Zeitschrift: Helvetica Physica Acta

Band: 34 (1961)

Heft: [6]: Supplementum 6. Proceedings of the International Symposium on polarization phenomena of nucleons

Artikel: Production and detection of a polarized deuteron beam using the atomic beam magnetic resonance method

Autor: Hughes, V.W. / Drake, C.W. / Bonar, D.C.

DOI: https://doi.org/10.5169/seals-513261

Production and Detection of a Polarized Deuteron Beam Using the Atomic Beam Magnetic Resonance Method[1])

By V. W. Hughes, C. W. Drake, Jr., D. C. Bonar, J. S. Greenberg, and G. F. Pieper, Gibbs Laboratory, Yale University

1. Introduction

The development of nuclear physics and particle physics has reached the stage where it is useful, possible, and perhaps necessary to consider the production of polarized accelerated beams of various kinds of particles. Use of such beams would allow the careful study of spin dependent interactions and tests of various symmetries and invariances in nuclear and particle physics.

Polarized particles can be produced by scattering unpolarized particles from nuclei, and a great deal of work has been done with polarized particles obtained in this way. However, the intensities of polarized particle beams so obtained are small, even when substantial energy and angular spreads are accepted. Furthermore, the energies at which polarized beams can be obtained and the magnitudes of the polarization depend on the particle-nucleus interaction and so are not readily controllable.

If a polarized ion source is produced and then the ions are accelerated, it is anticipated that a much higher intensity beam of polarized particles can be achieved than by the scattering method. The energy and the geometrical characteristics of the beam will be determined by the accelerator, and the magnitude of the polarization should be independent of energy. Hence much greater versatility should be available for experiments.

The present paper reports the progress of work at Yale on the production and detection of an accelerated beam of deuterons. This paper is the content of a report to the Basel International Symposium on Polarization Phenomena of Nucleons, 1960. Our approach has been to use the classic atomic beam magnetic resonance method to produce polarized atoms,

[1]) This research has been supported in part by the U. S. Atomic Energy Commission and the Office of Naval Research.

to ionize the atoms by electron bombardment, to accelerate the deuterons in an electrostatic accelerator, and finally to test for the deuteron polarization by use of the spin dependence of the nuclear reaction $T(d, n)\,He^4$.

The use of magnetic resonance to select polarized atoms, as opposed to the method using only deflection by inhomogeneous magnetic fields, has some advantages. Fast modulation techniques involving the alternate use of a polarized beam and an unpolarized beam are possible and should aid greatly in the subtraction of background counts. The use of magnetic resonance makes possible less critical requirements on the inhomogeneous magnetic fields and the use of larger fields and field gradients in the deflecting magnets. The resonance technique also allows different ions (for example, protons and deuterons) to be used with only a change in the frequency of the radiofrequency generator. The addition of a magnetic resonance transition is a negligible complication to the overall apparatus.

2. Theory of Experiment

2.1 *Production of Polarized Atoms Using the Atomic Beam Magnetic Resonance Method*

The production of polarized atoms by the use of inhomogeneous magnetic deflecting fields dates from the classic experiments of STERN and GERLACH [1][2]) in 1922 in which a beam of silver atoms was split into its two electronic magnetic substates $-{}^2S_{1/2}$, $m_J = +1/2$ and ${}^2S_{1/2}$, $m_J = -1/2$. The magnetic field they used was of the type shown in Figure 1.

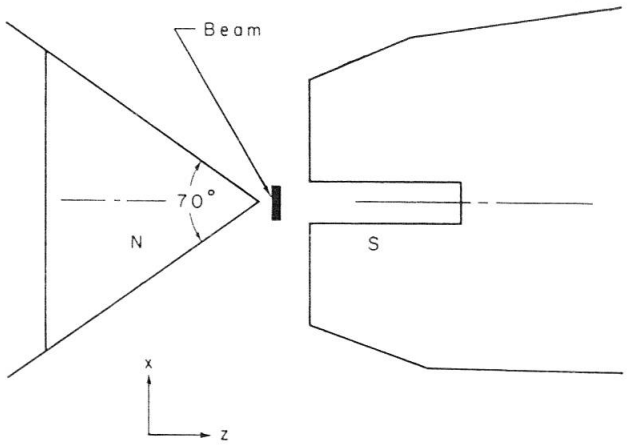

Figure 1

Magnet to produce inhomogeneous field of the type used in the Stern-Gerlach experiment. The force on an atom acts predominantly in the z direction

[2]) Numbers in brackets refer to References, page 106.

Several other types of inhomogeneous magnetic fields have been widely used to produce a spatial separation of the different polarization components of an atomic beam. The ideal geometry for the two wire deflecting field and its more practical realization with magnetic equipotentials are shown in figures 2 and 10, respectively [2]. This field is suitable for a beam of rectangular, ribbon-like cross section. Another type of field is a six-pole magnetic field [3] as shown in figure 3. This field is suitable for a beam having a circular or ring-shaped cross section.

