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# Spin of Neon-21†

J. C. HUBBS* AND G. M. GROSOF
*Department of Physics, Columbia University, New York, New York*

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The spin of neon-21 has been shown to be 3/2 by the atomic beam magnetic resonance method utilizing the metastable $2p^53s\,^3P_2$ state of neon. The assignment is made from a comparison of Zeeman frequencies in neon-20 and neon-21 at the same magnetic field.

## INTRODUCTION

THE spin and quadrupole moment of neon-21 are of particular interest because of the "anomalous" behavior of sodium-23 in a region where protons and neutrons are filling the $d_{5/2}$ level and should therefore, according to zero-order shell theory, result in spin 5/2. An explanation for the observed spin has been a $(d_{5/2})^3$ configuration, but recent measurements[1,2] have shown a relatively large and positive quadrupole moment entirely out of line with such a quadrupole-free assignment. A series of experiments designed to obtain the spin, magnetic moment, and quadrupole moment of neon-21 has therefore been undertaken.

The investigation by members of the Columbia molecular and atomic beams laboratory of the metastable states of the rare gases—especially the work of Hughes and Weinreich[3] on helium-3—has provided a basis for the research. The principal problem, then, has been the extension of existing techniques two orders of magnitude farther in signal-to-noise ratio so that observations might be made on a single transition in neon-21. K. Clausius had kindly furnished us a 10-cc sample of neon enriched to 9.8% in neon-21.

## THEORY OF THE EXPERIMENT

The $^3P_2$ metastable state of neon is the lowest member of the configuration $2p^53s$, which defines the first excited states of neon. The lifetime of the state has been estimated to be more than 1 second in a field-free region. No known electric or magnetic fields utilized in this experiment could result in an enhancement by more than a factor of ten of the decay rate. Detection of the state is accomplished by observation of the electrons that are ejected from a metal surface by impinging metastables. The probability of this process is approximately 1/2.

An interpretation-free determination of the spin of neon-21 may be made from a comparison of the Zeeman frequencies in neon-20 and neon-21 at a magnetic field which is sufficiently low so that the magnetic energy of the atom is negligible in comparison with hyperfine structure intervals in neon-21. The effective $g$-value ($g_F$) for the interacting system of nucleus and electrons is then the product of the Landé $g_J$ factor and the relative projection of the electronic angular momentum on the direction of total angular momentum, $F$. The ratio of Zeeman frequencies in neon-21 to that in neon-20, $g_F/g_J$, is then just the relative projection factor,

$$g_F/g_J=\frac{\langle\mathbf{J}\cdot\mathbf{F}\rangle}{\mathbf{F}^2}=\frac{F(F+1)+J(J+1)-I(I+1)}{2F(F+1)}.$$

An energy level diagram is shown in Fig. 1.

## APPARATUS

The apparatus, a modification of the system used by Hughes and Tucker,[3] is illustrated in Fig. 2. The gas system consists of several reservoirs for storing the 10-cc sample of enriched neon, a titanium metal cleaner operating at 750°–1000°C to remove hydrogen, oxygen, and nitrogen from the gas, the discharge tube,[4] and a

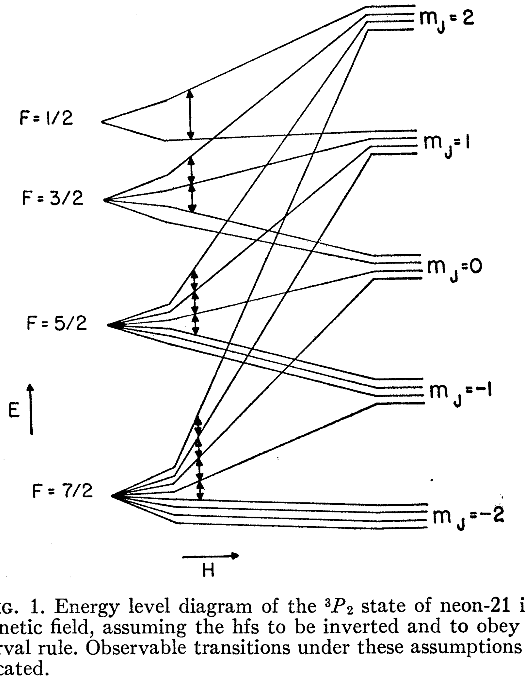

FIG. 1. Energy level diagram of the $^3P_2$ state of neon-21 in a magnetic field, assuming the hfs to be inverted and to obey the interval rule. Observable transitions under these assumptions are indicated.

