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Atomic and nuclear polarization of ^{12}C, ^{13}C, and ^{15}N by beam-foil interaction at 300–400 keV

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Induced nuclear spin polarization P by hyperfine interaction following passage of 0.5 μA 300-keV beams of $^{12}C^+$, $^{13}C^+$, and $^{15}N^+$ through single tilted carbon foils yields $|P| = (0.4 \pm 0.8)\%$, $(3.2 \pm 0.6)\%$, and $(5.7 \pm 0.9)\%$, respectively. The nuclear polarizations were enhanced by passage through two tilted foils, and the sign of the polarization flipped by a simple flip of the foil direction with respect to the beam direction. From quantum-beat measurements with circularly polarized light, experimental quantum beat frequencies $\omega = 6790 \pm 570$ and 747 ± 62 MHz for the unresolved 6578-6583 Å doublet in CII, and $\omega(5667\ \text{Å}) = 2860 \pm 240$, $\omega(5680\ \text{Å}) = 4810 \pm 40$ MHz in NII are determined.

[NUCLEAR REACTIONS Beam-foil interaction C(^{12,13}C, ^{12,13}C), C(^{15}N, ^{15}N), $E = 0.3-0.4$ MeV; measured optical CP and quantum beats. Deduced nuclear P.]

I. INTRODUCTION

The nuclear-spin polarization[1] of heavy ion beams is a subject of current interest. In this paper, a simple method is presented to induce nuclear-spin polarization of a beam of carbon or nitrogen ions at 300 keV by just passing the beam through a tilted carbon foil (see Fig. 1).

Excitation of an atom by collision through a foil leaves it generally in an anisotropic state. Light emitted in the subsequent decay manifests this anisotropy through its angular distribution and polarization. (In the present investigation, polarization is detected by observation of emitted circular-polarized light perpendicular to the beam.) In general, if a beam passes normal through a foil, only alignment of the excited atoms of the beam is possible, but by tilting the foil, the broken axial symmetry results in strong angular-momentum orientation of the electrons. In this remarkable process, despite the rough final surface of the carbon foil, the atom senses an average tilt, and the electrons receive an asymmetric net impulse.

The transfer of the polarization or alignment from the atomic electrons to the nucleus takes place along the beam path from the internal magnetic hyperfine interaction of the atom itself. Recalling that the total spin $\vec{F} = \vec{I} + \vec{J}$ is a constant of motion ($\vec{J}$ is the electronic angular momentum, and $\vec{I}$ is the nuclear angular momentum), since $\langle J \rangle$ oscillates in time [see Ref. 5 and Eq. (2)], the oscillations of $\langle J \rangle$ must reappear as a nuclear polarization $\langle I \rangle$ (for $I \neq 0$), oscillating π out of phase with $\langle J \rangle$. Thus, the induction of nuclear-spin polarization by the hyperfine interaction follows a collision, which aligns or polarizes the electrons rather than the nucleus itself. The nuclear polarization (see Fig. 1) is

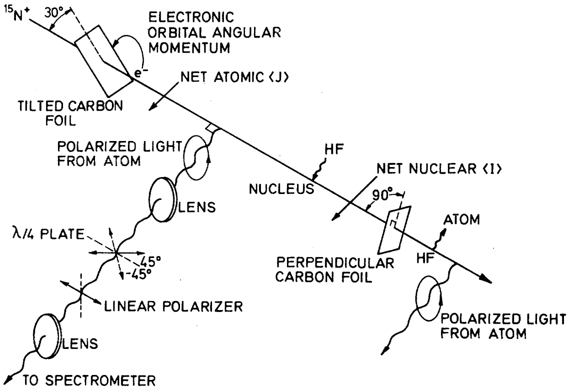

FIG. 1. Schematic experimental arrangement of production and detection of nuclear-spin polarization by beam-foil passage through a *tilted* foil: The atom is partially polarized after passage through the (first) tilted foil. The atomic polarization is detected by the emitted, circularly polarized light perpendicular to the beam direction. Along the beam path, the nucleus is spin-polarized through the magnetic hyperfine interaction of the atom itself. This nuclear polarization is detected after beam passage through a (second) *perpendicular* foil again from the emitted circularly polarized light.

determined by intercepting the beam with a second (perpendicular) foil, which realigns the atomic electrons so that the subsequent emission of circularly polarized light must come from the retransference of the nuclear-spin polarization back to the atom.

Polarization was described theoretically for nuclear orientation by Alder[4] and later for noncylindrically symmetric atomic-collision processes by Fano and Macek.[5] (Also, see authors in Refs. 6 and 7.) Atomic polarization by beam-foil interaction was first observed experimentally by Berry *et al.*[8] in 1974. The transfer of such polarization to the nucleus for a 300-keV beam of ^{13}C and ^{14}N via hyperfine interactions was demonstrated by Andrä *et al.*,[9] using grazing-incidence scattering of the beam. To achieve nuclear polarizations at higher energies, beam-foil techniques were introduced by a number of authors,[10] mainly to induce polarization of nuclear *excited* states at high recoil velocity ($\sim$50 keV/A). Enhancements of nuclear polarization induction have been reported by Winter and Andrä[2] with multigrazing surfaces and by Goldring[2] with multifoil arrays.