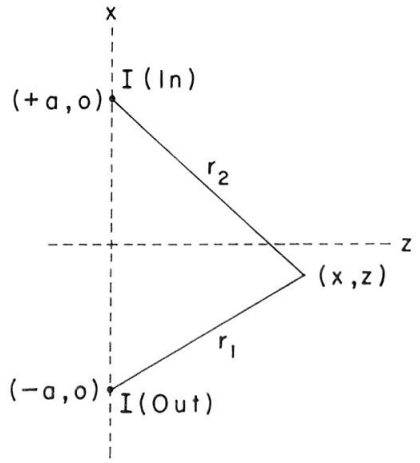

Figure 2

Geometry of two-wire deflecting field. The force on an atom acts predominantly in the z direction

For an atom with angular momentum quantum number J, which has only an electronic magnetic moment, there are $2J + 1$ polarization states – an example is ${}_2He^4$ in the ${}^3S_1$ electronic state with 3 different states of polarization. If the nucleus of the atom has a nuclear magnetic moment associated with the spin quantum number I, the total number of states of polarization is $(2I + 1)(2J + 1)$. Hence for hydrogen in the $1\,{}^2S_{1/2}$ ground electronic state with $I = 1/2$ there are 4 states of polarization and for deuterium in the $1^2S_{1/2}$ state with $I = 1$ there are 6 states of polarization.

The spatial separation of atoms in states of different nuclear polarization is more difficult than the separation of atoms in states of different electronic polarization, because a nuclear magnetic moment is much smaller than an electronic magnetic moment. Still the spatial separation of an atom in a particular state of nuclear polarization can be achieved in practice, particularly with the use of inhomogeneous magnetic fields having low average field values. This is possible in general because the effective magnetic moments of all the polarization states may differ by a significant fraction of a Bohr magneton at intermediate magnetic

field values where the hyperfine structure interaction is comparable in magnitude to the interaction of the atom with the external magnetic field.

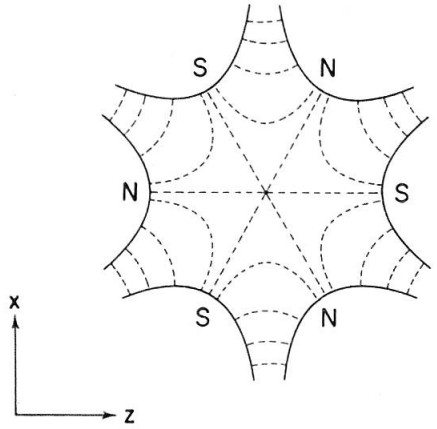

Figure 3a

Field and potential lines for a magnetic field which varies as the square of the distance from the axis. Field lines are dashed (– – – –); potential lines are solid (—); axis is through the geometrical center of diagram perpendicular to figure. The force on an atom acts in the radial direction

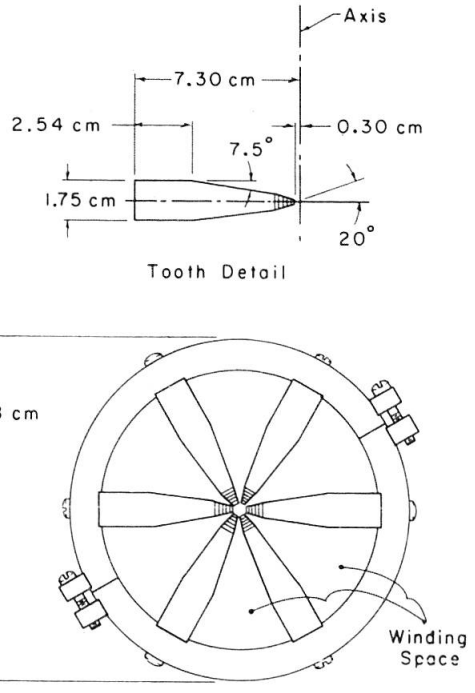

Figure 3b

Six-pole magnet to produce an inhomogeneous magnetic field of the type shown in figure 3a, view of the soft-iron structure. Magnet windings (not shown) fill space between teeth. Striations near tips of individual teeth correspond to the longitudinal shaping of the magnet

An alternative but related method of selecting an atom in a particular state of nuclear polarization involves the use of the well known atomic beam magnetic resonance method [4, 5]. The general scheme is indicated in figure 4. A discussion of the method can be given with reference to figures 5 and 6, which present the energy levels and magnetic moments of the hydrogen atom in an external magnetic field. The A- and B-regions have inhomogeneous magnetic fields and the C-region has a homogeneous magnetic field. The magnetic fields in the A- und B-regions are sufficiently high so that to an adequate approximation the hydrogen atom either has a magnetic moment of $+\mu_0$ or $-\mu_0$ (μ_0 = Bohr magneton). Hence in the A-region the hydrogen atoms are separated into two groups which follow different trajectories. Figure 4 indicates this situation and how it can be used to obtain polarized atoms. A wire stop is placed after the collimator between the B- and the C-regions so that only atoms with magnetic moment $-\mu_0$ in the A-region, i. e., atoms in the states with $m_J = +1/2$ (m_J = magnetic quantum number associated with the electronic angular momentum) pass by the wire; atoms with magnetic moment $+\mu_0$ in the A-region, i. e., atoms in the states with $m_J = -1/2$ will strike the wire. Hence with the inhomogeneous A-magnet and the wire stop atoms in two magnetic substates are selected.

