VI. MOLECULAR BEAM RESEARCH

Prof. J. R. Zacharias
Prof. B. T. Feld
Dr. B. Bederson
Dr. V. Jaccarino
A. G. Bousquet
J. H. Holloway
J. G. King
H. H. Stroke

A. Cl^{36} EXPERIMENT

The apparatus to be used for the Cl^{36} experiments is being extensively modified so that better vacuums may be attained. At the same time, the necessary high resolution of the mass spectrometer is being sought. The failure to obtain the desired resolution is probably traceable to two effects: stray electrostatic fields, and defocusing of the beam by the numerous electrons that accompany the negative ions. Attempts are being made to eliminate both of these effects.

Tests show that the concentration of Cl^{36}, originally 1 in 5000 with respect to the stable isotopes, can be increased to 1 in 150 by a Szilard-Chalmers reaction. The amount of material available, as well as radioactive hazards, makes it necessary to recirculate the gas by successive trapping with liquid nitrogen.

Battery power supplies have been replaced by carefully regulated ac-operated supplies, wherever possible, to avoid failure in the middle of a run. The ac-operated supplies appear entirely satisfactory. Rotating coil magnetometers are to be installed in all transition fields to allow rapid adjustment, thus eliminating the loss of time (sometimes ruinous in experiments on radioactive materials) entailed in finding a transition and "chasing" it up or down with varying field. The apparatus program has been concluded with some electrometer developments that are described below.

The electrometer tube and galvanometer combination hitherto used to measure ion beam currents had an over-all sensitivity of approximately 10^{-16} amp/mm with a time constant of approximately 8 sec. By using cathode followers to remove the mismatch between the high resistance plate circuit of the electrometer (50K) and the galvanometer, an additional gain of 100 can be realized. Introducing a highpass filter with an insertion loss of 3 allows the time constant to be reduced to 4 sec, except on the most sensitive range when the Ayrton shunt allows the low impedance output of the cathode follower to shunt the galvanometer, thus increasing the time constant to 10 sec. The improvement in performance can be seen from the table below.

Shunt loss	Sensitivity (amp/mm)	Time constant (sec)	Approximate noise (mm)
1	4.9×10^{-18}	≈ 10	± 3
1/3	1.5×10^{-17}	3.7	± 2
1/10	4.8×10^{-17}	3.7	$\pm 1/2$

The noise figures agree with calculations based on the measured input resistance δ (8.5×10^{10} ohms), over-all frequency response, and over-all voltage sensitivity.

Drift has been minimized by charging all batteries continuously (including dry cells for cathode followers) at a carefully regulated rate just sufficient to compensate for all currents drawn, including leakage. By using liquid air-cooled dual electrometer tubes with feedback to reduce the effective input capacitance, and additional dc amplification to allow the use of faster, less sensitive galvanometers (or recorders), electrometers may easily be pushed to maximum theoretical performance; their sometimes crucial role in atomic beam experiments may make such extensive development desirable, particularly if multipliers cannot be used.

J. G. King, V. Jaccarino

B. THE HYPERFINE STRUCTURE OF Cs^{134}

An atomic beam hfs investigation of the 2.3 year half-life radioisotope Cs^{134} has been made, using a fraction of a 200-mc sample prepared in the Brookhaven pile by slow neutron capture in Cs^{133}. At the time when the experiment was started, the ratio of Cs^{133} to Cs^{134} in the sample was approximately 6000:1.

The following values have been obtained for the nuclear spin I, the nuclear hfs $\Delta\nu$, and the nuclear magnetic dipole moment μ:

$$I = 4$$
$$\Delta\nu = 10,460 \pm 20 \text{ Mc/sec}$$
$$\mu = +2.95 \text{ nuclear magnetons.}$$

1. Mass Spectrometer Problem

The low concentration of Cs^{134} necessitated an enrichment factor of better than 1000 at the mass 134 position of the mass spectrometer, i.e. the Cs^{133} counting rate at the Cs^{134} position had to be down by a factor of 1000 or more from its peak counting rate. Electrostatic defocusing of the ion beam by the charges induced by the ions on the dielectric surfaces near the path of the beam, however, yielded enrichment factors as low as 10 at the 134 mass position. By shielding the entire ion beam with an electrically grounded metallic surface, heated to a temperature of about 100° C to prevent the pump oil and water vapor in the system from depositing, it was found possible to maintain the required resolution indefinitely, regardless of the intensity of the ion beam.

