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ATOMIC-BEAM METHOD FOR THE STUDY OF ISOTOPE SHIFTS*

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In this Letter a new method is described for the study of isotope shifts. This method, based on the atomic-beam technique, has the considerable advantage over optical techniques that it can be applied to radioactive nuclei in the presence of large amounts of stable carrier. Therefore, it will make possible an extension of our knowledge of isotope shifts to the large class of radioactive nuclei which can not be practicably studied by any currently existing techniques. As a demonstration we report here the application of this method to a measurement of the ^{133}Cs-^{134m}Cs(2.9 h) isotope shift in the $6\,^2P_{1/2}$-$6\,^2S_{1/2}$ transition (D_1 line).

The basic apparatus employed is a conventional atomic-beam apparatus with flop-in magnet geometry.[1] However, the C region consists of a pair of electric field plates capable of sustaining very large electric fields. The region between the plates is illuminated with D_1 radiation from a filtered lamp of stable ^{133}Cs. The lamp employed is a Varian X49-609 spectral lamp. The output of this lamp is a resolved doublet separated by approximately the ground-state hyperfine structure (hfs). The excited-state hfs is about 10% of the ground-state hfs.[2] It makes no essential difference in the following discussion and is ignored. The energy levels giving rise to the doublet are shown schematically in Fig. 1.

Consider now the action of a cesium-133 atom in the atomic beam irradiated by the resonance radiation at zero electric field. Under this condition, the absorption lines of the beam atom coincide with the centers of the emission lines of the lamp. Consequently, resonance absorption of photons takes place. In the subsequent decay, the spin-flip of half the cesium atoms occurs and a large flop-in signal is observed at the detector. As the electric field is turned on, the Stark effect shifts the center of the absorption lines to lower frequencies until resonant absorption no longer occurs, and the flop-in signal goes to zero. However, when the shift is equal to the ground-state hyperfine structure, a new overlap of the absorption line with the emission line of the lamp occurs (see Fig. 1); and another flop-in signal is observed. In this way the Stark effect

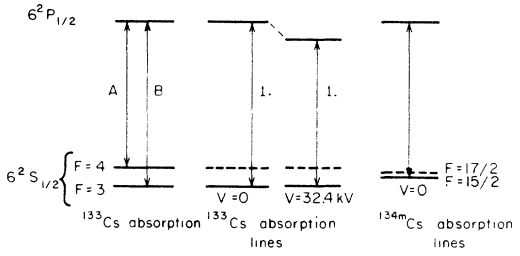

FIG. 1. Energy-level diagram. The lines labeled A and B are both present in the lamp. At zero applied voltage, the energy of the transition labeled 1 is in resonance with the emission line B and a flop-in signal is observed. At 32 kV, transition 1 now resonates with the emission line A. Our apparatus geometry precludes the observation of signals from the $F = 4$ state.

can be measured for the D_1 line; if the V^2 dependence characteristic of the Stark effect is assumed, a calibration of frequency shift versus applied voltage is obtained.

These same principles can be directly applied to the measurement of isotope shifts. Consider now a beam atom of some other cesium isotope. Because of the different ground-state hyperfine structure and the isotope shift, there is, in general, no signal at zero field. However, if the energy of the absorption lines is displaced to the high-energy side of either of the emission lines of the lamp, then the application of a suitable voltage brings the absorption lines into coincidence with the emission lines and a signal is observed at the detector. If the hyperfine splitting is large compared to the emission width of the lamp (≈1500 Mc/sec),[3] then the hyperfine stucture can be determined. The use of radioactive detection, which has been employed so successfully in the study of spins and moments, makes it possible to study rare radioactive isotopes.[4]

The spacing of the electric field plates used in our apparatus is sufficiently narrow (plate separation = 0.10 cm) that only the transition for which $m_J = -\frac{1}{2}$ in the A magnet and $m_J = +\frac{1}{2}$ in the B magnet is refocused. This precludes signals from the upper hyperfine level. Only signals resulting from atoms in the $F = 3$ state of ^{133}Cs and $F = 15/2$ state of ^{134m}Cs ($I = 8$) can be observed.

The flop-in signal for a ^{133}Cs beam as a function of applied voltage squared (V^2) is shown in Fig. 2. The signals at zero electric field and at 25 000 volts correspond to the absorption of the $F = 3$ and $F = 4$ hyperfine lines in the lamp by atoms in the $F = 3$ state in the beam. The separation between the peaks corresponds to the known hyperfine structure 9192 Mc/sec. The half-width of the peaks is about 1500 Mc/sec which agrees well with an independent measurement of the half-width of the lamp emission line.[3]

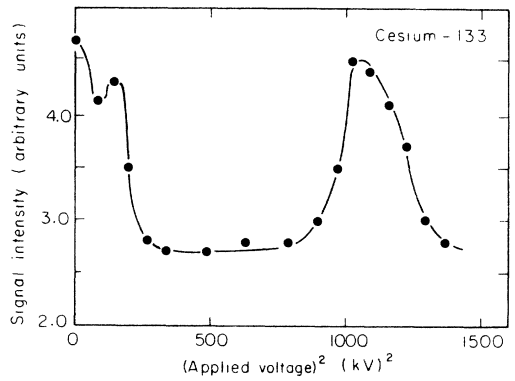

FIG. 2. Observed signal versus (applied voltage)^2 for a cesium-133 beam.