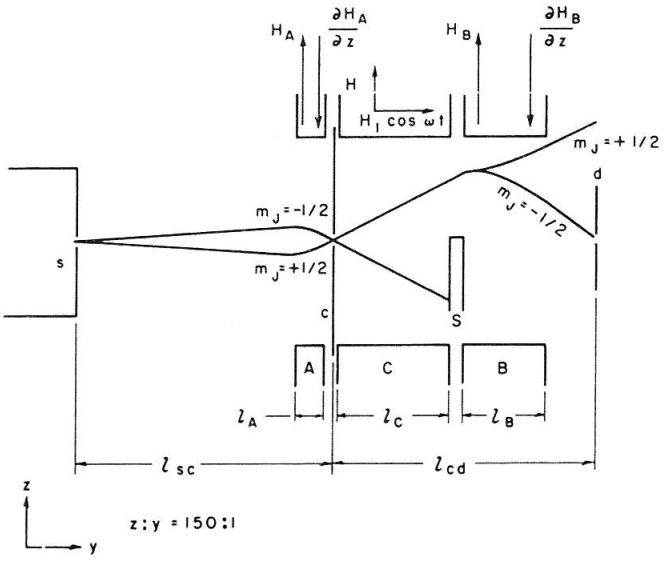

Figure 4

Schematic diagram of atomic beam magnetic resonance spectrometer. s is the source chamber with source slit. c is the collimator slit. The A- and B-regions are regions of inhomogeneous magnetic field. The C-region contains the oscillating electromagnetic field, and, in addition, a constant homogeneous field. d is the detector region. S is a wire stop. Trajectories of atoms in different m_J states are shown. $l_{sc} = 19.7$ cm, $l_{cd} = 16.3$ cm, $l_A = 2.0$ cm, $l_C = 8.0$ cm, and $l_B = 6.0$ cm.

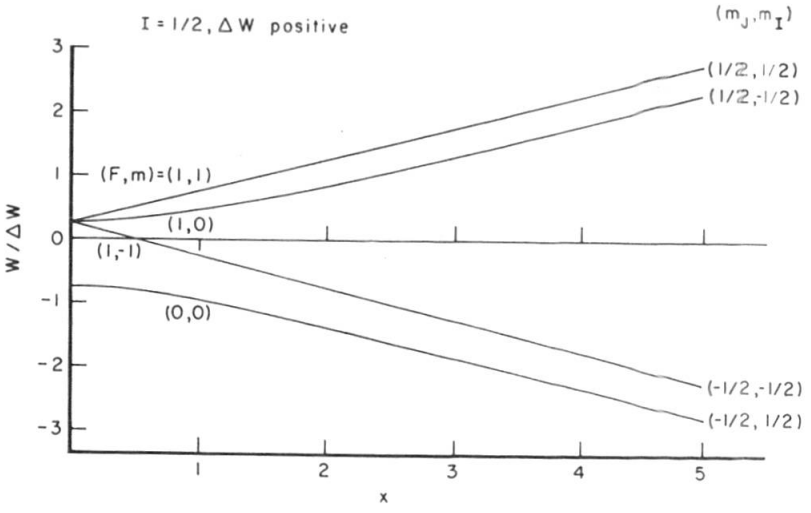

Figure 5

Energy level diagram for hydrogen in a magnetic field H, obtained from the Breit-Rabi equation:

$$W_{F=I\pm 1/2,\,m} = -\frac{\Delta W}{2\,(2\,I+1)} + \mu_0 g_I H m \pm \frac{\Delta W}{2}\left[1+\frac{4\,m\,x}{2\,I+1}+x^2\right]^{1/2}$$

ΔW is the zero field hfs separation between the states

$$F = I+1/2 \text{ and } F = I-1/2 \quad [\Delta W = W_{I+1/2}\,(H=0) - W_{I-1/2}\,(H=0)];$$

$x = (g_J - g_I)\,\mu_0\,H/\Delta W$; g_J and g_I are the electronic and nuclear g-values in units in which $g_J \simeq 2$; μ_0 = Bohr magneton. For hydrogen, $J = 1/2$, $I = 1/2$, $\Delta W/h = \Delta\nu = 1420.4$ Mc/s, $g_J = 2.002$, $g_I = -0.0030$. The levels are designated by both their weak field quantum numbers (F, m) and their strong field quantum numbers (m_J, m_I)

The remainder of the apparatus including the C- and B-regions is designed to select only one of these two magnetic substates. This can be done in one of two ways. The first involves selection of the substate $(F,m) = (1,1)$. In the C-region a constant, homogeneous magnetic field H is present. In addition, a radiofrequency field is applied of the proper frequency and amplitude so as to cause a transition of atoms in the magnetic substate $(F, m) = (1,0)$ to the magnetic substate $(1, -1)$. Atoms in the magnetic substate $(F, m) = (1,1)$ remain unaffected. If the B-field is high and if the direction of its field gradient is opposite to that of the A-field (this is not the condition shown in figure 4), then atoms in the state $(F, m) = (1,1)$ (high field quantum numbers are $m_J = +1/2$, $m_I = +1/2$.) can be refocussed onto a detector region, whereas atoms which are in the substate $(F, m) = (1, -1)$ (high field quantum numbers $m_J = -1/2$, $m_I = -1/2$.) will be deflected elsewhere. This scheme is often called the «flop-out» method because atoms which undergo the transition do not arrive at the detector. Because of the

velocity distribution in the atomic beam, the maximum fraction of the atoms which will theoretically undergo a transition is 0.77. Hence the atomic beam arriving at the detector region is composed of a mixture of the states $(F, m) = (1,1)$ and $(1,0)$. Since the relative numbers of the atoms in the states (1,1) and (1,0) are 1 and 0.23, respectively, the average nuclear polarization of the beam in the weak magnetic field region at the detector is[3]):

