Alignment of Atoms and Ions with the Beam-Foil Light Source

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We present conclusive evidence that the passage of fast Ne^+ ions through a thin foil results in a high degree of alignment of the transmitted excited atoms and ions. We use these observations to measure the mean lives and g values of electronic levels in atoms and ions. Our methods also lend themselves to the measurement of the speeds of fast atoms and ions.

One feature of the beam-foil light source is that the time (or place) of excitation is sharply defined. This permits the observation of quantum beats; such beats are a sensitive indicator of the presence of alignment of the excited electronic levels. We used the arrangement of Fig. 1 in order to look for quantum beats. If there is alignment, the detected intensity satisfies the relation[1]

$$I(t) \propto I_0[1 + A\cos(2\gamma H t)]\exp(-\Gamma t), \qquad (1)$$

where t is the time of observation after excitation, a is a constant, γ is the gyromagnetic ratio, H is the magnetic field, and Γ is the damping constant. Equation (1) holds for our geometry when the partial polarization of the light emitted from the beam of fast particles is parallel to the beam axis.

In our experiments, $^{20}Ne^+$ ions with a nominal energy of 425 keV were sent through a carbon foil $5\,\mu g/cm^2$ thick. We observed 6402-Å photons ($2p_9 \to 1s_5$) from Ne I, and 4220-Å ($4f\,^4D^\circ \to 3d\,^4D$) fron Ne II. Reasons for choosing neon are that it is a multielectron atom, there is no hyperfine effect, and the fine-structure levels are so widely separated that the interference frequency is too high to be seen.

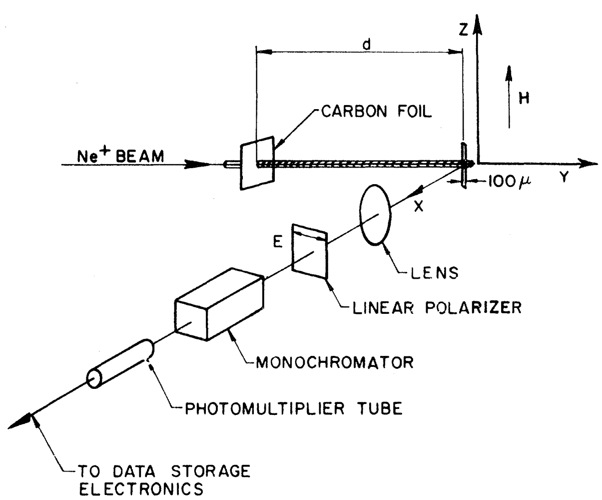

FIG. 1. Arrangement for observing quantum beats. The spectrometer viewed a 100-μm wide vertical slice of the beam (3 mm diam).

Equation (1) predicts that, for a fixed value of t, or, equivalently, for a fixed point of observation d downstream from the foil, $I(H)$ should vary sinusoidally with H. Using a linear ramp to vary H, we obtained the result shown in Figs. 2(a) and 2(b) for the Ne I transitions. In our similar work with the Ne II transition, the signal-to-noise ratio was less favorable than in the Ne I case, but the signals, which appear in Fig. 2(c), were still definite.

From Fig. 2 we deduce that the magnetic substates which are predominantly populated in the beam-foil interaction have $m_J = 0$, with the axis of quantization parallel to the beam axis. Such alignment has been discussed previously.[2] The effect of applying a magnetic field perpendicular to the beam axis is to create a coherent mixture of $+m_J$ and $-m_J$ states. This causes the oscillations displayed in Fig. 2.

From the period of oscillation we deduce that the particle speed v is given by

$$v = \gamma \overline{H} d/\pi, \qquad (2)$$

where $\overline{H}$ is the mean value of the change in the magnetic field from peak to adjacent peak. Thus, when g_J is known, the particle speed can be determined even when the particles are electrically neutral. In the present work, we use the known value[3] of $g_J = 1.329$ for the $2p_9$ level of Ne I and the mean of 24 periods to find $v = (2.02 \pm 0.06) \times 10^8$ cm/sec. This agrees with the speed of the accelerated Ne^+ ions as determined from the

