

momentum matrix element. Similarly, the Burgess-Seaton approximation—which is a dipole length approximation—gives greater weight to the long-range parts of the wave function and is specifically a low-energy approximation.

Results such as those shown lead us to the expectation that a use of the dipole acceleration Born approximation with the Burgess-Seaton approximation results in a representation of the atomic photoionization cross section of accuracy suitable for most opacity calculations.

## Rotational Magnetic Moments\*

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The presence in molecular-beam magnetic resonance of transitions with  $\Delta m >> 1$  has made possible measurements of gyromagnetic ratios which are very much smaller than the nuclear magneton. Such low values are normally associated with the rotation of  $\Sigma$  molecules. The following values of  $g_J$  in nuclear magnetons per rotational quantum number have been determined in this way:  $\text{CO}_2$ ,  $(-0.05508 \pm 0.00005)$ ;  $\text{OCS}$ ,  $-0.02889 \pm 0.00002$ ;  $\text{CS}_2$ ,  $(-0.02274 \pm 0.00002)$ ;  $\text{C}_2\text{H}_2$ ,  $-0.04903 \pm 0.00004$ ;  $\text{Fe}(\text{CO})_5$ ,  $0.0210 \pm 0.0005$ ;  $\text{Ni}(\text{CO})_4$ ,  $0.0179 \pm 0.0005$ ;  $\text{CF}_4$ ,  $0.031 \pm 0.005$ . The sign of  $g_J$  in  $\text{C}_2\text{H}_2$  has been found to be the same as that in  $\text{OCS}$ , which was known to be negative. The signs in parentheses are assumed. The technique also gives the spin-rotational interaction constant in  $\text{C}_2\text{H}_2$  as  $3.58 \pm 0.01$  kc/sec.

### I. INTRODUCTION

IT has been shown previously<sup>1</sup> that transitions of  $\Delta m_J \gg 1$  in molecular beam magnetic resonance of rotational moments give rise to deflections which are much greater than would otherwise be possible for the very small gyromagnetic ratios. Because of this it has been possible to make direct measurements of several rotational moments. Certain gaseous molecules which have been studied using the apparatus with an electron bombardment detector are reported in this paper.

### II. OSCILLATING FIELD REQUIREMENTS

The main modification of the apparatus from the original nuclear moment design involved the transition-producing oscillating field. The optimal magnitude of the rotating component is given by<sup>1</sup>

$$H_1 = 1.2H_0\alpha/\omega_0l.$$

Using a flattened solenoid coaxial with the beam to produce the field, the current required becomes

$$I = (11.4/gN)(T/M)^{1/2},$$

where  $I$  is the current in amperes,  $g$  the gyromagnetic ratio in nuclear magnetons per rotational quantum number,  $N$  the total number of turns in the solenoid,  $T$  the source temperature in degrees Kelvin, and  $M$  the molecular weight. For the molecule  $\text{OCS}$  at room

temperature,  $NI \approx 900$  At is required. The frequency in a field of 5000 G (the maximum for our  $C$  magnet) would be about 110 kc/sec.

In order to obtain the maximum number of turns, coils were made to fill the entire 20-in.  $C$ -magnet length except for the space occupied by the collimator in the middle. These coils had 64 turns each, so that the optimal current for  $\text{OCS}$  was about 7 A. The source of power for the coils was a McIntosh 60-W hi-fi amplifier which would supply about 4 A at 60 kc/sec. Because of the drop in field near the ends of the magnet, however, it was not possible to use the full length at the full field. The best value of the  $\text{OCS}$  moment was obtained using only 22 turns on each side in a field of about 900 G. All of the results reported here were observed using less than the optimal current. The technique used the two separated coils in series with phase reversal modulation of the second. This gives an interference pattern like that shown for  $\text{OCS}$  in Fig. 1.

### III. EXPERIMENTAL RESULTS

All of the molecules studied, excepting  $\text{C}_2\text{H}_2$  and  $\text{CF}_4$ , contain only spinless nuclei, so the spectrum of each consisted of a single pure line at the Larmor frequency of the rotational moment. In  $\text{C}_2\text{H}_2$  there is a splitting into three lines caused by the spin-rotational interaction, as shown in the recorder trace of Fig. 1. The central line, with  $m_I = 0$ , has contributions from all the para- $\text{C}_2\text{H}_2$  molecules and from one third of the ortho- $\text{C}_2\text{H}_2$  molecules for a total of one half the total intensity. The side peaks, each of one quarter the total intensity, are separated from the central line by just the spin-rotational interaction constant  $c$ , which can

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<sup>1</sup>J. W. Cederberg and N. F. Ramsey, Phys. Rev. 135, A39 (1964).

therefore be easily measured. The value obtained,  $3.58 \pm 0.01$  kc/sec, is much more accurate than that obtained from the nuclear resonance data.<sup>2</sup> The spectrum obtained from  $\text{CF}_4$  was very noisy and difficult to observe. Only two of the expected three peaks could be seen. It was assumed, but without any certainty, that the larger of these corresponded to the rotational moment. The  $\text{Fe}(\text{CO})_5$  is a symmetric top with  $I_x = I_y = 7/6 I_z$ . Nevertheless, only a single line was observed.