$$P_N = \frac{\bar{I}_z}{I} = 0.81$$

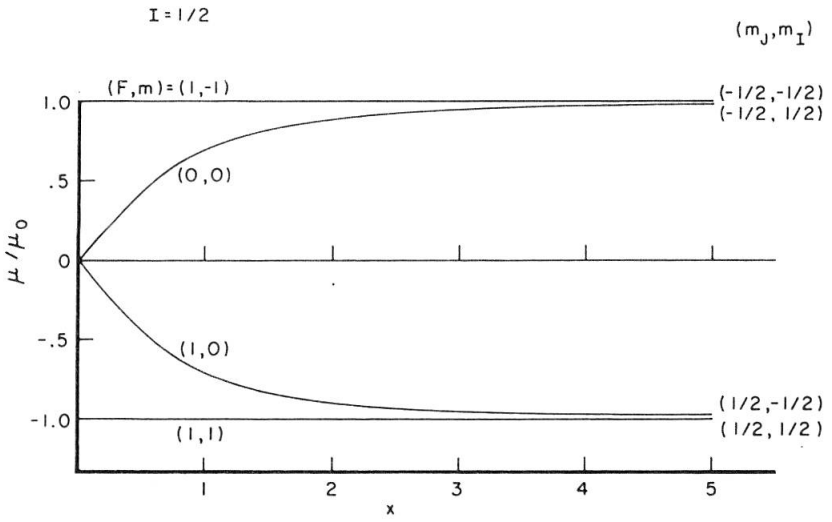

Figure 6

The magnetic moments of the magnetic sublevels of the hfs states of hydrogen with $J = 1/2$ and $I = 1/2$ as a function of magnetic field H, obtained from the equation:

$$\frac{\mu_{F=I\pm 1/2,\, m}}{\mu_0} = -\frac{1}{\mu_0}\frac{\partial W_{F,m}}{\partial H} = -g_I m \mp \frac{x/2 + m/(2I+1)}{[1 + 4mx/(2I+1) + x^2]^{1/2}}(g_J - g_I)$$

$$\text{for } m = I - 1/2,\ I - 3/2,\ \ldots,\ -(I-1/2),$$

$$\frac{\mu_{F=I+1/2,\, m=\pm(I+1/2)}}{\mu_0} = \mp(g_J/2 + g_I I)$$

The levels are designated by both their weak field quantum numbers (F, m) and their strong field quantum numbers (m_J, m_I)

A second method involves selection of the magnetic substate $(F, m) = (1, -1)$. As in the first method a transition is induced in the C-region from the state $(F, m) = (1, 0)$ to $(1, -1)$. Now, however, the direction

[3]) The discussion in this section is idealized in that slits of infinitesimal width or magnets with infinite deflecting power are assumed. The actual case is discussed in Section 3.1.

of the B-magnetic field gradient is the same as that of the A-field (this is the condition shown in figure 4), so that only the atoms which have undergone the transition $(F, m) = (1, 0) \rightarrow (1, -1)$ and hence have $m_J = -1/2$ in the B-region will be refocussed onto the detector region. This scheme is often called the «flop-in» method because atoms which undergo the transition do arrive at the detector. The entire beam at the detector will be in the magnetic substate $(F, m) = (1, -1)$ and the average nuclear polarization of the beam is $P_N = -1.0$. This second method is the one we are presently employing.

The «flop-out» scheme as discussed selects primarily the substate $(F, m) = (1, +1)$. Without change in the magnetic fields a «flop-out» scheme can also select primarily the substate $(F, m) = (1, -1)$. This can be accomplished by moving the wire stop so that only atoms with magnetic moment $+\mu_0$ in the A-region – i. e., atoms in the states with $m_J = -1/2$ – pass by the wire and by inducing the transition $(F, m) = (0, 0) \rightarrow (1, +1)$.

The «flop-in» scheme as discussed selects the magnetic substate $(F, m) = (1, -1)$. However, it can also select the magnetic substate $(F, m) = (1, +1)$ without changing the magnetic fields by moving the wire stop and by inducing the transition $(0, 0) \rightarrow (1, +1)$.

The above discussion has been illustrated by the case of hydrogen. The principles are the same for obtaining other polarized atoms. In particular, our work is being done with deuterium. The energy levels and magnetic moments of the deuterium atom in an external magnetic

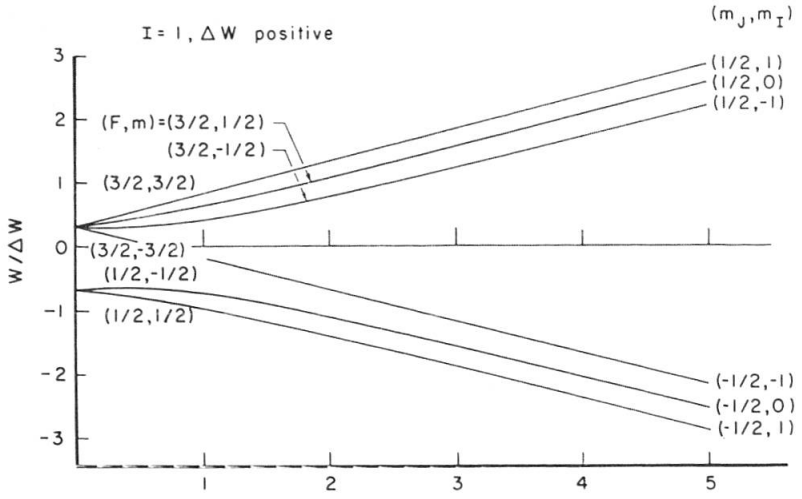

Figure 7

Energy level diagram for deuterium in a magnetic field H, obtained from the Breit-Rabi equation as given in caption to figure 5. For deuterium, $J = 1/2$, $I = 1$, $\Delta\nu = 327.38$ Mc/s, $g_J = 2.002$, and $g_I = -0.00047$. Further description is the same as for figure 5

field are shown in figures 7 and 8. We are using a «flop-in» scheme which selects the magnetic substate $(F, m) = (3/2, -3/2)$ and hence in principle produces an atomic beam with complete nuclear polarization, $P_N = -1$.

