This is the same as saying

$$p+d\rightarrow\tfrac{1}{2}(p+p+p+\pi^-)+\tfrac{1}{3}(p+p+n+\pi^0)+\tfrac{1}{6}(p+n+n+\pi^+),$$

where the coefficients give the relative probabilities of the different processes.

2. Final nucleon state $T^N=\frac{1}{2}$. As before,

$$\phi(T=\tfrac{1}{2},\ T_3=\tfrac{1}{2})=(1/\sqrt{3})\Psi(T_3{}^N=\tfrac{1}{2},\ t_3=0)+(\sqrt{2}/\sqrt{3})\Psi(T_3{}^N=-\tfrac{1}{2},\ t_3=1),$$

from Condon and Shortley. This is the same as writing

$$p+d\rightarrow\tfrac{1}{3}(p+p+n+\pi^0)+\tfrac{2}{3}(p+n+n+\pi^+),$$

the coefficients giving the relative probabilities once again.

Now suppose the probability of going into $T^N=\frac{3}{2}$ is x, $T^N=\frac{1}{2}$ is $1-x$ (x is of course a function of angle and energy in general). Then, apart from a common factor, we have

$$\sigma_+=\tfrac{1}{6}(x)+\tfrac{2}{3}(1-x)=\tfrac{2}{3}-\tfrac{1}{2}x,$$
$$\sigma_-=\tfrac{1}{2}(x),$$
$$\sigma_0=\tfrac{1}{3}(x)+\tfrac{1}{3}(1-x)=\tfrac{1}{3},$$

where σ_+ is the cross section for producing π^+ mesons at any angle and energy, and σ_-, σ_0 are the corresponding cross sections for π^- and π^0 mesons, respectively. Adding the first two equations, we obtain $\sigma_++\sigma_-=\frac{2}{3}$ and thus

$$\sigma_++\sigma_-=2\sigma_0(p+d \text{ or } n+d \text{ collisions}). \quad (1)$$

This relationship between the production cross sections for pions must hold independent of energy and angle, and it should be subject to direct experimental check as soon as our knowledge of these cross sections improves.

Proceeding in an exactly similar manner, we can obtain the following relationship among the cross sections for pion production in nucleon-nucleon collisions:

$$\sigma(p+p\rightarrow p+n+\pi^+)=2[\sigma(n+p\rightarrow n+p+\pi^0)+\sigma(p+p\rightarrow p+p+\pi^0)-\sigma(n+p\rightarrow n+n+\pi^+)], \quad (2)$$

which is also independent of energy or angle. This result may also be derived at once from Watson and Brueckner's[1] Eq. (17). In the special cases they considered, it reduces to their results. It is important to stress, however, that (1) and (2) assume only charge independence of the pion-nucleon interaction and make no assumptions whatever as to the details of this interaction.

* Since completing this work, I have been informed by Mr. A. M. L. Messiah that he has submitted identical results in the Letters to the Editor Section [Phys. Rev. **86**, 430 (1952)].

[1] W. Heitler, Proc. Roy. Irish Acad. **51**, 33 (1946); K. M. Watson and K. A. Brueckner, Phys. Rev. **83**, 1 (1951).

[2] E. V. Condon and G. Shortley, *The Theory of Atomic Spectra* (Cambridge University Press, London, 1951), p. 76.

Angular Distributions of Inelastically Scattered Protons from C^{12} and Mg^{24} †

