for the first excited state of the unsymmetrical vibration ν_3 takes the form

$$\psi(0,0,1,J,K,M)=\{\psi^0(0,0,1)-iKC\sum_{s=1}^{2}[\zeta_{3s}/(\omega_3-\omega_s)] \times[(\omega_3+\omega_s)/(\omega_3\omega_s)^{\frac{1}{2}}]\psi^0(V_s=1,V_{s'}=0)\}\Theta(\theta,\psi)e^{iK\zeta},$$

C being $h/8\pi^2I_{zz}c$ and ζ_{3s} the Coriolis coupling factors which depend upon the nature of the normal coordinates. Similar wave functions are obtained for the first excited states of ν_1 and ν_2.

Assuming the dipole moment induced by vibration to be

$$E=\sum_{s=1}^{3}a_sq_s,$$

where a_s is a constant and q_s are the normal coordinates the intensities of the lines in ν_s ($s=1$, 2 or 3) are proportional to the squares of the matrix elements $(0,0,0,K|I|V_s=1,V_{s'}=0,K\mp1)$, which are the following

$$(0,0,0,K|I|V_s=1,V_{s'}=0,K\mp1) =\{a_s\pm\Sigma'_{s'}a_{s'}(K\zeta_{3s'}C/\Delta_{s'})[(\omega_s+\omega_{s'})/(\omega_s\omega_{s'})^{\frac{1}{2}}]\},$$

$\Delta_{s'}$ being $\omega_s-\omega_{s'}$.

It is, of course, well known that in molecules like H_2O and H_2S the band ν_2 is intense compared with the band ν_3, which is intense compared with ν_1, i.e., $a_2\gg a_3\gg a_1$. Taking ω_1, ω_2, and ω_3 to be 2610 cm^{-1}, 1290 cm^{-1}, and 2684 cm^{-1} for H_2S and letting $C=h/8\pi^2I_{zz}c$ be approximately 5 cm^{-1} and finally assuming the values of $\zeta_{31}=4.5\times10^{-3}$ and $\zeta_{32}=-1.0$ calculated by Darling and Dennison[1] for water vapor to be valid for H_2S as well, it may be shown that the term in I containing a_1K may be neglected. Moreover, the factor I will decrease to zero as the term containing a_2K approaches 1.4×10^2a_3 for transitions of the type $K\rightarrow K-1$. I will, for the same value of K, have assumed double its original value for transitions of the type $K\rightarrow K+1$. Since $a_2\gg a_3$, the above may happen for small values of K (i.e., $K\approx10$). The general effect upon the intensities is to enhance the transitions $K\rightarrow K+1$ at the expense of the transitions $K\rightarrow K-1$. By choosing the ratio of a_2 to a_3 in the proper manner the transitions $K\rightarrow K-1$ can almost entirely be suppressed so that, as in the case of H_2S, only about one-half of the band may be observed.

The effect of the perturbation on the band ν_2 is small and would probably not be observable. The effect of the perturbation on ν_1 is less readily estimated, but would probably not be observable as long as $a_3\gg a_1$.

* This work was assisted by the ONR.

[1] B. T. Darling and D. M. Dennison, Phys. Rev. 57, 128 (1940).

Magnetic Moments of Even-Odd Nuclei

F. Bloch
Department of Physics, Stanford University, Stanford, California
(Received June 27, 1951)

The success of the shell model[1] indicates that it is a good approximation to consider even-odd nuclei as single-particle systems with the odd nucleon moving in a spherically symmetrical potential provided by the even-even core. The model leads thus to the basic classification of nuclear states by the orbital angular momentum $l\hbar$ of the odd nucleon as well as by the spin I and to the expectation that the magnetic moment μ should have one of the two Schmidt values,[2] determined by $l=I\pm\frac{1}{2}$.

Two modifications have been proposed to explain the observed deviations from these values:

A.—l is not a good quantum number, and nuclear states represent actually a mixture of states[3] with $l=I+\frac{1}{2}$ and $l=I-\frac{1}{2}$.