The present investigation[11] was made at energies between 300 and 400 keV, around the original beam energy used in the grazing-incidence experiment, to determine first and foremost whether indeed a nucleus in its ground state can be polarized to a sizable extent by a beam-foil interaction. The ^{13}C and ^{15}N were chosen for this work since both nuclei have nuclear spin $\frac{1}{2}$; this greatly simplifies determinations of the quantum-beat frequencies involved (thus determination of polarization-transfer distances) for cross terms from hyperfine interactions (quadrupole, etc.) are absent. The ^{12}C nucleus utilized has nuclear spin zero; it cannot be (nuclear) polarized and thus serves as a calibration probe of the method. This article shows that after enhancement through multiple (two) carbon tilted foils, up to 10% of the transmitted ^{13}C and ^{15}N beam have nuclei which are polarized, and the sign of this polarization can be reversed by a simple flip of the foils with respect to the beam direction.

II. MATERIALS AND METHOD

The carbon and nitrogen ions were produced in the Aarhus 600-keV accelerator and excited by passage through carbon foils. These foils were of 10-μg/cm^2 thickness, set at either a 30° or a $-30°$ angle to the beam direction (see Fig. 1) and mounted on a movable drive. (The direction of the tilt determines the sign of the atomic or nuclear polarization; the absolute magnitude of the atomic orientation monotonically increase with normal-to-the foil tilt angle. The 30° angle is usually referred to as a 60° normal-to-the-foil-surface angle.) The carbon foils were made by an ethylene/argon mixture, which was cracked in a glow discharge.[12] A "Kinderman" plate[13] was first coated with a 20—30 μg/cm^2 layer of sodium chloride and masked with space for several 12-cm diameter holes. At 10^{-5}-Torr chamber pressure, the 10% argon and 90% ethylene mixture (total pressure 7.5×10^{-2} Torr) was admitted and cracked at -2.5 to -3 kV cathode voltage and glow-discharge current density 1.6 mA/cm^2 for 3—4 min to give a layer of 10—15-μg/cm^2 carbon film. The carbon film was covered with collodium, floated off on water and mounted on frames having 8-mm diameter holes. When these foils were irradiated with 0.5-μA, 300-keV carbon or nitrogen beams, they often lasted for several hours compared with the $\sim$10-min lifetimes of commercial foils at this energy. Our foils are still nonuniform in quality and lifetime; their breakage remains somewhat of a nuisance at low energies. However, at higher beam energies (8 MeV), their durability improves; some of our foils have lasted for more than 48 h due to the lower atomic stopping in the carbon at these higher energies.

The polarization of the emitted optical radiation in a direction perpendicular to the beam and parallel to the foil tilt axis was determined with a rotating quarter-wave plate followed by a fixed linear polarizer (see Fig. 2). The phase plate was mounted coaxially between a lens system focused on the beam. The light was dispersed with a McPherson-218, 35-cm monochromator and detected with a cooled photomultiplier of type EMI 6256QS for nitrogen and EMI 9863QB for carbon. The entrance slit of the spectrometer was set parallel to the tilted foil for quantum-beat determinations to maximize coherence in the measured emitted atomic radiation and narrow enough to resolve the beat. Average polarizations were measured with the slit set either parallel or perpendicular to the beam. A light guide was mounted below and downstream from the target-foil assembly to provide count-rate normalization in order to offset any systematic errors due to the beam fluctuation or deterioration in the foil. The 300-keV beam of C$^+$ or N$^+$ was kept at currents below 0.5 μA during runs with single foils to avoid foil damage. In runs with multiple tilted foils, the beam energy was increased to 400 keV to

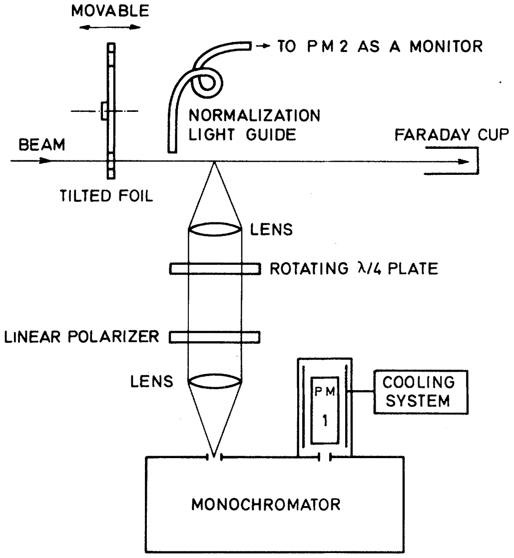

FIG. 2. Schematic experimental arrangement to measure the emission of circularly polarized light from an atomic beam passing through a tilted foil.

compensate for energy loss through the foils.

For the quantum-beat determinations of the 5667-Å and 5680-Å lines in N^+ (NII), the slits of the spectrometer were set at high resolution (~2 Å) (see spectra in Fig. 3). However, most determinations were made at lower resolution (above 20 Å) with the full lines for both the $2s^23s\,^2S$-$2s^23p\,^2P$ multiplet in CII and the $2s^22p3s\,^3P$-$2s^22p3p\,^2D$ multiplet in NII (see Table I, which lists the components of these multiplets).

The circular polarization of these lines was determined by rotation of the λ/4 plate through 360° at 18° intervals by a step-motor drive. Quantum-beat measurements were done with the phase plate set at an angle ±45° with respect to the axis of the linear polarizer and at equidistant points downstream from the foil (corresponding to a total distance of 2 cm) via a movable carriage governed by another step-motor drive. The spectra and background were stored automatically in a NORD computer, and the step-motor drives of the phase plate and movable carriage were electronically controlled.