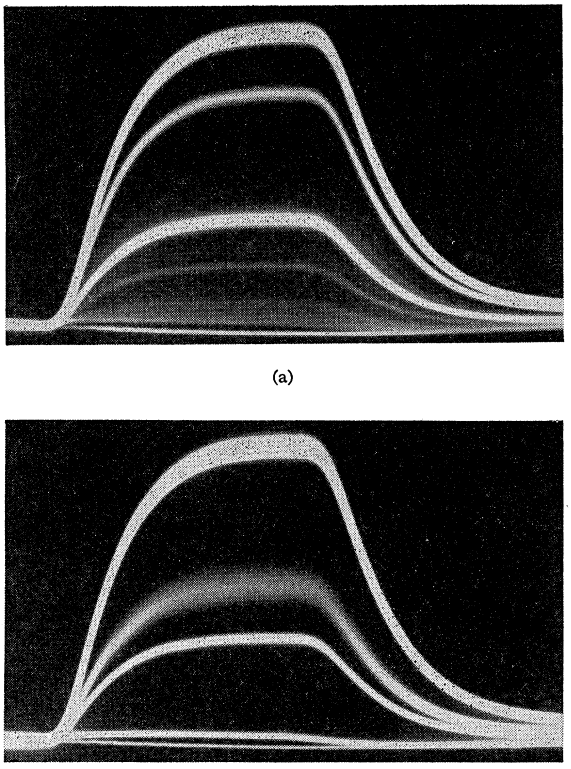
H. E. Gove and H. F. Stoddart

Department of Physics and Radioactivity Center of the Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received March 27, 1952)

A NaI scintillation counter for detecting heavy charged particles has been built and used for measuring the angular distributions of inelastically scattered protons from targets bombarded with 7.3-Mev protons from the M.I.T. cyclotron. A complete description of this detector will be published at a future date but, briefly, it consists of a thin flat NaI crystal cleaved on all six sides and mounted in an aluminum reflector arrangement on the end of an RCA 5819 photomultiplier. Sodium iodide was chosen because of the linear relation between the output pulse height and the proton energy.[1]

The counter, which has no window and can detect protons of all energies, is mounted on one of the movable arms in the M.I.T. scattering chamber.[2] Its angular position relative to the incident proton beam can be varied continuously from 20° to 160° to an accuracy of ±0.5°.



(a)

(b)

FIG. 1. Photographs of the pulse-height distribution of protons from magnesium (a) and carbon (b) bombarded by 7.26-Mev protons.

The pulse-height distribution can be obtained by photographing the oscilloscope face with a time exposure. In the photographs presented here there are a total of about 10^5 counts. Figure 1(a) shows the proton groups emitted at about 45° from a thin isotopic magnesium target. The two strongest inelastic groups correspond to the well-known levels in Mg^{24} at 1.38 and 4.14 Mev.[3] From the position of these two groups and the elastic group it is possible to calculate the incident proton energy (7.26±0.04 Mev) and to conclude that NaI has a linear response to proton energy to within 4 percent. Figure 1(b) shows the proton groups from a 0.4 mg/cm² aquadag target. The two sharp groups correspond to the ground state and first excited level in C^{12} at 4.45 Mev.[4] The broad group is due to elastically scattered protons from hydrogen contamination.

The angular distributions of the inelastic proton groups corresponding to the 1.38-Mev level in Mg^{24} and the 4.45-Mev level in C^{12} have been measured with a very stable single-channel analyzer.[5] The results are shown in Fig. 2. The broken curves through the data points represent the best fit obtained with a Legendre polynomial expansion whose coefficients are given in Table I. The average standard deviation of the data from the expansion is 3 percent for C^{12} and 4.5 percent for Mg^{24}, which can be accounted for on the basis of statistical fluctuations in the counts and, in the case of Mg, inaccuracies in subtracting out a small satellite peak,

TABLE I. Legendre polynomial coefficients for center-of-mass angular distributions.

Reaction	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7
$C^{12}(p,p')$	1.00	0.24	0.77	0.17	0.06	−0.04	−0.08	0
$Mg^{24}(p,p')$	1.00	0	0.65	0.40	−0.45	0.10	0	−0.10

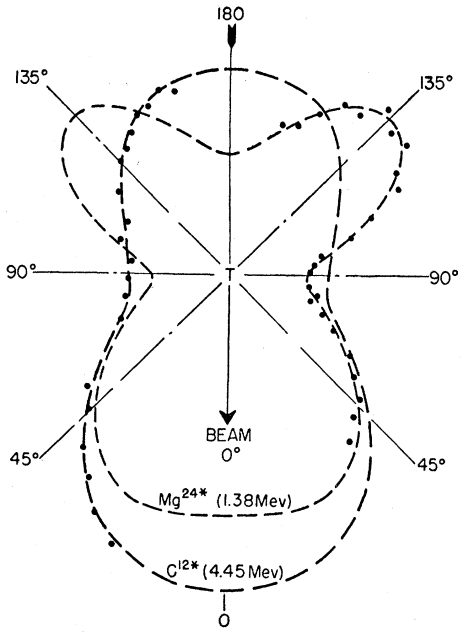


FIG. 2. The angular distributions of the $C^{12}(p,p')C^{12*}$ $Q=-4.45$ Mev and the $Mg^{24}(p,p')Mg^{24*}$ $Q=-1.38$ Mev-reactions in the center-of-mass system.

present to about 10 percent on the low energy side of the 1.38-Mev level.