2. Use of a Directional Oven

Some research has been done in this laboratory in the use of a directional oven as a source of beams of radioisotopes (1). A rather radical departure in the design of the oven has enabled us to produce directional beams required when working with low-abundancy radioisotope beams. The body of the oven is made of monel metal, with three hypodermic needles serving as exit channels. A load of approximately 3 mc,

instead of approximately 30 mc, needed with a nondirectional oven, was found sufficient for an average run of six hours.

3. Experimental Procedure

With the mass spectrometer set at the mass-134 position, the A and B fields were varied until an increase in beam, corresponding to a "zero moment," was noted at the detector. The nuclear spin was then obtained by finding the last two consecutive "zero moments" from which I may be determined from the relation that the ratio of the corresponding A and B fields is $(m_{F\ max\ -\ 2})/(m_{F\ max\ -\ 1})$ where m_F is half-integral for a nucleus with an even number of nucleons.

The spin was also determined by setting the A and B fields for a "zero moment" of Cs^{134} and observing the decrease in beam, at low values of the C field, at a frequency for which

$$\nu^{134} = \frac{I^{133} + \frac{1}{2}}{I^{134} + \frac{1}{2}}\ \nu^{133}$$

where ν is the Zeeman frequency of the hfs interaction. A spin $I^{134} = 4$ was found to satisfy this relationship.

$\Delta\nu$ was determined in three ways: (a) by noting the A and B fields for which the "zero moments" of Cs^{134} occur as compared with those of Cs^{133}, (b) by comparing the frequencies ν^{134} $(9/2, -7/2 \leftrightarrow 9/2, -9/2)$ with ν^{133} $(4, -3 \leftrightarrow 4, -4)$ and noting the quadratic departure from the linear Zeeman effect, (c) by measuring the splitting of the lines ν^{134} $(9/2, -7/2 \leftrightarrow 9/2, -9/2)$ and ν^{134} $(9/2, -5/2 \leftrightarrow 9/2, -7/2)$ which to terms in x^2 is given by $(2/81)\ x^2 \Delta\nu$ for I = 4, where

$$x = \frac{(g_J - g_I)\ \mu_o H}{h\Delta\nu}.$$

Consistent results were found only for the nuclear magnetic moment assumed positive.

Our results are in agreement with the as yet unpublished work of K. F. Smith and E. H. Bellamy of the Cavendish Laboratory in England (2).

V. Jaccarino, B. Bederson, H. H. Stroke

References

1. L. Davis: Hyperfine Structure of Na^{22}, Technical Report No. 88, Research Laboratory of Electronics, M.I.T. Dec. 1948
2. Private communication from B. T. Feld

C. A DETECTOR FOR RADIOACTIVE ATOMIC BEAMS

Up to the present time, most of the work done with atomic beams for determining hyperfine structure and nuclear moments has employed a hot wire detector. Thus, the studies have been confined to those elements which will ionize when they strike a hot wire. In order to expand the number of elements which may be studied, a detector which will detect radiation from unstable isotopes has been designed and constructed.

In this detector, a liquid air cooled tape is used where the hot wire is normally placed. The beam is allowed to deposit for a while on one spot of the tape, and the tape is then reeled along so that the deposition area is brought in front of a counter. The number of counts per second registered is proportional to the amount deposited. So far the study at M. I. T. has centered about the necessary conditions for a beam of P^{32} to adhere to a tape. P^{32} was chosen because it has a suitable half-life, and it is easily shielded since it is only a β^--emitter.

Work with radioactive atomic beams has already been begun in England by K. F. Smith, who has successfully determined the spin of Na^{24}, using radioactive measuring techniques.