The circular-polarization parameter S/I was measured; the relative Stokes parameter S/I is defined

$$S/I=\frac{I(\sigma^-)-I(\sigma^+)}{I(\sigma^-)+I(\sigma^+)}\,, \tag{1}$$

where $I(\sigma^-)$ and $I(\sigma^+)$ are the intensities of the right-handed and left-handed circular-polarized

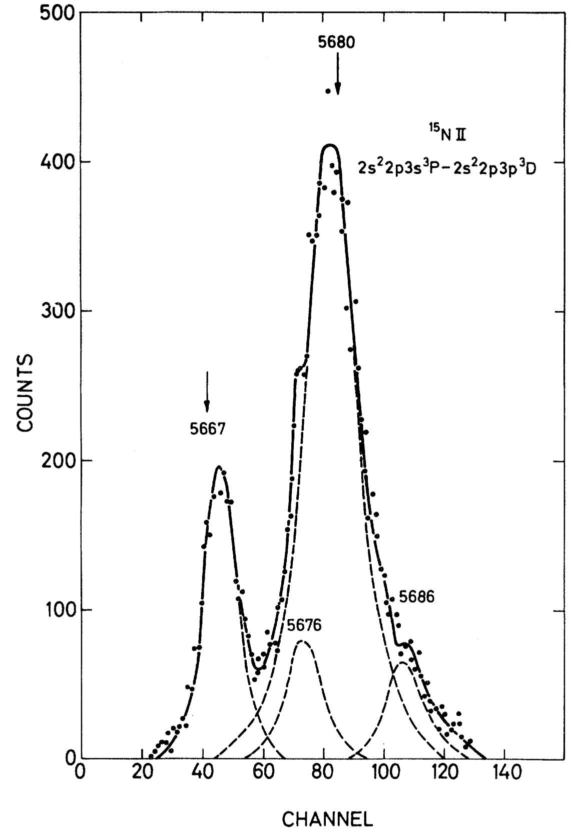

FIG. 3. The components of the $2s^22p3s\,^3P$-$2s^22p3p\,^3D$ multiplet in N^+ (NII). The arrow indicates the spectrometer settings at high-resolution observation of the components.

TABLE I. Multiplet components and their theoretical intensities I in LS coupling.

	λ (Å)	I
CII, $2s^23s\,^2S$-$2s^23p\,^2P$		
$J_0=\frac{1}{2}$ $J=\frac{3}{2}$	6578	100
$\frac{1}{2}$ $\frac{1}{2}$	6583	50
NII, $2s^22p3s\,^3P$-$2s^22p3p\,^3D$		
$J_0=1$ $J=2$	5667	54
0 1	5676	24
2 3	5680	100
1 1	5686	18

light in the optical convention, respectively. Atomic polarizations were least-squares-fitted as a function of the $\lambda/4$ phase-plate angular settings to a sinusoidal function[3] on a computer. The quantum beat(s) as a function of the relative distance from the foil was (were) calculated from the measured $I(\sigma^+)$, $I(\sigma^-)$ curves which were computer-fitted to a sinusoidal function times a decaying exponential, and the beat frequency was extracted after accounting for the beam velocity (energy).

III. THEORETICAL CONSIDERATIONS

Fano and Macek[5] give the time dependence of the polarization (or alignment) $S_{IJ}^{(k)}(t)$ of the radiating atoms after collision through a tilted foil, averaged over nuclear spin states, as

$$S_{IJ}^{(k)}(t)=S_J^{(k)}\Sigma_{F'F}\frac{(2F'+1)(2F+1)}{(2I+1)}\begin{Bmatrix}F' & F & k\\ J & J & I\end{Bmatrix}^2\cos\omega_{F'F}t\ , \tag{2}$$

where $S_J^{(k)}$ represents a reduced electron matrix element, whose value is determined by initial conditions such as the amount of orientation obtained at foil exit, and $k=0,1,2$ characterizes the population (monopole polarization), the orientation (dipole polarization), and the alignment (quadrupole polarization), respectively. The factor multiplying $S_J^{(k)}$ is unity at $t=0$ and represents a periodic loss of polarization for $k=1$ (and loss of alignment for $k=2$). Thus, atomic polarization can be observed by perpendicular emission of time-modulated, circularly polarized light of the excited atoms.

Since the electron angular-momentum polarization is partially transferred to the nucleus as a function of time after the collision process under the influence of the hyperfine interaction ($\vec{F}$ is a good quantum number), the nucleus is also polarized. This time dependence of the *nuclear* polarization (or alignment) $M_{IJ}^{(k)}(t)$ has also been calculated by Fano and Macek and is given by

$$M_{IJ}^{(k)}(t)=M_I^{(k)}\Sigma_{F'F}(-1)^{F'-F}\frac{(2F'+1)(2F+1)}{2I+1}\begin{Bmatrix}F' & F & k\\ I & I & J\end{Bmatrix}\begin{Bmatrix}F' & F & k\\ J & J & I\end{Bmatrix}\cos\omega_{F'F}t\ , \tag{3}$$

where the same modulation factor $\cos\omega_{F'F}t$ as in Eq. (2) appears, and $M_I^{(k)}$, a reduced nuclear matrix element, replaces the previous electronic matrix element.

The transfer of orientation (alignment) from the electrons to the nucleus (the relation between $S_J^{(k)}$ and $M_I^{(k)}$) is discussed by Fano and Macek [see Ref. 5, Eqs. (30)–(39)]. The nuclear polarization can be calculated from the measured atomic circularily polarized light via the transfer coefficients $B(k)$ given later in this paper [see Eqs. (6)–(8)]. The atom and nucleus beat with the *same* frequency $\omega_{F'F}$ but π out of phase with each other. In the transfer process to the *nucleus,* all oriented atomic states take part, including optically unobservable ground P states, which may have large polarizations. The amplitude of transferred polarization is also a complicated time-dependent function of the decaying excited atomic states.

