

We have examined the effect of the inclusion of these terms on the theory of the cohesion of the alkali metals. In the cellular approximation, the potential V in (1) is the ion core potential, and we consider the change in the ground-state energy E_0 and in the reciprocal of the effective mass E_2 . We may treat the corrections in first-order perturbation theory to sufficient accuracy (the error may be as large as 6% for cesium), using ordinary nonrelativistic wave functions. Since the ground state is, to good approximation, a pure S -state, the change in the ground-state energy is

$$\Delta E_0 = - \int \psi^* \left[\frac{(E_0 - V)^2}{2mc^2} + \frac{\hbar^2}{4m^2c^2} \frac{dV}{dr} \frac{d}{dr} \right] \psi d\tau, \quad (2)$$

where ψ is the wave function for the ground state Γ_1 . The change in the effective mass is a little more difficult to obtain. If we consider Bloch functions $u_k e^{i\mathbf{k} \cdot \mathbf{r}}$, u_k satisfies

$$\left\{ H + \mathbf{k} \cdot \left[\left(1 - \frac{E - V}{2mc^2} \right) \frac{\hbar \mathbf{p}}{m} - \frac{i\hbar^2 \nabla V}{4m^2c^2} + \frac{\hbar^2}{4m^2c^2} (\boldsymbol{\sigma} \times \nabla V) \right] \right\} u_k = \left[E_k - \left(1 - \frac{E - V}{2mc^2} \right) \frac{\hbar^2 k^2}{2m} \right] u_k, \quad (3)$$

where H is the Hamiltonian of (1). The correction terms transform as vectors. To find the energy to second order in \mathbf{k} and first order in the relativistic corrections, we calculate

$$E_k = \int e^{-i\mathbf{k} \cdot \mathbf{r}} u_k^*(r) H e^{i\mathbf{k} \cdot \mathbf{r}} u_k(r) d\tau / \int u_k^* u_k d\tau. \quad (4)$$

For the alkalis, we may use Bardeen's form³ of u_k , $u_k = u_0 + i\mathbf{k} \cdot \mathbf{r} u_1$, where u_1 vanishes on the surface of the atomic sphere. We find, using (3)

$$E_k = E_0 + \frac{\hbar^2 k^2}{2m} E_2 - \left\{ \Delta E_0 \left(1 - \frac{4\pi}{3} k^2 \int (ru_1)^2 r^2 dr \right) + \frac{4\pi}{3} k^2 \int ru_1 \left[\frac{(E_0 - V)^2}{2mc^2} + \frac{\hbar^2}{4m^2c^2} \frac{dV}{dr} \frac{d}{dr} \right] (ru_1) r^2 dr \right\}, \quad (5)$$

plus some terms which are negligibly small. Here E_0 and E_2 have their nonrelativistic values.

A detailed numerical analysis of these effects is being carried on by the author and Mr. V. Sirounian for the cases of potassium and cesium, using self-consistent field wave functions. Some of the essential features of the results, which will be published in detail at a later date, are as follows: The corrections yield an increased binding. This occurs because the probability that a valence electron will be found near the nucleus, is, on the average, greater in the solid than in the free atom, owing to the compression of the valence electron

charge within the atomic sphere. The effect is not negligible (order of 1 kcal/mole) in potassium, and may be quite large in cesium because of an expected Z^4 dependence on atomic number. In cesium, one would expect an effect of the same order of magnitude as the entire cohesive energy.

I am indebted to Dr. Morrel H. Cohen for valuable discussions.

* Research supported by the Office of Naval Research.

¹ R. J. Elliott, Phys. Rev. **96**, 280 (1954); G. Dresselhaus, Phys. Rev. **100**, 580 (1955); R. H. Parmenter, Phys. Rev. **100**, 573 (1955).

² L. I. Schiff, *Quantum Mechanics* (McGraw-Hill Book Company, Inc., New York, 1955), second edition, p. 333.

³ J. Bardeen, J. Chem. Phys. **6**, 367 (1938).

Multiple Thermal Relaxation Times and Nuclear Spin Energy Transfer in Liquids*

JOHN E. WERTZ, P. L. JAIN, AND R. L. BATDORF

School of Chemistry, University of Minnesota,
Minneapolis, Minnesota

(Received February 27, 1956)

WE offer several lines of evidence to suggest that just as distinguishable protons in a molecule may show discrete nuclear induction lines, they may also have their own characteristic time for return to the ground state from an excited spin state. This would lead to different optimum values of the rf field H_1 . We have observed such differences for protons in groups such as CH_3 , CH_2 , CH , OH and others. Further, one frequently notes the appearance of more "wiggles" after one line has been traversed than for others of similar intensity and width. Thus, for example, a long spin-spin relaxation time t_2 is indicated for the OH protons in some phenols. Since $t_2 \leq t_1$, one has an indication of a relatively

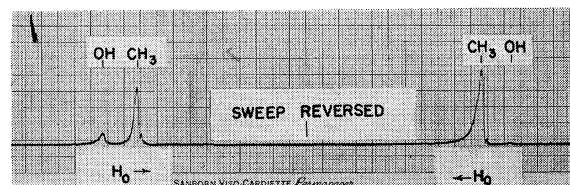


FIG. 1. The proton lines for the OH and CH_3 groups appear as expected when the field is increasing. For decreasing field the OH line is missing. The field H_1 is large and constant.

long time t_1 . The nonidentity of t_1 for distinguishable protons in the same molecule leads to line intensities which are not proportional to their number. Inferences from such intensities must therefore be made with caution.