B.—A tidal wave which contributes to μ can be formed in the core by the interaction with the odd nucleon.[4]

It has been pointed out before[4] that either modification has its peculiar serious difficulties: modification A requires a considerable mixing of states which, according to the shell model, are widely separated in energy and which have different parity in the odd nucleon; modification B fails to give deviations from the Schmidt values for nuclei with $I=\frac{1}{2}$, while they occur here actually with comparable magnitude as for other nuclei. Unless they are considered as small corrections, insufficient to explain the observed deviations, both proposals require besides a major departure from essential features of the shell model.

TABLE I. The effective intrinsic moment μ' of the odd nucleon, calculated from the Landé formula for an even-odd nucleus with magnetic moment μ, spin I and for both values of the orbital quantum number $l=I\pm1/2$.

	Odd proton	Odd neutron
l	μ'_P	μ'_N
$I-1/2$	$\mu-I+1/2$	μ
$I+1/2$	$I+(3/2)-(I+1/I)\mu$	$-(I+1/I)\mu$

We propose an alternative interpretation of the empirical results which is compatible with a strict adherence to the shell model.

C.—The intrinsic magnetic moment of the odd nucleon is affected by the binding to the core; depending upon the nucleus, it can differ by an appreciable amount from the magnetic moment of the free nucleon.

Accepting this interpretation, one can use the Landé formula to determine the effective intrinsic moments μ_P' or μ_N' of the odd proton or neutron, respectively, from the observed magnetic moment μ and spin I of an even-odd nucleus. They are given in Table I for either alternative $l=I\pm\frac{1}{2}$ in units of the nuclear magneton.

Using available data for both odd-proton and odd-neutron nuclei, we have plotted in Fig. 1 the corresponding deviations $\Delta\mu_P=\mu_P-\mu_P'$ and $\Delta\mu_N=-(\mu_N-\mu_N')$ of the intrinsic moment from its magnitude $\mu_P=2.79$ and $-\mu_N=1.91$ in the free nucleon against the number n of odd nucleons up to $n=83$. For each nucleus the assignment of l in Table I was made according to the shell model, i.e., according to the Schmidt value which is closer to μ; it leads in our presentation equivalently to the smaller deviation $\Delta\mu$.

Within minor fluctuations and particularly up to $n=40$, the odd neutron points not only follow remarkably well those for the odd protons[5] but the plot reveals also a certain regularity for both: a very coarse general trend, indicated by C_1, exhibits an initial rise to the approximately constant value $\Delta\mu\cong1$ for $n>20$. A pronounced alternating variation is superimposed on this general trend and is indicated by C_2; its periods are evidently related to the shells, closed at $n=2$, 8, 20, 50, 82, insofar as the maxima occur approximately in the middle and the minima towards the end of each shell. Possible secondary variations in the second half of the fourth and fifth shell are indicated by

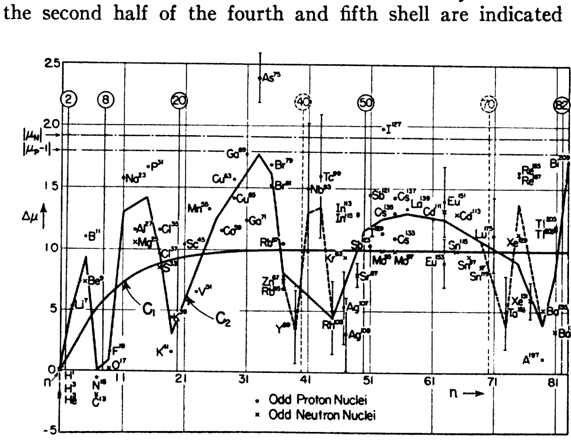

FIG. 1. The defect $\Delta\mu$ of the effective intrinsic moment of the odd nucleon *versus* the number n of odd nucleons in even-odd nuclei. Odd-proton nuclei are indicated by dots, odd-neutron nuclei by crosses. The encircled numbers on top represent the closing of shells; the subshells closed before the filling of the $g_{9/2}$ and $h_{11/2}$ states, are indicated by broken numbers and circles.

broken lines; they are similar to each other and may relate to the filling of the $g_{9/2}$ states (for $40<n\leqq 50$) and $h_{11/2}$ states (for $70<n\leqq 82$) in the scheme of Mayer, but more accurate data in these regions are required to establish their reality. The remaining minor fluctuations of the order of 0.2 magneton seem rather irregular.