The transfer of atomic polarization to the nucleus can be observed as quantum beats in the circularly polarized light emission as a function of distance along the beam path after the foil. The complete knowledge of quantum-beat frequencies, in principle, could determine the point of maximum polarization transfer to the nucleus. When the hyperfine interaction has the simple magnetic form of $AI\cdot J$, the quantum-beat frequency takes the form

$$\omega_{F'F}=(A/2\hbar)[F'(F'+1)-F(F+1)]\ , \tag{4}$$

where A is the magnetic hyperfine constant. For resolved (spectral or time) components in ^{13}C and ^{15}N, an experimental A can be defined, which also obeys Eq. (4) since these nuclei have nuclear spin $\frac{1}{2}$ and cross terms from hyperfine interactions are absent. For example, for the spectrally resolved 5667-Å component in ^{15}N, A has the value

$$A(5667)=\frac{2\hbar}{5}\omega(5667)\ , \tag{5}$$

and for this case and the 5680-Å component in ^{15}N, the quantum-beat pattern consists of a single frequency. Equivalent experimental magnetic hyperfine constants for each of the components of the doublet 6578-6583 Å line in ^{13}C can be defined similarly. In ^{13}C, resolution of the doublet could not be achieved with reasonable counting rates, and due to this lack of spectral resolution, the experimental quantum-beat pattern consists of two frequencies.

In principle, the average nuclear polarization can be determined from one of two different experimental approaches: either by measurements on nuclear properties (or radiations), or by measurements on atomic properties (or radiations). A direct measurement of nuclear polarization would require a suitable nuclear reaction from which, for example, the asymmetric β decay of the reaction product is determinable. The constraints are too severe with a beam of low-energy carbon and nitrogen 15 and direct nuclear measurements were ruled out. Instead, an indirect method, based on the effects from retransferring the nuclear polarization back to the atom, was utilized (see Ref. 9). However, due to the small (re)transfer coefficients involved, this indirect method has the drawback that the measurable effects from emitted circularly polarized light are small. Nevertheless, the effects are observable and require minimal simple equipment.

With the optical-(atomic) method, the average nuclear polarization was determined from the amount of circularly polarized light emitted from the beam after transmission through two foils, a tilted foil followed by a perpendicular foil. Recall that if the beam is sent through a foil at normal incidence, only the k = even terms occur in Eq. (2); no atomic polarization or circularly polarized light emission is possible. However, a nucleus, which has been polarized by a tilted foil, will transfer back this polarization to the atom even after disorientation of the electron shell in the perpendicular foil. (Nothing happens to the polarized nucleus during the 10^{-14} s transmission time through the foil.) Circularly polarized light emission after the perpendicular foil is a manifestation of retransferred polarization to the atom from the nucleus. The nuclear polarization can be calculated from (see Ref. 9)

$$S/I = -(3/2)^{1/2} \times I_{\rho_0}^{(1)} / I_{\rho_0}^{(0)} \times B(k=1) \times B^{-1}(k=0) \tag{6}$$

with

$$B(k) = \Sigma_F (2F+1)^2 \begin{Bmatrix} 1 & 1 & k \\ J & J & J_0 \end{Bmatrix} \begin{Bmatrix} F & F & k \\ I & I & J \end{Bmatrix} \begin{Bmatrix} F & F & k \\ J & J & I \end{Bmatrix} . \tag{7}$$

The S/I from the double-foil measurement is thus directly proportional to the nuclear fractional polarization $I\rho_0^{(1)}/I\rho_0^{(0)}$. From this, the degree of nuclear polarization

$$P_I = [(I+1)/3I]^{1/2} I_{\rho_0}^{(1)} / I_{\rho_0}^{(0)} \tag{8}$$

can be calculated. In principle, quantum beats after the *double* foil can also be determined, but for this measurement, the counting rates were too small.

A further idea may be used to enhance the polarization.[2] This is simply to pass the beam through a sequence of several tilted foils. If the tilted foils are placed at distances corresponding to the maximum polarization transfer to the nucleus, one can build up the effect. The problem of enhancement is experimental because the quantum-beat frequency corresponding to this maximum transfer point may arise from the hyperfine splitting of unknown states (for example, a nonradiative ground state or an unobserved excited state). Furthermore, at low beam energies (300 keV) due to beam-current attenuation and increased chance for foil fracture with the increased number of foils, the application of a tilted, multiple foil technique is limited. In this study, only a sequence of two tilted foils was utilized to enhance the effect.

IV. RESULTS AND DISCUSSION

A. Atomic polarization

Figure 4 displays atomic polarization of the 5667-Å line in N II after passage of a 300-keV ^{15}N beam through a single tilted carbon foil. Note that the initial foil polarization is slightly higher than the computer-fitted average, but that the equilibrium-polarization amplitude is stable. In fact, angular position 5π corresponds to a foil lifetime of 2 h. The sign of $|S/I|$ reverses (a π phase change in the display of the circular-polarization maximum with respect to the linear-polarization direction) with a flip of the foil from a positive to a negative tilt angle with respect to the beam direction. This is displayed in Fig. 5 with the similarly polarized 5680-Å line (see Ref. 8 for sign convention).