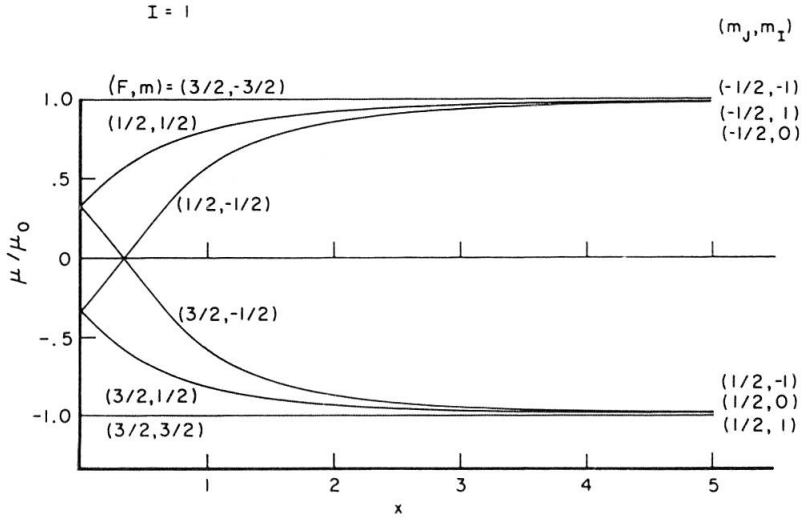

Figure 8

The magnetic moments of the magnetic sublevels of the hfs states of deuterium with $J = 1/2$ and $I = 1$ as a function of magnetic field H, obtained from the equations given in the caption to figure 6. Further description is the same as for figure 6

2.2 *Ionization of Polarized Atoms*

In order to be suitable for injection into an accelerator the polarized atoms must, of course, be ionized to produce polarized nuclei. The practical and obvious method is to ionize the polarized atoms by electron bombardment. Important questions in practice are the magnitude of the ionization cross sections both for the atom of interest and for other atoms or molecules which might constitute important ionic background and the realizable characteristics of an electron gun. The only question in principle is whether, or to what extent, the nuclei may lose their polarization in the process of ionization of the atom.

The ionization cross section of a hydrogen atom by an electron,

$$e^- + H \rightarrow H^+ + 2\,e^- \qquad (1)$$

has been measured recently [6] by an atomic beam method. The cross section as a function of energy is shown in figure 9a. The cross section for the ionization of deuterium will be the same as that of hydrogen.

Other processes which may contribute in an important way to the background are the following:

$$e^- + H_2 \rightarrow H_2^+ + 2\,e^- \tag{2}$$

$$e^- + H_2 \rightarrow H^+ + H + 2\,e^- \tag{3}$$

The cross section for process (2) is shown in figure 9a. The cross section for process (3) is shown [7, 8] in figure 9b. Processes (2) and (3) may constitute an important source of background because of the presence of molecular hydrogen or deuterium. Process (3) clearly produces an unpolarized proton as background. Process (2) may also be troublesome unless the scheme for detection of polarization clearly distinguishes between the atomic and molecular ions. Indeed, in our experiment with deuterium, in which the T(d, n) He^4 nuclear reaction is used, the principal background will be from D_2^+.

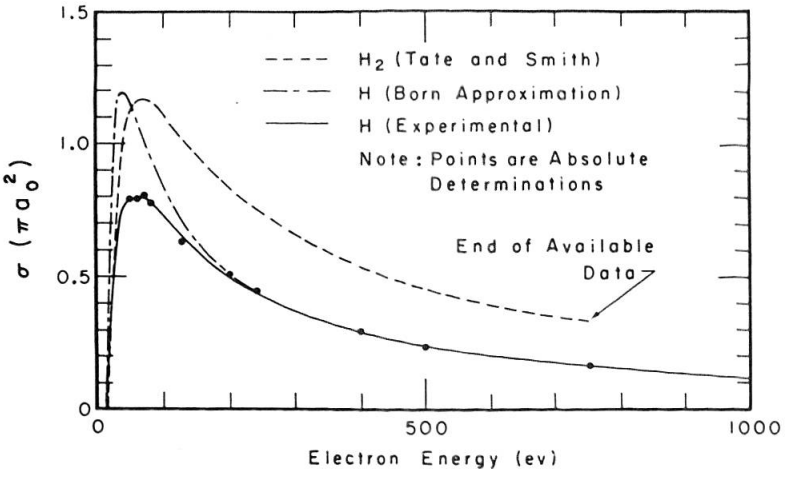

Figure 9a

Ionization cross sections for atomic and molecular hydrogen as a function of electron bombarding energy. The solid (——) and dot-dash (– · – · –) curves refer to the process: $e^- + H \rightarrow 2e^- + H^+$. The dashed (– – – –) curve refers to the process: $e^- + H_2 \rightarrow 2e^- + H_2^+$

The probability for the loss of nuclear polarization in the atomic ionization process is believed to be negligibly small. A qualitative argument is that the ionization occurs primarily through an electrostatic interaction; magnetic effects, which are required for reorientation of the nuclear spin, are expected to be relatively unimportant since the electrons have non-relativistic velocities. An alternative view is that the nucleus will experience a disorienting magnetic field due to the electrons during the collision. A characteristic value for this field is $\mu_0/a_0^3 \sim 10^5$ gauss (μ_0 = Bohr magneton; a_0 = Bohr radius for hydrogen) and a characteristic time for the collision is $2\,a_0/v \sim 5 \times 10^{-17}$ s (v = electron velocity $\simeq 2 \times 10^8$ cm/s). The angle of precession of a proton magnetic

moment in a 10^5 gauss field in a time of 5×10^{-17} s is only 10^{-7} radian and hence the change in the direction of the proton magnetic moment is negligible. Since the ionization process produces two free electrons and a free proton, electron exchange effects will not contribute to a change in proton polarization.