In both cases the spin of the target nucleus is zero, even parity, and that of the residual Mg^{24} nucleus in the first excited state is two, even parity,[6] while that of the first excited state of C^{12} is also predicted to be two, even parity.[7] Both angular distributions are asymmetric about 90°, indicating that at least two levels of different parity are involved in the compound nuclei (Al^{25} and N^{13}), but nothing is known about the levels of these nuclei in this region. It is not too surprising that such a striking difference exists in the lobe pattern of the two distributions in view of the possible complexities in the compound nucleus.

† This work was supported in part by the joint program of the ONR and AEC.

[1] Taylor, Jentschke, Remley, Eby, and Kruger, Phys. Rev. **84**, 1034 (1951).
[2] Boyer, Gove, Harvey, Deutsch, and Livingston, Rev. Sci. Instr. **22**, 310 (1951).
[3] *Nuclear Data*, National Bureau of Standards Circular No. 499 (1950).
[4] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950).
[5] Designed by C. W. Johnstone, Los Alamos Scientific Laboratory.
[6] E. L. Brady and M. Deutsch, Phys. Rev. **78**, 558 (1950).
[7] R. R. Haefner, Revs. Modern Phys. **23**, 228 (1951).

Nuclear Resonance and the Electronic Structure of Transition Metals*

W. D. KNIGHT AND C. KITTEL
Department of Physics, University of California, Berkeley, California
(Received March 31, 1952)

ZENER[1] has suggested that the occurrence of body-centered cubic (b.c.c.) crystal structures in the transition metals V, Cr, Nb, Mo, Ta, and W may be attributed to antiferromagnetic coupling between the 3*d* shells on adjacent atoms, because a b.c.c. lattice has a lower ground state with respect to nearest-neighbor antiferromagnetic interactions than a closest-packed lattice. The usefulness of this model has been emphasized in a series of papers by Zener[2] and his collaborators.

It is fair to ask to what extent the ground states of the b.c.c. transition metals actually exhibit characteristic antiferromagnetic properties in the ordinary antiferromagnetic salts. States with alternating spin arrangements in solids may be described by diverse types of wave functions.[3] We may represent antiferromagnetism at one extreme by an ionic model using Heitler-London wave functions. This gives a fairly good account of the properties of MnO, MnF_2, and similar antiferromagnetics. At the other extreme we have a free electron or running wave model, with a kind of antiferromagnetism implied in the correlation energy[4] which keeps electrons of parallel spin farther apart than electrons of antiparallel spin, as in metallic Na. Therefore, it may not be necessary to accept all the literature consequences of the Zener theory in order to retain some of the insight it brings to cohesive energy problems.

The experimental evidence is rather against the possibility that all of these metals have "ordinary" antiferromagnetism:

(1) Susceptibility and heat capacity data do not show the susceptibility peaks and thermal anomalies commonly associated with the Curie point of antiferromagnetics, but of course it may be that the Curie points are too high to be observed.

(2) Shull[5] has been unable to detect the presence of an ordered spin state at room temperature in V, Nb, and W, using the neutron diffraction technique successfully employed on the antiferromagnetic salts. Weak antiferromagnetism is observed in Cr and Mn.

(3) Nuclear resonance results[6] for V and Nb are incompatible with a static antiferromagnetic array, as discussed below.

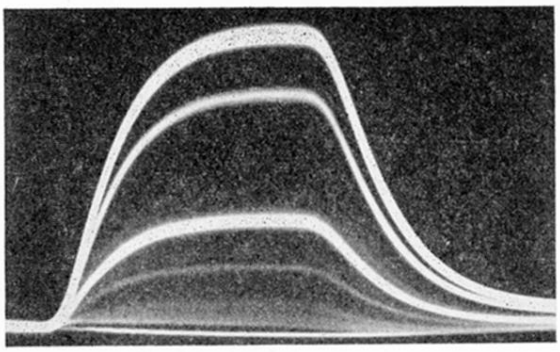
If vanadium had an antiferromagnetic array of the spins of the 3*d* electrons, then the nuclear resonance spectrum would have a zero-field splitting of the order of 2×10^5 oersteds, caused by electron spin-nuclear spin interaction. The experimental results[6] for V (and Nb) do not show any splitting within the experimental limits of about five oersteds. From these facts we may conclude either (a) the 3*d* bonding is completely covalent in V or (b) if the 3*d* shell is in a magnetic configuration, the direction of the total spin of each ion must change with a correlation time much less than 10^{-4} sec, corresponding to the observed nuclear resonance line width. That is, if an antiferromagnetic array exists, it must move about rapidly.[7]