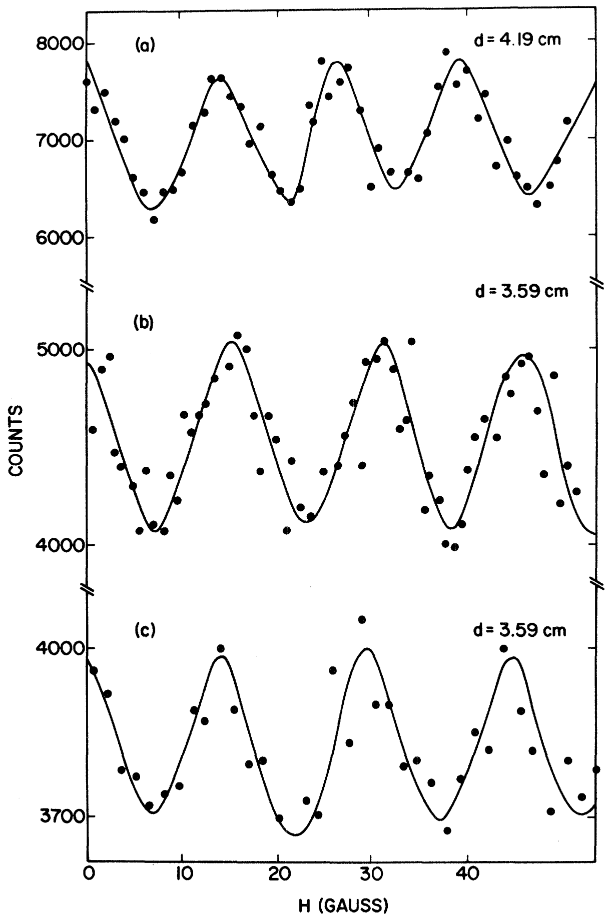

FIG. 2. (a), (b) Intensity of $\lambda = 6402$ Å as a function of magnetic field for two different values of d. (c) Intensity of $\lambda = 4220$ Å as a function of magnetic field.

calibrated generating voltmeter reading of the terminal voltage of the Van de Graaff accelerator we used; the method based on Eq. (2) is intrinsically suitable for a high-precision measurement of v. With the speed determined from Eq. (2), we find g_J for the $4f\,^4D°$ level of Ne II to be 1.25 ± 0.05; this has not been measured before.

The data of Fig. 2 permit us to determine the degree of polarization, defined as

$$P = (I_{\parallel} - I_{\perp})/(I_{\parallel} + I_{\perp}), \qquad (3)$$

where $I_{\parallel,\perp}$ are the line intensities when the polarizer is parallel, perpendicular to the beam axis at zero magnetic field. It can be shown that $I_{\parallel} - I_{\perp}$ is the peak-to-peak intensity difference, while $I_{\parallel} + I_{\perp}$ is twice the mean intensity. This gives $P = (12 \pm 2)\,\%$; the maximum theoretical polarization is 43.9 %.

By rotating the spectrometer by 90°, the spectrometer slit was illuminated by light from a beam segment 4 cm long with its upstream end located 2 mm from the foil. This resulted in an integration of Eq. (1), or a Hanle effect.[4] The Hanle-effect signal we obtained for the Ne I transition appears in Fig. 3(a). It is important to note that the resonance-type signal disappeared when the polarizer was rotated parallel to H. We extended our Hanle-effect measurement to the $4f\,^4D°$ level in Ne II with results as seen in Fig. 3(b).

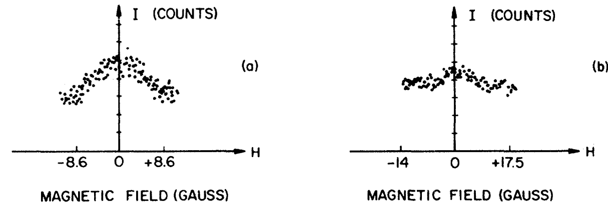

FIG. 3. Hanle effect from (a) Ne I ($2p_9$) observed with $\lambda = 6402$ Å, corresponding to the $2p_9 \rightarrow 1s_5$ transition, and (b) Ne II ($4f\,^4D°$) observed with $\lambda = 4220$ Å, corresponding to the $4f\,^4D° \rightarrow 3d\,^4D$ transition.