After passage of 300-keV beams of ^{15}N and ^{13}C

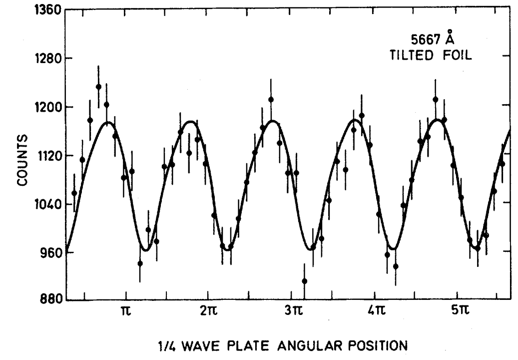

FIG. 4. Atomic polarization displayed as intensity of emitted, circularly polarized, 5667-Å light from NII as a function of the $\lambda/4$ wave-plate angular setting with respect to the linear-polarization axis. It corresponds to an $|\langle S/I\rangle|$ average of 12.6±0.7%.

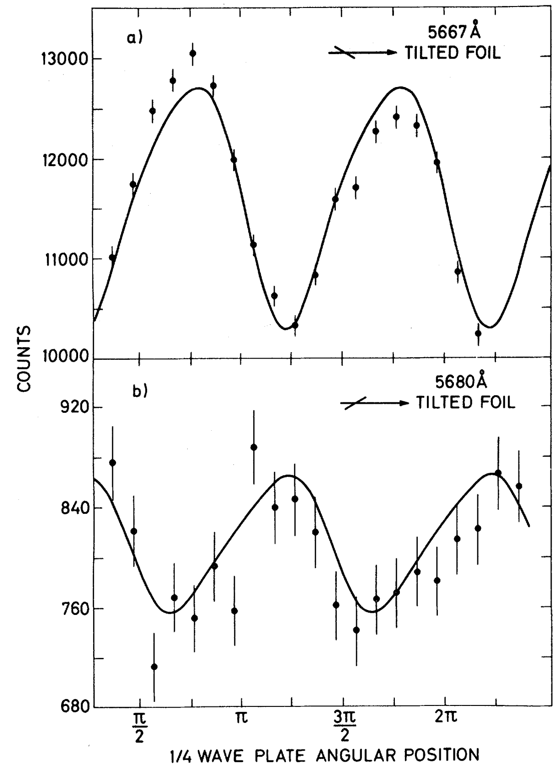

FIG. 5. (a) 5667-Å line. Atomic polarization displayed as intensity of emitted, circularly polarized 5680-Å light from NII as a function of the $\lambda/4$ wave-plate angular setting with respect to the linear-polarization axis. (b) 5680-Å line. Same as (a) except that the tilt of the foil is flipped to a negative tilt angle with respect to the beam direction, resulting in reversal of the sign of $|\langle S/I\rangle|$ in comparison with (a). The function used to computer fit the data, given in Ref. 3, is symmetric about the sinosoidal axis; the lack of symmetry in the fit indicates a poor quantitative fit. The curves are included mainly to illustrate the unambiguous π change of phase with foil flip.

through a single tilted foil, the average measured value of atomic polarization of the 5667-Å line in NII $|S/I|_N = 10.6 \pm 0.6\%$, while for the 6578-6583-Å doublet in CII, the average measured value of $|S/I|_C = 4.3 \pm 0.4\%$. With such large atomic polarizations, it was possible to measure the atomic beat pattern at positions downstream in order to have a rough idea of the transfer distances needed to polarize the respective nuclei.

As expected, the beat pattern from the 5667-Å line in ^{15}N consists of a single frequency (see Fig. 6), whereas the 6578-6583-Å doublet in ^{13}C has a pattern composed of two independent frequencies (see Fig. 7). The measured computer-fitted quantum-beat frequencies (calculated for beam energies 240 keV, after corrections for atomic stopping in the foil), and their corresponding magnetic hyperfine constants as defined by Eq. (4), are listed in Table II for the two possible frequency assignments of the lines in the unresolved 6578-6583-Å doublet in ^{13}C as well as for the resolved lines in ^{15}N. The experimental ratio of low frequency to high frequency quantum beat *amplitudes* from the unresolved 6578-6583-Å doublet in ^{13}C is 1.2±0.3.

In the carbon case since the 6578- and 6583-Å lines are components of a single state based on a one-electron configuration, the A factors cannot depend upon atomic spin-orbit mixing or departure from the LS limit. Furthermore, with nuclear spin $\frac{1}{2}$, the A factor will also not depend upon hyperfine interactions other than the magnetic dipole. For such a single-electron case, it can be shown[14] that the A factor for both $j = l + \frac{1}{2}$ and $j = l - \frac{1}{2}$ results in the simple expression

$$A_{nlj} = a_{nl} \frac{l(l+1)}{j(j+1)} , \tag{9}$$

where a_{nl} is a constant, n is the principle quantum number, l is the orbital quantum number, and j is the total electronic quantum number of the electron. Thus, from Eq. (9) one finds for the $2s^2 3p\,^2P$ configuration in CII the ratio of A factors of the 6583-Å to 6578-Å components of the measured multiplet

$$\frac{A(6583, j_2)}{A(6578, j_1)} = \frac{j_1(j_1+1)}{j_2(j_2+1)} , \tag{10}$$

which for values $j_1 = \frac{3}{2}$ and $j_2 = \frac{1}{2}$ yields a theoretical A factor ratio of 5. For the assignments $\omega(6578)=6790\pm570$ and $\omega(6583)=747\pm62$ or $\omega(6578)=747\pm62$ and $\omega(6583)=6790\pm570$ MHz, the experimental A factor ratio is 0.22 ± 0.04 or 18 ± 3, respectively. Neither possible quantum beat frequency assignment to the components of the doublet yields an experimental A factor ratio in good agreement with theory.