J. H. Holloway

D. AN IONIC BEAM MAGNETIC RESONANCE METHOD

The atomic beam rf magnetic resonance technique (the Rabi method) can be applied to relatively few members of the periodic table for two reasons: (a) Considerable experimental difficulty is encountered in producing and detecting, with reasonable efficiency, atomic beams of any given element. (b) If the total electronic angular momentum of an atom is zero ($J\hbar = 0$), the Zeeman effect of hyperfine structure naturally cannot be observed; therefore, such elements as He, A, Kr, etc. and Mg, Ba, Sr, etc. (all of which have ground states with $J = 0$) cannot be investigated.

Although, for the first reason given above, the technical problems of producing and detecting beams of atoms which have not been investigated, are at present insoluble, there are no theoretical obstacles. The second reason, however, represents an inescapable theoretical barrier to the application of the Rabi method to atoms with $J = 0$. Consequently, atomic beam research has been largely restricted to the alkalis, alkaline earths, halogens and hydrogens.

By using beams of ions instead of neutral atoms in a method to be described, the severe limitations discussed above may be removed. In the Rabi method, neutral atoms are deflected in inhomogeneous magnetic fields normal to the beam by forces arising from the component of the atomic magnetic moment in the direction of the field, interacting with the gradient of the field. In one type of experiment two inhomogeneous fields

are so arranged that the atoms are deflected from the path to the detector, unless a transition which causes a reversal in the sign of the effective magnetic moment is induced by an oscillatory field in the intervening homogeneous field, whereupon the atoms are refocused and detected. Ions cannot be used in the conventional Rabi method, because the Lorentz force on the ion is so very much greater than the force on the atomic magnetic moment, due to the inhomogeneity of the deflecting fields, that the ion would spiral out of the beam into the magnet pole pieces.

Suppose, however, that the magnetic field and its gradient are principally in the direction of the beam. The Lorentz force will be minimized and the force $(\mu \cdot \nabla H)$ will either accelerate or decelerate the ion, depending on the sign of its effective magnetic moment. If the ion beam is pulsed, each single pulse going into the apparatus will be split into $2J + 1$ successive pulses at the detector; these pulses will be distributed symmetrically in time about a pulse travelling down the apparatus with the magnets off. Measuring the time separation (by using a suitable synchronized sweep CRO) corresponds to measuring the deflections in a Stern-Gerlach experiment. If two inhomogeneous fields and an intervening homogeneous field with superposed oscillatory field are used, a Rabi type of resonance experiment can be performed, with time instead of spatial separation.

To make the time separation easily observable, ion velocities less than approximately 5×10^6 cm/sec must be used, since the maximum acceleration obtainable is limited by the maximum gradient ($\nabla H \approx 100$ gauss/cm) and the magnetic moment ($\mu \approx 1$ B.M. $\approx 10^{-20}$ ergs/gauss). An approximate analysis shows that the total splitting in time, Δt in seconds, is

$$\Delta t \approx (0.4 \times 10^6)\, \mu \nabla H \ell L\, A^{1/2} E^{-3/2}$$

where ℓ is the total accelerating magnet length, L is the length of the apparatus, A is the mass number of the ion in question, E is its energy in electron volts, and μ and ∇H are the effective magnetic moment and gradient, respectively, all in cgs units. If one takes $\nabla H = 100$ gauss/cm, $\ell = 200$ cm, L = 1000 cm for the constants of the apparatus, and $\mu = 1$ B.M., A = 16 amu and E = 3 ev for the ions, Δt becomes approximately 6×10^{-8} sec. Evidently fairly elaborate pulse techniques must be applied, so that an unequivocal indication of the presence of a transition may be obtained, that is, when an unaccelerated pulse appears between the two split pulses.

The technical problems in producing focused low-energy ion beams are considerable, but not insurmountable. Detection can be accomplished with an electron multiplier.

A rather important feature of this method is that presumably all the ions that enter the apparatus reach the detector, whereas in the conventional atomic beam experiments the solid angle factor reduces the beam by a factor of 10^6 to 10^7. The applicability of

such techniques to short-lived radioactive isotopes, where hazardous amounts would be required in the conventional method, is evident.

V. Jaccarino, J. G. King