The coupling of the nuclear spin with the $3d^x$ shell in a solid occurs principally (for $x\leq5$) through the excited configuration $3s3p^63d^x4s$, as shown by Abragam.[8] In ionic crystals containing Mn^{++} or V^{++} ions it is known from paramagnetic resonance studies[9] that the hyperfine interaction term $A\mathbf{S}\cdot\mathbf{I}$ has $A\approx0.01$ cm^{-1}. In terms of an effective field acting on the nuclei, we have $H_{\max}=ASI/\mu_{\text{nuc}}$, which for Mn^{++} is $\approx3\times10^5$ oersteds, and for V^{++} is $\approx2\times10^5$ oersteds. Experimental work is planned on the direct observation of the predicted zero-field nuclear splitting in paramagnetic salts.

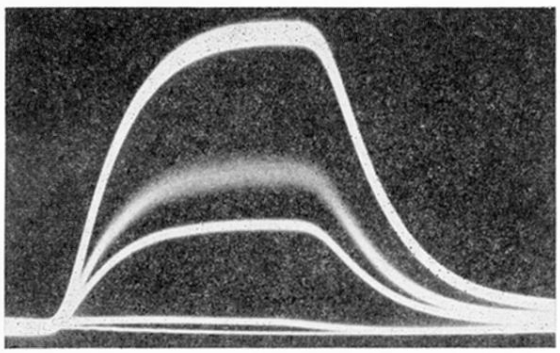
It is interesting to speculate on the basis of the first transition group whether the presence of a static antiferromagnetic (or ferromagnetic) array is not incompatible with superconductivity, either because the dipolar magnetic fields exceed the critical field or for other reasons.

We are indebted to Dr. C. G. Shull for several helpful letters.

* This work has been assisted in part by the ONR.
[1] C. Zener, Phys. Rev. **81**, 440 (1951).
[2] C. Zener, Phys. Rev. **83**, 299 (1951); **85**, 324 (1952); I. Isenberg, Phys. Rev. **83**, 637 (1951); Yee-Chuang Hsu, Phys. Rev. **83**, 975 (1951).
[3] Preliminary work on this question is reported by J. C. Slater, Phys. Rev. **82**, 538 (1951).
[4] C. Herring, Phys. Rev. **82**, 282 (1951), has suggested that the correlation energy may be higher as the effective mass of the electrons increases. H. Jones and N. F. Mott, Proc. Roy. Soc. (London) **A162**, 49 (1937), account on the band model for the high heat capacity and magnetic susceptibility of the transition metals using a high effective mass.
[5] C. G. Shull and M. K. Wilkinson, Phys. Rev. (to be published).
[6] W. D. Knight, Phys. Rev. **85** 762 (1952).
[7] Shull's negative result by neutron diffraction suggests that the correlation time is less than 10^{-13} sec. Similar correlation time considerations apply to ferromagnetic elements for which Shull and collaborators find good agreement with the calculated form factors; it is not then possible to postulate a model with two different types of magnetic ions present unless these exchange positions in a time $<10^{-13}$ sec. This objection may be raised against Zener's latest models and also that of K. H. Stevens, Proc. Phys. Soc. (London) **A65**, 149 (1952).
[8] A. Abragam, Phys. Rev. **79**, 534 (1950).
[9] B. Bleaney, Physica **17**, 175 (1951); A. Abragam and M. H. L. Pryce, Proc. Roy. Soc. (London) **A205**, 135 (1951); Tinkham, Weinstein, and Kip, Phys. Rev. **84**, 848 (1951).



(a)



(b)

FIG. 1. Photographs of the pulse-height distribution of protons from magnesium (a) and carbon (b) bombarded by 7.26-Mev protons.