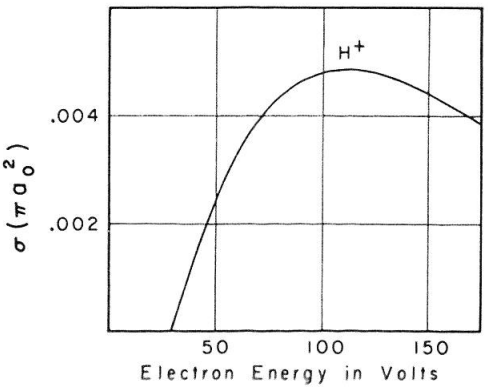

Figure 9b

Ionization cross section for molecular hydrogen as a function of electron bombarding energy. The curve refers to observed cross sections for the process:

$$e^- + H_2 \rightarrow 2e^- + H + H^+$$

Although the nuclear moment will not change its orientation during the ionization process, once it is free of the hydrogen electron and the associated large magnetic field, its orientation will be determined by the relatively small magnetic field in which it may find itself. If the nucleus moves slowly enough through a region where the magnetic field is not zero so that it does not experience a substantial frequency component at the frequency characteristic of the Larmor precession of the nucleus in the field, then the nuclear spin direction will follow adiabatically the external field direction [9].

Design and Operation of Apparatus

3.1 *Atomic Beam Magnetic Resonance Apparatus*

For our initial experiments a relatively standard atomic beam magnetic resonance apparatus for hydrogen work has been constructed. Because of the scheme we plan to use for the detection of polarized nuclei, the work is actually being done now with deuterium rather than with hydrogen. Figures 4 and 13 show the essential features of the apparatus including pertinent dimensions.

The source of deuterium atoms is a water-cooled Wood's discharge tube, operated at 10 000 volts ac with a current of 240 ma. The pressure

in the discharge tube as estimated from the flow rate and slit area is 0.35 mm of Hg. The slit in the discharge tube is 1 cm high by 0.013 cm wide. (The collimator slit is the same as the source slit.) Hence for the source temperature of 300° K, the particle flux from the source is 7×10^{18}/s. In the absence of the static and radiofrequency fields, the fraction of these particles which enter through the opening of 1 cm by 0.015 cm to the detector region is 3.5×10^{-6} [Detector area/π (source to detector distance)^2].

The positions and lengths of the magnets are indicated in figure 4. A detailed drawing of the A-magnet is shown in figure 10. It is a permanent magnet (Alnico) with high permeability (Permendur) pole tips and soft iron (Armco) return path as indicated. A magnetic field of 7.5 kilogauss and a field gradient of 11 kilogauss/cm is achieved at the position of the atomic beam. The B-magnet is identical in structure except that its length is 6.0 cm. A detailed drawing of the C-magnet is shown in figure 11. It is designed to produce a homogeneous magnetic field of about 100 gauss.

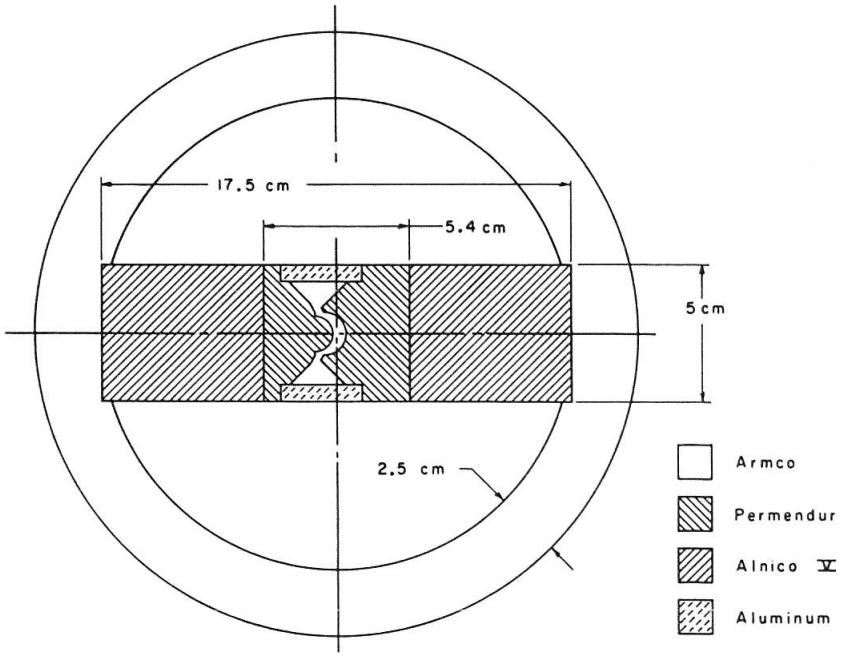

Figure 10a
Cross section of iron deflecting magnet, complete view.
Length of A-magnet is 2.0 cm

A radiofrequency field with a component of magnetic field perpendicular to the static C-field is introduced through a loop in the C-region extending for a length of 0.3 cm along the direction of beam propagation. In order to obtain resonance for the transition in deuterium from

$(F, m) = (3/2, -1/2)$ to $(3/2, -3/2)$ in a field $H = 101$ gauss, a frequency of 155 Mc/s is chosen. The radiofrequency is generated by a Hewlett-Packard 608D oscillator, amplified, and fed through a double stub tuner to the rf loop. The observed width of the resonance line is 700 kc/s whereas the natural width associated with the transit time of the atoms through the rf region is 560 kc/s; the excess width over the natural width is due to magnetic field inhomogeneity.