The amplitude E of each quantum-beat frequency is[15]

$$E=c[2j+1]^2[2F+1][2F'+1]\begin{Bmatrix} L & L & 1 \\ j & j & S \end{Bmatrix}^2 \begin{Bmatrix} j & j & 1 \\ F' & F & I \end{Bmatrix}^2 , \tag{11}$$

where the standard spectroscopic notation has been used and c is a proportionality constant. From Eq. (11), the ratio of the amplitudes of the quantum beats of the 6583-Å to 6578Å components in C II are

$$\frac{E(6583,j_2)}{E(6578,j_i)}=\frac{[2j_2+1]^2[2F_2+1][2F_2'+1]\begin{Bmatrix} L_2 & L_2 & 1 \\ j_2 & j_2 & S_2 \end{Bmatrix}^2 \begin{Bmatrix} j_2 & j_2 & 1 \\ F_2' & F_2 & I \end{Bmatrix}^2}{[2j_1+1]^2[2F_1+1][2F_1'+1]\begin{Bmatrix} L_1 & L_1 & 1 \\ j_1 & j_1 & S_1 \end{Bmatrix}^2 \begin{Bmatrix} j_1 & j_1 & 1 \\ F_1 & F_1 & I \end{Bmatrix}^2} . \tag{12}$$

Upon substituting the quantum numbers $F_2'=1$, $F_2=0$, $S_2=\frac{1}{2}$, $j_2=\frac{1}{2}$, $L_2=1$, $l_2=1$ for the 6583-Å component and $F_1'=2$, $F_1=1$, $S_1=\frac{1}{2}$, $j_1=\frac{3}{2}$, $L_1=1$, $l_1=1$ for the 6578-Å component with nuclear spin $I=\frac{1}{2}$, the ratio of the quantum-beat amplitudes yields a theoretical value of 1.6. The experimental value, 1.2 ± 0.3, is in rough agreement with theory, when the 6578 Å and the 6583 Å line are assigned the quantum beat frequency 6790 ± 570 and 747 ± 62 MHz, respectively. If the assignments are reversed, the experimental ratio $E(6583)/E(6578)=0.8\pm0.3$ and comparison with theory is poorer. In conclusion, both the experimental A factor ratio and amplitude ratio yielded from quantum

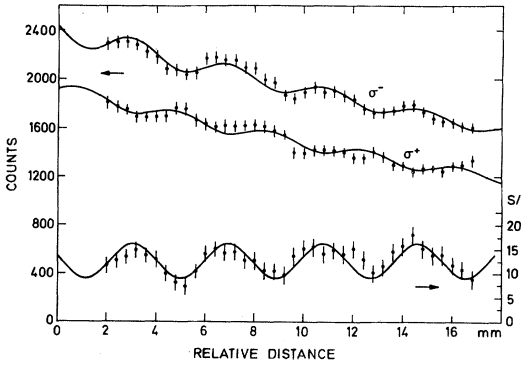

FIG. 6. Atomic quantum beats of the 5667-Å line in $^{15}N^+$ (at 300 keV) downstream after a single tilted foil. The circular-polarization parameter S/I is defined in the text.

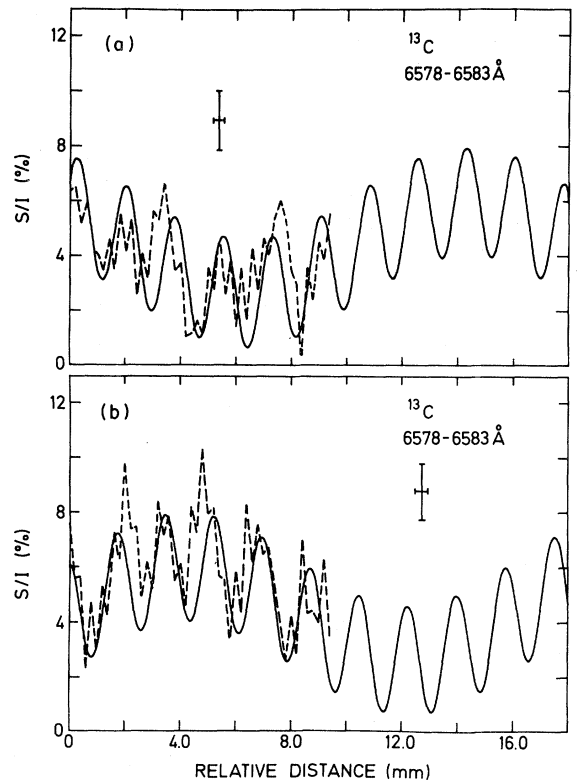

FIG. 7. (a) Atomic quantum beats of the 6578-6583-Å doublet in $^{13}C^+$ (at 300 keV) downstream after a single tilted foil. The circular-polarization parameter (S/I) is defined in the text. Dashed curve connects the experimental points. Solid curve is a computer fit composed of two frequencies. (b) Same as (a) but at a different arbitrary distance downstream from the foil. The same two frequencies fit both curves (a) and (b).

TABLE II. Measured quantum beat frequency ω. The experimental magnetic hyperfine constants A are calculated from Eq. (4) in the text for the two possible combinations of ω in ^{13}C and the determined values of ω in ^{15}N. The theoretical spectroscopic factor ratio $A(6583)/A(6578)$ has been calculated from Eqs. (9) and (10) of the text.