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* Present address: University of California Radiation Laboratory, Berkeley, California.

[1] Perl, Rabi, and Senitzky, Phys. Rev. **98**, 611 (1955).

[2] P. L. Sagalyn, Phys. Rev. **94**, 885 (1954).

[3] V. W. Hughes and G. Weinreich, Phys. Rev. **95**, 1451 (1954).

[4] G. M. Grosof and J. C. Hubbs, Rev. Sci. Instr. (to be published).

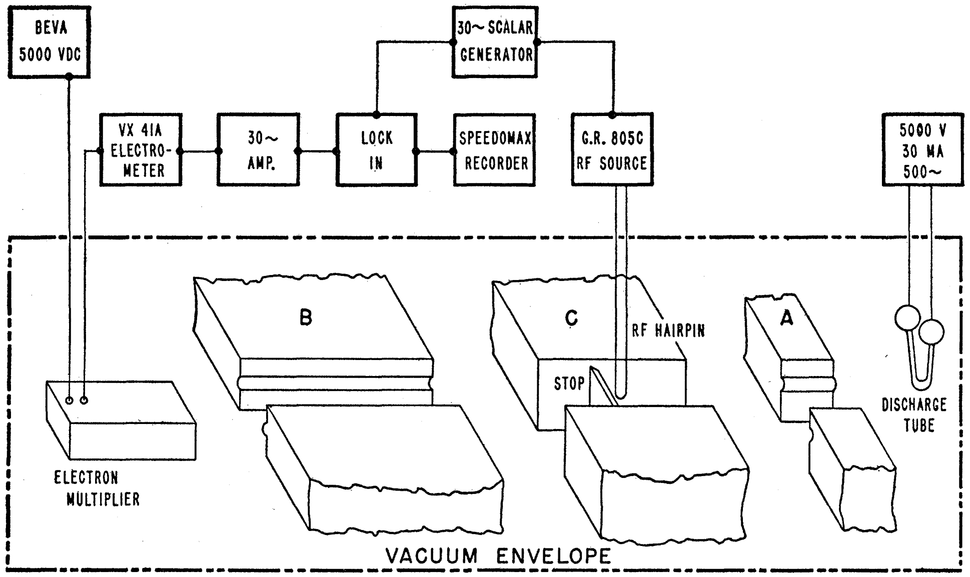


FIG. 2. The modified atomic beam apparatus.

mercury diffusion pump which backs the oil pumps on the can and returns the neon to the discharge tube at operating pressure. Approximately 1 cc of circulating gas is required to bring the discharge tube pressure to 0.3 mm Hg. A Toeppler pump is used to return the gas to the reservoirs after conclusion of a run.

Metastable atoms issue from a 0.003-by-0.7-cm slit in the wall of the discharge tube. The direct beam at the detector contains approximately $3\times10^7$ electrons per second liberated by high-energy photons issuing from the source and $2\times10^6$ electrons per second from metastable neon-20 atoms. Thus approximately $10^4$ electrons per second are to be expected from a transition between two magnetic substates in neon-21.

The principal modification to the apparatus was the introduction of an ac detection scheme using an electron multiplier, a tuned amplifier at 30 cps, and a lock-in detector having an output time constant from 10 seconds to 1 minute. The beam is chopped at a 30-cps rate by pulsing the radio-frequency magnetic field. All combined sources of noise in the electronic system are smaller than the signal obtained from a transition in neon-21 by a factor of 10 or more. The signal-to-noise ratio obtained for Zeeman transitions in neon-20 by use of the flop-out system, which permits the direct beam to hit the detector, proved to be 7/1 as compared to the expected 1000/1 for statistical processes.

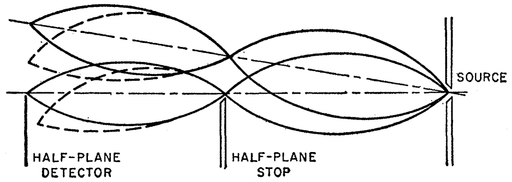


FIG. 3. Collimator and detector arrangement for the resonance system. Refocused trajectories and trajectories for the appropriate moment change are shown.