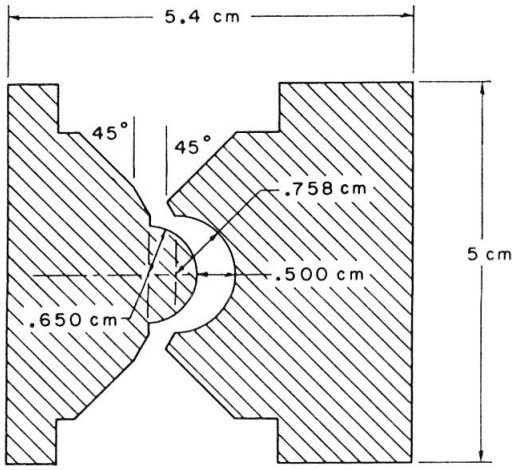

Figure 10b
Cross section of iron deflecting magnet, details of pole faces

The operation of the atomic beam magnetic resonance apparatus has been studied with the use of a Pirani gauge of a usual modern design as a detector [10]. The dimensions of the entrance slit to the Pirani gauge are 0.32 cm by 0.0025 cm. The absolute sensitivity of the Pirani gauge for D atoms was obtained by observing the Pirani signal when a beam of D_2 molecules is allowed to effuse from the slit of the discharge tube. (No voltage is applied to the discharge tube so only deuterium molecules are present.) From a knowledge of the rate of the total flow of D_2 gas from the reservoir feeding the discharge tube and of the dimensions of the system the number of D_2 molecules entering the Pirani detector per unit time can be calculated by use of the kinetic theory of gases, and hence the Pirani gauge sensitivity can be determined for D_2 molecules. To obtain the sensitivity for D atoms the assumption is made that two D atoms produce the same effect as one D_2 molecule [10]. The sensitivity of our Pirani gauge, including its associated circuitry, is 1 cm of deflection on a galvanometer scale for 4×10^9 D_2 molecules entering the gauge per second.

With the use of this measured sensitivity of the Pirani gauge and the known entrance area of the Pirani gauge, the observed resonance signal

can be converted into the number of polarized atoms per second that would enter the larger detector area (0.015 cm^2) actually to be used as the entrance to the ionizer. The flux of polarized deuterium atoms in the state $(F, m) = (3/2, -3/2)$ is thus measured to be 10^{12} atoms per second. This figure agrees with the theoretical design value within the experimental uncertainty of about 30%. Deuterium atoms in other magnetic substates have only a small probability of entering the detector region. Thus the deflection, s_α, of an atom which is in any one of the magnetic substates with $m_J = +1/2$ in the strong B-field away from the center of the detector opening is 3.8×10^{-2} cm for an atom having the most probable velocity of an atom in the source. This value of s_α implies that the fraction of the atoms in the $m_J = +1/2$ state in the B-field which enter the detector region is only about 0.2. In practice the fraction will depend on the position of the wire stop and can be made smaller than 0.2. Atoms which were in the $m_J = -1/2$ states in the A-field should be blocked by the wire stop. All atoms in the $m_J = -1/2$ state in the B-field (low field state $(F, m) = (3/2, -3/2)$) should enter the detector. Hence the relative numbers of atoms entering the detector region in the states $(F, m) = (3/2, -3,2)$, $(3/2, -1/2)$, $(3/2, +1/2)$, and $(3/2, +3/2)$ are 0.8, 0.05, 0.2 and 0.2. The nuclear polarization of the beam entering the detector region should then be $P_N = -0.44$. By proper positioning of the wire stop a larger negative value of polarization can be obtained.

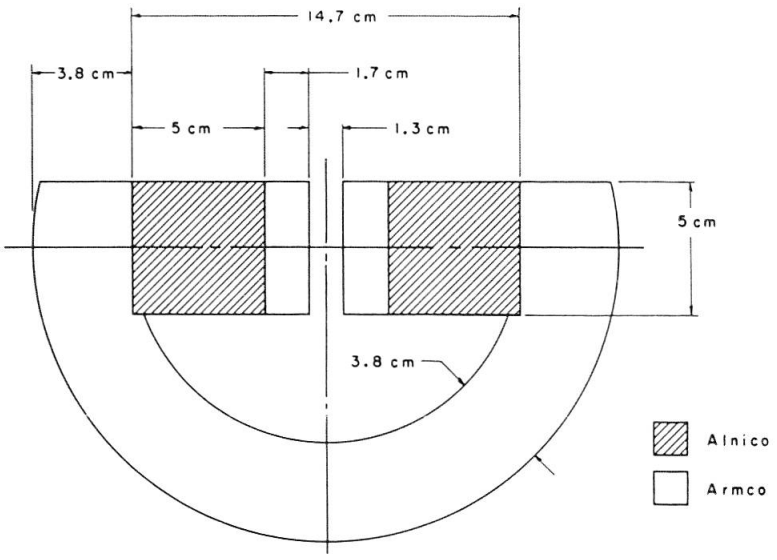

Figure 11
Cross section of homogeneous C-magnet, complete view

A major practical problem is the background of unpolarized hydrogen or deuterium present in the ionization region. For our deuterium experiment since the eventual detected event is the product of a specific

nuclear reaction induced by an accelerated deuteron, the only troublesome background will be due to unpolarized deuterium in the ionization region. The unpolarized deuterium may be present either as molecules or as unpolarized atoms.