Nucleus	Line	ω	A_{exp}	$A(6583/A(6578)$	
	(Å)	(MHz)	10^{-6} eV)	Exp	Theor.
	6578	6790±570	2.22±0.19	0.22±0.04	
	6583	747±62	0.49±0.04		
^{13}C		or		or	5
	6578	747±62	0.25±0.02	18±3	
	6583	6790±570	4.45±0.36		
	5667	2860±240	7.49±0.62		
^{15}N	5680	4810±40	9.00±0.75		

beat measurements in ^{13}C are not well explained by theory.

It is not possible to extract the same information from determinations of the quantum-beat frequencies in ^{15}N because of the more complex $2s^22p3p\,^3D$ configuration of N II. The frequencies (A factor) would depend upon six parameters; our measurements for only two frequencies (with large experimental error) are not sufficient to constrain the problem.

B. Nuclear polarization

The average nuclear polarization in a given beam interval was determined from the amount of circularly polarized light emitted from the beam after transmission through two foils, a tilted foil followed by a perpendicular foil. Figure 6 illustrates some difficulties in determining *nuclear* polarization by a double beam-foil technique. The nuclear polarization is a function of the distance downstream of the beam and also may be a function of unobservable frequencies betweeen the two foils. On the other hand, in principle, a subsequent nuclear-polarization measurement could yield those optically unobservable states involved in the polarization process which do not have radiative transitions such as atomic ground states of large-orbital angular momentum, which may be highly polarized.

The average results of S/I from a number of such double-foil experiments with ^{12}C, ^{13}C, and ^{15}N at 300 keV are listed in Table III together with the values of P_I, the degree of nuclear polarization calculated by Eq. (8) (see Sec. III). As stated previously, the sign of both the atomic and nuclear polarization depends upon the direction of the foil tilt with respect to that of the beam. The sign changes were always consistent in all the independent runs, on which Table III is based. The large uncertainty in the yielded values of nuclear polarization stems from the lack of uniformity of the carbon foils utilized, which could attenuate the measured polarization and result in a variation of nuclear polarization from foil to foil. With respect to the latter, the measured atomic polarization for each foil was consistent, but it did vary from foil to foil. Also, the uncertainity reflects the fact that the data were taken at an arbitrary distance between the foils and at an arbitrary point downstream. At 300 keV, the average degree of polarization P_I from a 0.5 μA beam of ^{13}C and ^{15}N passing through a single tilted foil was, respectively, (3.2±0.6) % and (5.7±0.9) %. As expected that within statistics, the ^{12}C could not

TABLE III. Nuclear polarization at 300-keV beam energy after passage through single or multiple foils. The directions 0, −60, and 60 refer to the angle in degrees between the beam and the normal-to-the-foil-surface (the sign is relative). The sequence of angles refer to the sequence of foils through which the beam passes. (Note that angle 0 refers to a foil whose surface is perpendicular to the beam and is always the last foil through which the beam passes for any foil sequence.) The degree of nuclear polarization P_I is defined by Eq. (8) of the text; the sign is relative. The value of P_I of ^{12}C is based upon Eq. (8) with $I=\frac{1}{2}$, the ^{13}C or ^{15}N value, for comparison.

Ion	Foils sequence and direction	S/I (%)	P_I (%)
^{15}N$^+$	0	−0.04±0.30	−0.2±1.8
	60,0	+0.89±0.24	+5.7±1.5
^{15}N$^+$	−60,0	−0.90±0.17	−5.7±1.1
	Average $\lvert P_I \rvert$	0.90±0.14	5.7±0.9
	60,0	+0.80±0.21	+3.0±0.8
^{13}C$^+$	−60,0	−0.92±0.23	−3.5±0.8
	Average $\lvert P_I \rvert$	0.86±0.16	3.2±0.6
^{12}C$^+$	60,0	−0.12±0.23	(−0.4±0.8)
^{15}N$^+$	60,60,0	+1.50±0.22	+9.5±1.4
^{13}C$^+$	60,60,0	+1.10±0.20	+4.1±0.8

be polarized, and these data are a stringent check on the consistency of the experimental method.

In further experiments, two *tilted* foils were used to enhance the nuclear polarization. (These two tilted foils were also followed by a perpendicular foil.) The distance between the tilted foils was ~2 mm, the distance to the perpendicular foil was ~1 cm (both distances were arbitrary and did not reflect a particular beat frequency). The beam energy was increased to 400 keV to compensate for energy losses through the three foils, and the beam current was decreased to about 300 nA due to the greater probability of foil breakage when such large numbers of foils are used in a sequence. The results are also shown in Table III and indicate that the polarization was enhanced for ^{13}C and ^{15}N to $(4.1\pm0.8)\%$ and $(9.5\pm1.4)\%$, respectively. Although a higher percent of nuclei were polarized with the addition of the extra tilted foil, the lower beam current means that the actual current of polarized nuclei is lower.

V. CONCLUSION

In summary, this paper explores a simple method to induce nuclear-spin polarization,[2] which aligns or orients the electrons rather than the nucleus itself. It should be a general method to polarize nuclei. The atomic-polarization studies will be summarized first.

