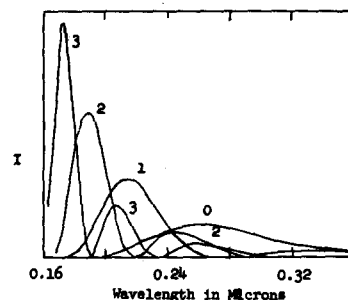


FIG. 2. Intensity of the $^3\Sigma_g-^3\Sigma_u$ transitions for the $v=0, 1, 2, 3$ vibrational levels of the $^3\Sigma_g$ state.⁴

state with a lifetime γ_a^{-1} is given by

$$g(\nu) = 2\gamma_{ab} / [(\omega - \omega_{ab})^2 + \gamma_{ab}^2], \quad (2)$$

where $\gamma_{ab} = \frac{1}{2}(\gamma_a + \gamma_b)$. The integral over $d\Omega d\nu$ with $n=0$ yields the spontaneous emission rate and is of the order of $\gamma_b \cong 10^8$. From previous considerations the value of $\gamma_a \cong 3 \times 10^{14}$. n is the photon number for stimulated emission and is related to intensity by $I(\nu) = n(h\nu^3/c^2)$ and to the electric field by $I(\nu) d\Omega d\nu = \frac{1}{2} c \epsilon_0 E_\nu^2$. The polarization index u is omitted in the remainder of the discussion.

More detailed information concerning the line shape uses the Franck-Condon principle that the nuclei remain fixed during the emission process. The length of the vertical lines between the vibrational level of the upper state and the repulsive curve of the lower state indicate that photons with wavelengths between 0.16 and $0.5\ \mu$ can be emitted. With this approach the product of the electric dipole matrix element and the line shape in Eq. (1) is replaced by

$$C |(a' | P | b')|^2 |\psi_\nu(r)|^2 V^{-1}, \quad (3)$$

where a' and b' denote the electronic states, ψ_ν is the vibrational wave function of the upper level, V is the relative velocity of the dissociation products, and C is a constant. The coordinate r in the vibrational wave function is determined by the transition frequency ν and the line shape is very sensitive to the square of the vibrational wave function of the upper level. James and Coolidge⁴ noted that the variation of the electric dipole with nuclear spacing must be considered and they examined the validity of the Franck-Condon principle and the line intensity in great detail. Their results for the intensity as a function of wavelength⁴ are shown in Fig. 2 for $v=0, 1, 2, 3$. The main features of the line shape are due to the nodes of the Hermite polynomials. Integration over all wavelengths yields a lifetime of approximately 1×10^{-8} sec for each vibrational state or $\gamma_b = 10^8$. Their calculations also show that the strength of the electric dipole matrix element $|(a' | P | b')|^2 \cong (ea_0)^2 \cong 10^{-68}$.

Since the H_2 molecule dissociates with each transition the number of H_2 molecules in the repulsive state can be neglected. Linear gain is almost entirely due to the number of molecules in the upper vibrational levels. Thus the linear gain is approximately

$$\alpha(\nu) \cong N_\nu (2\pi^2 \nu / hc \epsilon_0) |(a | P | b)|^2 g(\nu) \cong 10^{-21} N_\nu (m^{-1}). \quad (4)$$

Since the number of H_2 molecules per cubic meter is of the order of $3 \times 10^{22} P$ where P is the pressure in Torr and the temperature is of the order of 300 K, a reasonable fraction of the H_2 molecules must be excited to the $^3\Sigma_g$ state to produce reasonable gain. At a pressure of 2-3 Torr a gain $\alpha(\nu) \cong 1$ would require 1% of the molecules in the upper states.

Both the upper $^3\Sigma_g$ and the repulsive $^3\Sigma_u$ states are excited by electrons which collide with the $^1\Sigma_g$ ground-state molecules. There is some evidence⁵ that the cross section for electronic excitation of the $^1\Sigma_g-^3\Sigma_u$ transition is of the order of $0.45\pi a_0^2$ between 9.5 to 19 eV and zero at greater energies. Electron excitation of the $^1\Sigma_g-^3\Sigma_g$ transition begins at electron energies of 12 eV, has a cross section of the order of $0.15\pi a_0^2$, and falls to zero for energies