The widths of these curves are not so simply related to $g_J\tau$ as in the usual Hanle-effect experiments. In the usual experiments, the measurements of the radiated light are carried out for infinite time. In our case, the particles are observed only for a finite time. The equation appropriate to the present work cannot be easily reduced to a simple form, and we resort to numerical solutions. The result, based on $g_J = 1.329$, is $\tau = 23 \pm 1.5$ nsec, in good agreement with other values[5] (see below).

Finally, we constructed an oscillating rf magnetic field by sending dc through a series of slotted copper washers so arranged that the direction of the current reversed from washer to washer. The beam passed along the axis of the set of washers and the frequency of the field was determined by the spacing of the washers and the particle speed.[6] Our Hanle-effect work and other experiments[5] show that the $2p_9$ level of Ne I has a mean life of 23 nsec. This means that inducing transitions between the magnetic substates with a conventional rf generator would require the generator to supply considerable power in the awkward region of 150 MHz. Our technique avoids this difficulty. Moreover, there are no rf pickup effects. It is worth pointing out that the present magnetic resonance work is not restricted to levels which connect to the ground state.

For the magnetic-resonance situation, we have the approximate expression[1,7]

$$I \sim [\sin^2\theta + (\cos^2\theta - \tfrac{1}{2}\sin^2\theta)] \frac{(\gamma H_1)^2[4(\omega-\omega_0)^2 + (\gamma H_1)^2 + \Gamma^2]}{[(\gamma H_1)^2 + (\omega-\omega_0)^2 + \Gamma^2][4(\omega-\omega_0)^2 + 4(\gamma H_1)^2 + \Gamma^2]}, \tag{4}$$

where θ is the angle of the polarizer with respect to H; H_1, the amplitude of rf field; ω_0, the circular resonance frequency; and ω, the circular frequency.

In Fig. 4 we display our data for several values of the current through the washers, i.e., for several values of H_1. Power broadening is clearly present. In these measurements, H_1 is sufficiently strong to induce the transition between the Zeeman levels during the observation time; hence that time is effectively infinite.[7] Therefore we do not here have to make the finite-time correction that was required in our treatment of the Hanle effect. From these curves we determined $\tau = \Gamma^{-1} = 22.7 \pm 1.1$ nsec. We have also measured the mean lifetime by the beam-foil technique and obtained $\tau = 22.0 \pm 1.0$ nsec.

In our experiments, the moving particles see an electric field as well as a magnetic field. However, the maximum motional electric field in our work was <200 V/cm, at which value any Stark effects are too small to be noticeable.

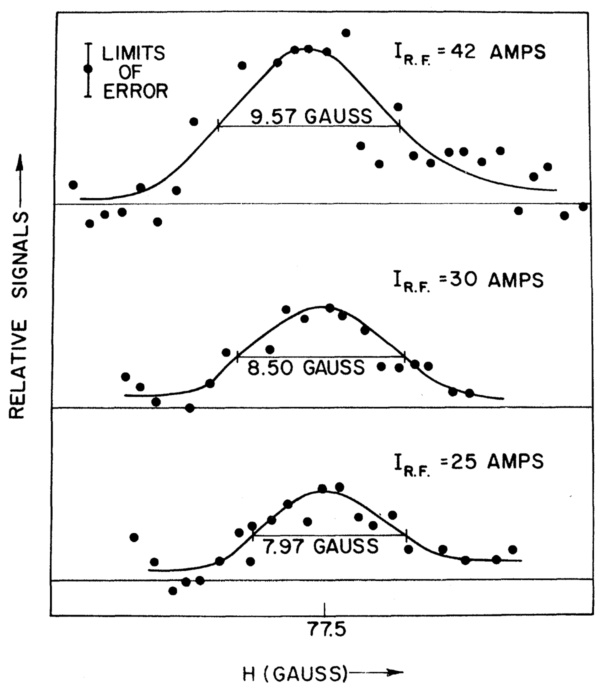

FIG. 4. Magnetic-resonance curves as a function of H_1 for the $2p_9$ level of Ne I.

One should note that the collisional excitation we have used may well populate levels which can cascade into the level of interest. Such cascades can affect the $g\tau$ value deduced from Hanle-effect measurements on the lower level. This matter is treated by Wangsness.[8] In the case of magnetic resonance, the cascade contributions are of no consequence.

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