For ^{13}CII, the measured quantum beats of the 6578-6583-Å doublet component of the $2s^23s\,^2S$-$2s^23p\,^2P$ multiplet are either $\omega(6578)$-747 ± 62 and $\omega(6583)=6790\pm570$ or $\omega(6578)=6790\pm570)$ and $\omega(6583)=747\pm62$ MHz, yielding experimental magnetic hyperfine constants either 0.25 ± 0.02 and 4.45 ± 0.36 or 2.72 ± 0.19 and $0.49\pm0.04\times10^{-6}$ eV, respectively. The ratio of these experimental magnetic hyperfine constants $A(6583)/A(6578)$ is either 18 ± 3 or 0.22 ± 0.04 for the respective previous quantum beat frequency assignment in the doublet. Neither ratio is in good agreement with the theoretical value of 5 calculated on the basis of a one-electron configuration and simple magnetic-dipole interaction. The experimental quantum-beat amplitude ratio of either 1.2 ± 0.3 or $0.8\pm$ 0.2 (again the values depend upon component frequency assignment) are compared with the calculated value of 1.6. The lack of definitive agreement between theory and experiment prevents an assignment of the measured magnetic hyperfine constants to the components of the multiplet and points out the need for a future quantum beat study from spectroscopically resolved 6578 and 6583 Å components in ^{13}CII.

For ^{15}NII, the measured quantum beat of the 5667- and 5680-Å resolved components of the $2s^22p3s^2$-$2s^22p3p\,^3D$ multiplets are $\omega(5667)=2860\pm240$ and $\omega(5680)=4810\pm400$ MHz, yielding experimental magnetic hyperfine constants of 7.49 ± 0.62 and $9.00\pm0.75\times10^{-6}$ eV, respectively. For this more complicated configuration, which would be based on six theoretical constants, no calculations are presented. Only theoretical spectroscopic factors for lithiumlike states in C^{+3} and N^{+4} are reported in the literature.

With respect to the nuclear-polarization studies, induced nuclear-spin polarization by passage of 0.5 μA beams of ^{12}C$^+$, ^{13}C$^+$, and ^{15}N$^+$ at 300 keV through single tilted carbon foils yielded $|P_T|=(0.4\pm0.8)\%$, $(3.2\pm0.8)\%$, and $(5.7\pm1.4)\%$, respectively. The sign of the nuclear polarization flipped by a simple flip of the tilt of the foil to negative angles with respect to the beam direction. For ^{13}C and ^{15}N, the nuclear polarization was enhanced to $(4.1\pm0.8)\%$ and $(9.5\pm1.4)\%$, respectively, by passage through two tilted foils. The ratio of the measured, induced nuclear polarization in ^{13}C/^{15}N is not yet understood quantitatively.

Note that although neither the quantum-beat frequencies nor the nuclear polarization itself has been determined yet to precisions better than $\pm10\%$, one can still utilize the nuclear polarization as a signal for hyperfine techniques, which in themselves can yield precise information of many physical parameters. For example, recently the Osaka group used NMR techniques with asymmetric β-decay detection from polarized ^{12}N (at 700 keV, ~25% polarized) and polarized ^{28}Al to measure the internal magnetic field of nitrogen in nickel[16] to 0.1% precision, and the magnetic moment of the 3 + state in ^{28}Al (Ref. 17) to an accuracy of seven parts in 3000.

Unlike the comparable grazing-incidence technique[9] (scattering off a metallic plate), the present method utilizes the full strength of a transmitted beam (~0.5 μA), has improved timing (the foil thickness remains the same), and can flip the sign of the nuclear polarization with a simple flip of the foil direction. The latter will allow self-normalization and internal experimental check. Due to improved foil stability at higher energies, the enhancement displayed with multiple tilted foils should be more effective at higher beam energies, higher (≥1 MeV) than those used in the present investigation. The cost of these advantages at present is lower nuclear polarizability with respect to the grazing-incidence technique (about one third for carbon and nitrogen at equivalent energies). Both techniques can observe effects from nonradiative, highly oriented atomic ground states through polarization transfer from the atom to the nucleus and back again. However, the simplicity of producing nuclear-spin polarization by beam passage through tilted foils should be inspiring for the further study of the underlying physical processes involved in the polarization and via polarized particles.

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[1] We note our choice, following normal procedure in nuclear physics literature, of the term polarization when referring to a source atom or nucleus, the anisotropy of which can be described by a vector proportional to its average angular momentum. This is generally referred to as "orientation" in atomic physics literature and is distinct from the use of "polarization" when discussing emitted radiation. See Eq. (2) for a more quantitative characterization of polarization and alignment.

[2] The method of polarization enhancement off multigrazing surfaces was first utilized by H. Winter and H. J. Andrä, Z. Phys. A 291, 5 (1979). The multifoil array technique was reported by G. Goldring, invited paper, V, International Conference on Hyperfine Interactions Berlin, 1980, regarding even Nd and Sm isotopes recoiling out of a tilted target surface into vacuum following Coulomb excitation with 42 MeV ^{16}O beams.

[3] Specifically, the computer fitted Eq. (5) in H. G. Berry, G. Gabrielse, and A. E. Livingston, Appl. Optics 16, 3200 (1977). The Eq. (5) reads:

$$I(\alpha,\beta,\gamma)=\frac{1}{2}\left\{I+(M\cos 2\beta+C\sin 2\beta)\times\cos 2(\alpha-\beta)+[(C\cos 2\beta-M\sin 2\beta)\times\cos\delta+S\sin\delta]\times\sin 2(\alpha-\beta)\right\}.$$

The symbols are defined in the reference.

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[14] See, e.g., W. J. Childs, *Case Studies in Atomic Physics*, 3 (North-Holland, Amsterdam, 1973), p. 215.

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