Figure 3 is a graph of signal versus V^2 for a beam of ^{134m}Cs atoms. The presence of a single peak at 24.1 kilovolts establishes the zero-field positions of the ^{134m}Cs hyperfine levels to be as shown in Fig. 1, relative to the ^{133}Cs hfs. The energy of the D_1 transition in ^{134m}Cs is smaller than that in ^{133}Cs by 900(350) Mc/sec or 0.030(0.012) cm^{-1}, where the difference is taken between the centers of gravity of the hyperfine levels.

In this experiment we have chosen to use an electric field to "tune" the absorption lines of beam atoms. Similar optical-resonance experiments have been performed which utilize magnetic fields for line tuning.[5] Electric fields have the advantage that to second order all the hyperfine components of a $J = \frac{1}{2}$ level are shifted together; i.e., there is a displacement of only the center of gravity. Relative shifts of the hyperfine levels[6] and of their Zeeman components[7] are much smaller, and for the purpose of this experiment are entirely negligible. This makes for easily interpretable signals which are much larger in intensity than those which would be obtained with magnetic tuning. However, the Stark effect shifts the energy in one direction only, whereas magnetic tuning increases the energy of some transitions and decreases the energy of others. For some isotopes, therefore, only magnetic tuning will make possible isotope-shift measurements.

An interesting way to regard this experiment is to think of the beam machine as a tunable spectrometer for studying the emission pro-

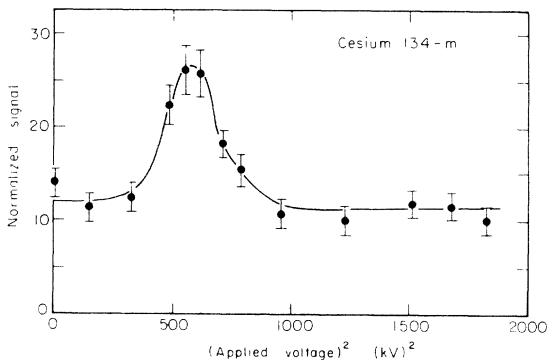

FIG. 3. Observed signal versus (applied voltage)^2 for a cesium-134m beam.

file of the lamp. Since the light is perpendicular to the beam direction, there is no Doppler effect and the resolution of the instrument is the natural linewidth of the transition – about Mc/sec for the cesium D_1 line,[8] but perhaps much less for other transitions. We are currently investigating the ultimate sensitivity and the useful frequency range for an atomic-beam apparatus used in this way.

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OPTICAL EXCITATION WITH VERY LOW ENERGY IONS*

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We have observed radiation due to the impact of very slow helium ions on the rare gases and on some molecular gases.[1] The dependence of the cross section for this process on the kinetic energy of the He^+ beam shows unexpected features down to the lowest energies studied (5 eV). For example, there is a sharp peak at 10 eV for the production of uv photons in Xe. The absolute cross sections are typically of the order of 10^{-16} cm^2 and in some cases are almost an order of magnitude larger. In at least one case the radiation has been shown to result from charge exchange with simultaneous excitation. Previous studies of optical excitation by ion impact have been performed at much higher energies and have not revealed the structure at the lower energies.[2] Energy balance considerations show that the reactions studied here involve the transfer of a large fraction of the kinetic energy into internal electronic energy. The excitation clearly involves nonadiabatic nonradiative transitions between the levels of the molecular-ion complex formed during the collision. The low-energy peaks in the cross section imply that the molecular energy levels are shifted in energy during the collision until they nearly cross.[3] Aside from their intrinsic interest, these results may have important bearing on plasma, laser, and atmospheric phenomena.

The apparatus consists of an electrostatically focused electron-bombardment ion source, a differential pumping chamber for pressure reduction, and a collision chamber. The photons produced in the collision region are detected with either a broad-band windowless EMI 9603 particle multiplier which responds from about 200 Å to about 1200 Å, a broad-band LiF-window EMR 541-*F* "solar-blind" photomultiplier which responds from 1050 to 3500 Å, or a 0.5-m Jarrell-Ash Ebert grating monochromator with quartz optics and a photodetector with an *S*-13 spectral response. The EMI and EMR tubes are mounted in the collision chamber with their photocathodes located about 5 cm from the ion beam. Counting techniques were used to record individual photon events with each of the detectors. The electron bombarding energy in the ion source is typically 350 eV. The ion beam passes through a microwave cavity which may be excited at 14 kMc/sec (the Lamb shift in He^+) to quench ions in the metastable $2\,^2S_{1/2}$ state. The ion current in the collision chamber varies from 5×10^{-9} A at a beam energy of 10 eV to 2×10^{-7} A at 500-eV beam energy. The energy spread in the ion beam is less than 0.5 eV at a beam energy of 10 eV.