For large values of H_1 , the relative intensities of multiple lines may depend on the direction of field

sweep. If H_1 has an appropriate value for methyl alcohol (CH_3OH), one observes weak lines due successively to OH and CH_3 protons as the large field H_0 is linearly increased. When the sweep direction is reversed, the CH_3 line becomes more intense, but the OH line does not appear. This is shown in Fig. 1, in which the field sweep is reversed during the trace. One observes a gradual emergence of the OH line as the value of H_1 is reduced. At low H_1 values, the traces in the two sweep directions are essentially identical. Similar behavior has been observed for other molecules.

The initial nonappearance of the OH line when another had first been traversed suggests transfer of spin energy between nuclei having nearly identical resonant field values. We suggest the $\mathbf{I}_1 \cdot \mathbf{I}_2$ interaction¹ between protons 1 and 2 would be modulated at the Larmor frequency when resonant conditions are satisfied for proton 1. This would tend toward equalization of the population of the spin levels of proton 2. At low H_1 values this effect would not be noticed.

It is a pleasure to acknowledge helpful discussions with H. C. Torrey, R. Norberg, H. S. Gutowsky, and T. M. Sanders. Figure 1 was made by Frisic Dravnieks.

* This research was supported in part by the United States Air Force through the Office of Scientific Research of the Air Research and Development Command.

¹ N. F. Ramsey and E. M. Purcell, *Phys. Rev.* **85**, 143 (1952).

Example of an Antiproton-Nucleon Annihilation

O. CHAMBERLAIN, W. W. CHUPP, A. G. EKSPONG, G. GOLDBABER,
S. GOLDBABER, E. J. LOFGREN, E. SEGRÈ, AND C. WIEGAND,
*Radiation Laboratory and Department of Physics,
University of California, Berkeley, California*

AND

E. AMALDI, G. BARONI, C. CASTAGNOLI, C. FRANZINETTI,
AND A. MANFREDINI, *Istituto Fisico dell'Università
Roma, Italy and Istituto Nazionale di Fisica
Nucleare Sez. di Roma, Italy*

(Received March 8, 1956)

THE existence of antiprotons has recently been demonstrated at the Berkeley Bevatron by a counter experiment.¹ The antiprotons were found among the momentum-analyzed (1190 Mev/c) negative particles emitted by a copper target bombarded by 6.2-Bev protons. Concurrently with the counter experiment, stacks of nuclear emulsions were exposed in the beam adjusted to accept 1090-Mev/c negative particles in an experiment designed to observe the properties of antiprotons when coming to rest. This required a 132-g/cm² copper absorber to slow down the antiprotons sufficiently to stop them in the emulsion stack. Only one antiproton was found² in stacks in which seven were

expected, assuming a geometric interaction cross section for antiprotons in copper. It has now been found³ that the cross section in copper is about twice geometric, which explains this low yield.

In view of this result a new irradiation was planned in which (1) no absorbing material preceded the stack,

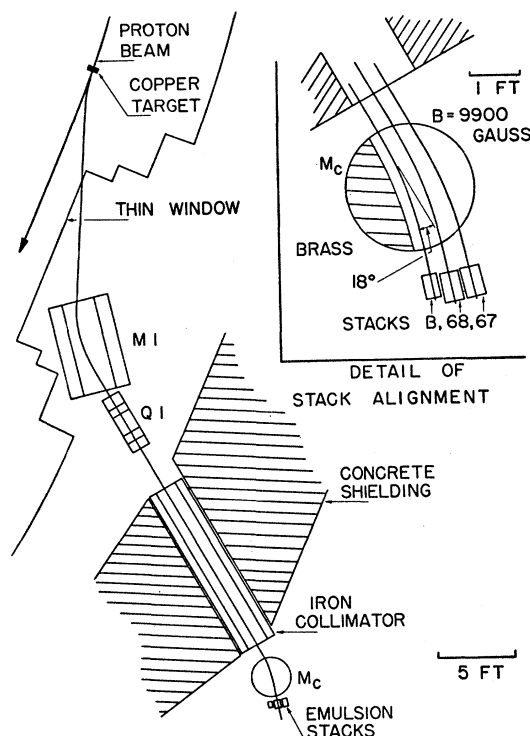


FIG. 1. Plan of the irradiation.

(2) the range of the antiprotons ended in the stack, and (3) antiprotons and mesons were easily distinguishable by grain density at the entrance of the stack. In order to achieve these three results it was necessary to select antiprotons of lower momentum, even if these should be admixed with a larger number of π^- than at higher momenta.

In the present experiment we exposed a stack in the same beam used previously, adjusted for a momentum of 700 Mev/c instead of 1090 Mev/c. Since the previous work² had indicated that the most troublesome background was due to ordinary protons, the particles were also passed through a clearing magnetic field just prior to their entrance into the emulsion stacks. The clearing magnet (M_c) had $B=9900$ gauss, circular pole faces of diameter 76 cm, and a gap of 18 cm, so particles scattered from the pole faces of the clearing magnet could be ignored on the basis of their large dip angle in the emulsions. With this arrangement we have achieved conditions in which the negative particles enter the emulsions at a well-defined angle, and extremely few positive particles enter the emulsions within the same

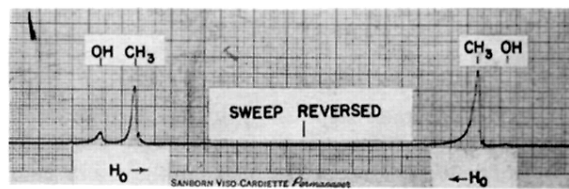


FIG. 1. The proton lines for the OH and CH₃ groups appear as expected when the field is increasing. For decreasing field the OH line is missing. The field H_1 is large and constant.