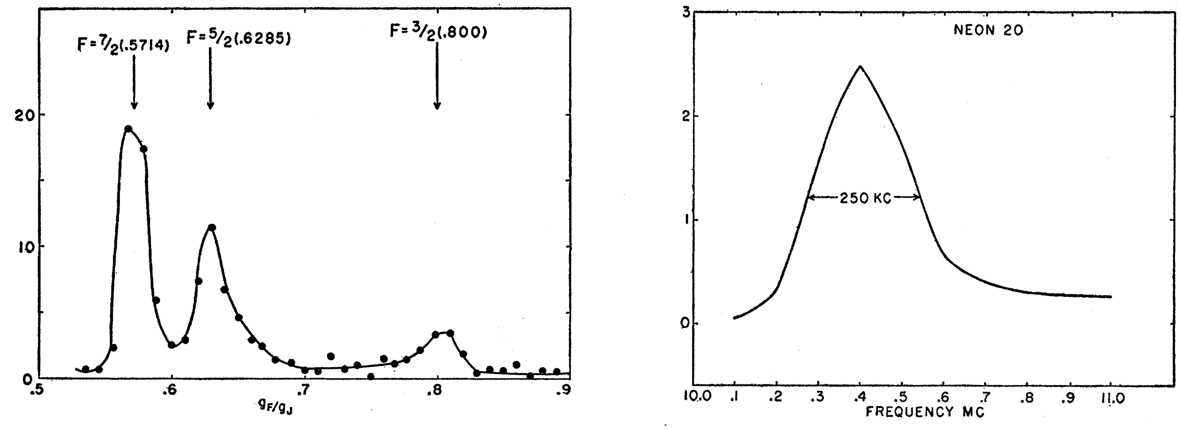
## THE RESONANCE METHOD

A resonance method was sought which would combine the discrimination of the flop-in method against components of the beam that do not experience a change of state with the spectroscopic advantages of the flop-out system, particularly the applicability of the latter system to atoms with integral electronic angular momentum. Several possibilities have been considered: one for which the standard flop-out system is used but the central (refocused) beam is simply blocked and everything that experiences a change of state is captured by a large detector to the rear of the stop, the other a scheme which was adopted, as follows (Fig. 3). The collimator is replaced by a half-plane stop, and an extended detector, also half-plane, is placed in the shadow of the collimator stop. For a refocused beam the points of intersection of any trajectory with the source, collimator, and detector plane define a straight line. Thus a transition which results in a change of the high-field magnetic moment in one direction produces deflections toward the detector. The deflection so experienced is given by $\Delta m_J S_\alpha E_0/E$, where $S_\alpha = g_J \mu_0 (dH/dz) L^2/4E_0$, so that the fraction of atoms that experience a deflection $x$ or greater is given by

$$\rho(x) = \int_{\Delta m_J S_\alpha E_0/x}^{\infty} E_0^{-2} E \exp(-E/E_0)\,dE = (1+\Delta m_J S_\alpha/x)\exp(-\Delta m_J S_\alpha/x).$$

The effective detector width is thus given by

$$\bar{x} = \int_0^\infty \rho(x)\,dx = S_\alpha \Delta m_J.$$



(a)

(b)

FIG. 4. (a) Zeeman transitions in neon-21 for a magnetic field of 6.6 gauss. (b) Typical Zeeman transition in neon-20.

Since the system throws away moment changes of one sign, a transition results in an intensity equivalent to the number of appropriate atoms in the direct beam $S_\alpha \Delta m_J/2$ wide.

Application of this scheme to the apparatus led to a reduction of the background from photons and neon-20 by a factor of 30 to 40, and an improvement in the signal-to-noise ratio to a consistent 1/1 for a single-line transition in neon-21.

## RESULTS

Zeeman resonances in neon-21 have been observed for magnetic fields between 1 and 10 gauss; a typical set of data is given in Fig. 4. The experimental data show values for the ratio of Zeeman frequencies in neon-21 to the resonance frequency of neon-20 of $0.57 \pm 0.005$, $0.63 \pm 0.01$, and $0.80 \pm 0.04$. Theoretical values of $g_F/g_J$ for $J=2, I=3/2$, are 0.5714, 0.6285, 0.800, and 2.00 for Zeeman transitions in the states $F=7/2$ through $F=1/2$ respectively. The Zeeman resonance in the state $F=1/2$ has not been observed.

In addition to these data a large number of transitions in the intermediate field region have been observed. Interpretation of the data is so equivocal, because of the very low signal-to-noise ratio and the presence of many multiple quantum transitions, that determination of the hyperfine structure intervals will have to await further improvements in the experimental technique.

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