Current theories suggest that our presentation should be plausibly interpreted as a variation of the "anomalous moment," due to modifications of the meson field by the binding of the odd nucleon.[6] Accordingly, the values $|\mu_P-1|$ and $|\mu_N|$ of $\Delta\mu$ in Fig. 1 represent the limits where the anomalous moment would be completely quenched; with very few exceptions, the points are seen to fall between zero and these limits, indicating partial quenching as the general case. We hope that further developments of the meson theory of nuclear forces will tend to corroborate this interpretation and to explain the characteristic features of our plot.[7]

[1] Haxel, Jensen, and Suess, Phys. Rev. **75**, 1766 (1949); E. Feenberg and K. C. Hammack, Phys. Rev. **75**, 1877 (1949); L. W. Nordheim, Phys. Rev. **75**, 1894 (1949); M. G. Mayer, Phys. Rev. **75**, 1969 (1949), **78**, 16 (1950); E. Feenberg, Phys. Rev. **77**, 771 (1950).

[2] T. Schmidt, Z. Physik **106**, 358 (1937).

[3] L. W. Nordheim (reference 1), and A. L. Schawlow and C. H. Townes [Phys. Rev. **82**, 268 (1951)] have recently pointed out that approximately equal mixtures are found for nuclei with the same spin and the same number of odd protons or odd neutrons.

[4] L. L. Foldy and F. T. Milford, Phys. Rev. **80**, 751 (1950).

[5] In spite of its different interpretation, this agreement is closely related to that observed by Schawlow and Townes (reference 3) for nuclei of equal spin; it is noteworthy, however, that it holds also for O^{17} and F^{19} with spins 5/2 and 1/2, respectively.

[6] F. Villars [Phys. Rev. **72**, 256 (1947); Helv. Phys. Acta **20**, 476 (1947); **21**, 354 (1948)] has previously considered such variations, due to exchange currents of the meson field, and has applied them successfully to the nuclei H^1 and He^3.

[7] The mechanism introduced by F. Villars (reference 6), will certainly have to be considered in this connection. In another approach, which seems to us more promising, nonlinear terms are introduced in the meson field to explain the validity of the single-particle model and the saturation of nuclear forces; they appear at the same time to lead quite naturally to the quenching of the anomalous moments, postulated here. (Private communication by L. I. Schiff and S. D. Drell.)

Resonant Scattering of Slow Neutrons by Cadmium

B. N. Brockhouse, D. G. Hurst, and M. Bloom
Atomic Energy Project, National Research Council of Canada, Chalk River, Ontario, Canada
(Received June 21, 1951)

SCATTERING of slow neutrons by cadmium has been measured over a range of neutron energy (0.02 to 0.4 ev) which includes the resonance at 0.176 ev. The apparatus shown in Fig. 1 was mounted on the arm of the crystal spectrometer previously described,[1] replacing the usual counter and shielding. Two circular apertures in slabs of boron carbide limited the monoenergetic beam to $\frac{1}{2}$-inch diameter. Scattered neutrons were detected in six boron trifluoride counters symmetrically arranged in an annular bank about the neutron beam. To reduce background, the scattering chamber was evacuated and the equipment was shielded with paraffin wax and boron carbide. A thin sample of vanadium was used as a standard scatterer because of the almost complete lack of coherent scattering in vanadium.[2]