The relative sign of  $g_J$  in OCS and  $\text{C}_2\text{H}_2$  was measured using the two coils with a  $90^\circ$  phase shift between, modulated between a lead and a lag. The resonance curve then passes through zero at resonance with a slope whose sign depends on the sign of  $g_J$ . The signs of  $g_J$  for OCS and  $\text{C}_2\text{H}_2$  were found in this way to be the same, and since the sign of the OCS moment was previously reported to be negative,<sup>3</sup> the  $\text{C}_2\text{H}_2$  moment is also negative.

The calibration of the OCS moment was made with the proton resonance in HD using each 22-turn section separately. The field at the two sides differed by about 0.2%, so the average was used to calculate the effective field for the OCS resonance. The error quoted in Table I of about 0.1% arises primarily from the error introduced by this difference, and could therefore not be reduced by using either a higher field or a longer magnet without also improving the homogeneity. The

TABLE I. Values of rotational gyromagnetic moments obtained by molecular beam magnetic resonance. The spin-rotational interaction constant of  $\text{C}_2\text{H}_2$  is also given.

Molecule	$g_J$	$ C $
$\text{CO}_2$	$(-)\ 0.05508 \pm 0.00005$	
OCS	$-0.02889 \pm 0.00002$	
$\text{CS}_2$	$(-)\ 0.02274 \pm 0.00002$	
$\text{C}_2\text{H}_2$	$-0.04903 \pm 0.00004$	$3.58 \pm 0.01$ kc/sec
$\text{Fe}(\text{CO})_5$	$0.0210 \pm 0.0005$	
$\text{Ni}(\text{CO})_4$	$0.0179 \pm 0.0005$	
$\text{CF}_4$	$0.031 \pm 0.005$	

<sup>2</sup> C. H. Anderson, Ph.D. thesis, Harvard University, 1961 (unpublished).

<sup>3</sup> C. H. Townes and A. L. Schawlow, *Microwave Spectroscopy* (McGraw-Hill Book Company, New York, 1955), p. 294.

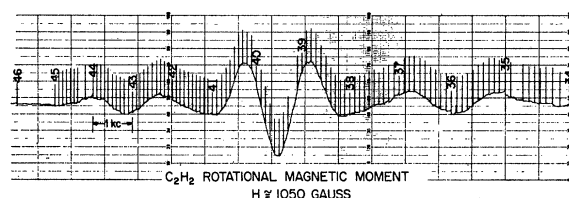
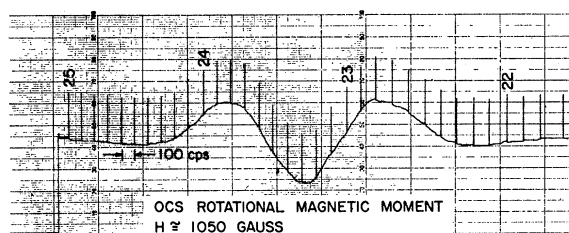


Fig. 1. Typical observed resonance curves. The structure of the OCS resonance is an interference pattern resulting from two separated coils. The  $\text{C}_2\text{H}_2$  resonance consists of three lines separated by the spin-rotational interaction.

moments of the other molecules were calibrated using OCS. The centers of the lines for  $\text{CO}_2$ ,  $\text{CS}_2$ , and  $\text{C}_2\text{H}_2$  could be located to greater accuracy than 0.1%, so the error in calibration of the OCS remained the determining error. For  $\text{Fe}(\text{CO})_5$ ,  $\text{Ni}(\text{CO})_4$ , and  $\text{CF}_4$  greater noise resulted in greater errors.

The values of  $g_J$  measured here are averages over all  $J$  states present in the source at room temperature. The width of the lines is at present limited by the inhomogeneity of the magnetic field, so that any broadening due to a dependence of  $g_J$  on  $J$  (centrifugal stretching) must be less than about 0.1%. It may be possible to measure the dependence by observing a shift with temperature, but this has not yet been attempted. It is conceivable, but does not seem likely, that such a shift could account for the discrepancy with the microwave Zeeman measurement<sup>3</sup> of  $g_J = 0.025 \pm 0.002$  for OCS, since the latter gives the value for  $J = 1$ .