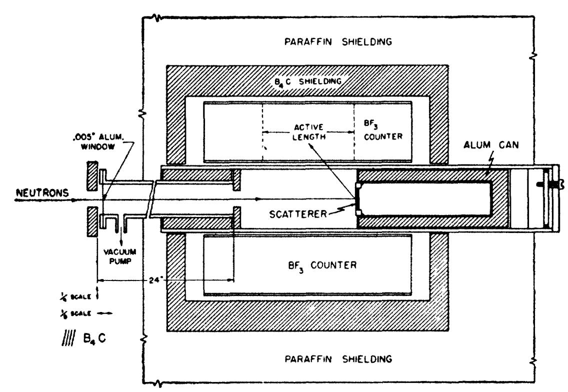

FIG. 1. Resonant scattering apparatus. The vertical and horizontal scales are such that the figure is compressed horizontally in a ratio 2:1.

The counting rates from the standard scatterer and from specimens of cadmium thick enough to absorb nearly all the incident neutrons were measured under the same conditions. The ratio of scattering to absorption cross sections for cadmium is then given by $\sigma_s/\sigma_a=Kn_v\sigma_{sv}N/N_v$, provided $\sigma_s\ll\sigma_a$, where K is an instrumental constant, n_v is the number of vanadium atoms per cm^2, σ_{sv} is the scattering cross section of vanadium, and N and N_v are the counting rates due to cadmium and vanadium, respectively.

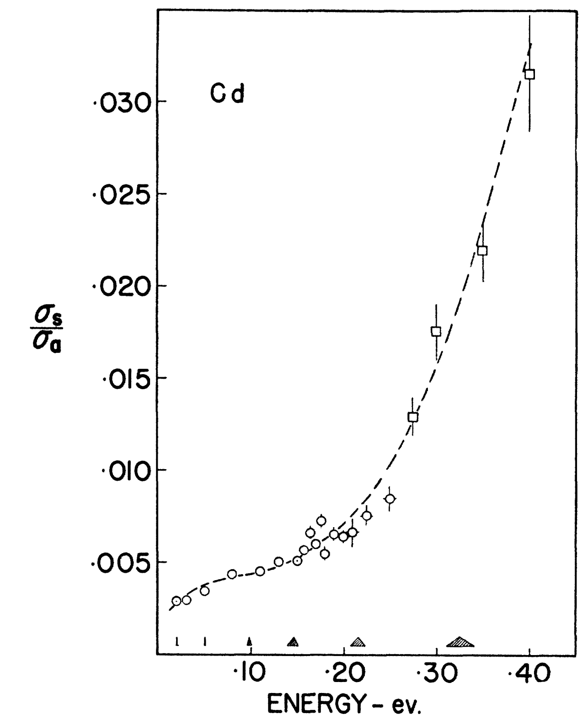

FIG. 2. Ratio of scattering to absorption cross sections in Cd. The circles and squares are experimental points with their standard deviations. The dashed curve is the Breit-Wigner curve calculated with $E_0=0.176$ ev, $\Gamma_a=0.115$ ev, $\sigma_{a0}=7200$ barns, $\sigma_P=5.3$ barns, $a=6.5\times10^{-13}$ cm, $f=0.1230$, $g=0.75$. The triangles indicate the resolution of the apparatus.

The essentially cylindrical symmetry of the apparatus permits the calculation of the angular distribution of the scattered neutrons for both specimen and standard. From these distributions and the measured counter sensitivity the constant K was computed. A small energy dependence of K, due to absorption in the vanadium, was taken into account.

The quantity $n_v\sigma_{sv}$ was determined by measuring the transmission of the standard vanadium sample as a function of energy. The total cross section of the sample was linear in $1/v$. The $1/v$ term was identified with absorption and the constant term with scattering. This constant term, which is considered accurate to ± 3 percent, was used as $n_v\sigma_{sv}$.

The ratio σ_s/σ_a for cadmium is shown in Fig. 2 with standard deviations. A correction for contamination of the beam by higher diffraction orders has been applied.

In the same figure a curve is drawn showing the ratio predicted