With a view in particular to the production of a polarized proton source, our apparatus is provided with freon-cooled mercury pumps and liquid nitrogen traps (see figure 12). Conventional oil mechanical pumps are used. The vacuum envelope is constructed of stainless steel. There is provision for metal gaskets and for baking out the entire apparatus including the magnets at 250° C, although it has been convenient thus far to take data with the use of polyethylene gaskets and no bake-out has been attempted. The vacuum system is divided into three separately pumped sections – the source chamber, the interchamber, and the main chamber, which includes the atomic beam magnetic resonance components, the ionizer, and the attached electrostatic accelerator. These sections are separated by small openings which allow passage of the atomic beam.

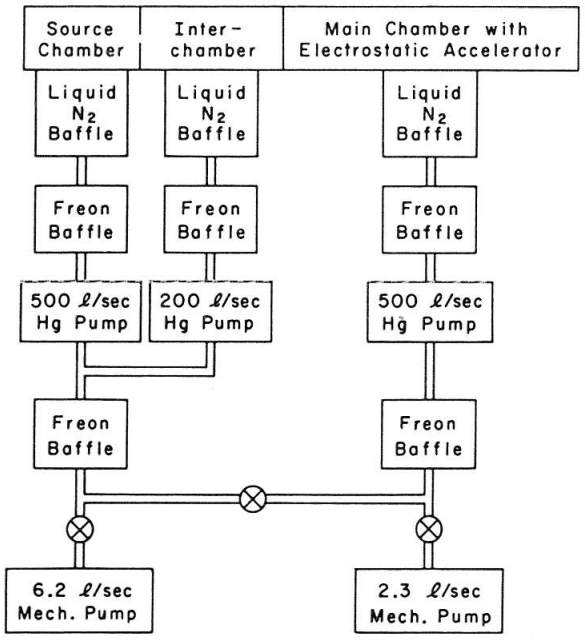

Figure 12
Schematic diagram of vacuum system

With no flow of deuterium gas into the vacuum system, an ionization gauge placed near the beam ionizer region indicates a pressure of 3×10^{-7} mm of Hg. With the customary rate of flow of deuterium gas through the discharge tube, the pressure increases to 3.3×10^{-7} mm of Hg. The increase in pressure of 3×10^{-8} mm of Hg is a measure of the pressure of unpolarized deuterium – presumably predominantly

molecular deuterium. This pressure corresponds to a density of 2×10^9 particles/cm^3. The background of unpolarized deuterium atoms in the ionization region is contributed principally by those atoms in the magnetic substates with $m_J = +1/2$ in the B-field which are not deflected away from the detector opening. As discussed in the previous paragraph, the number of atoms in these states which enter the detector opening depends on the geometry of the atomic beam and upon s_α and is about 5×10^{11} atoms/s.

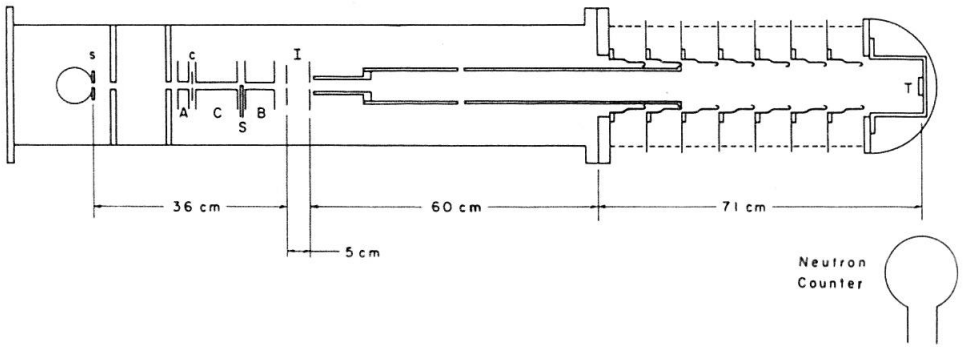

Figure 13

Schematic diagram of entire experimental setup, showing atomic beam magnetic resonance spectrometer, ionizer, electrostatic accelerator, and neutron counters

3.2 *The Ionizer*

The polarized deuterium atom flux entering the ionization region is 10^{12} atoms/s as was mentioned in section 3.1. Since the average velocity of the deuterium atoms from a discharge tube at 300° K is 2×10^5 cm/s and the opening for the beam into the ionization region is 0.015 cm^2, the density of polarized atoms will be 3×10^8/cm^3. It was noted in section 3.1 that the background density of D_2 molecules is 2×10^9/cm^3 and of D atoms in unwanted magnetic substates about 1.5×10^8/cm^3. If the energy of the electron beam in the ionizer is 200 ev, then in view of the cross sections as given in figure 9, the relative numbers of D^+ nuclei of the desired polarization, D^+ nuclei of undesired polarization, and D_2^+ molecular ions are 1, 0.5, and 11.

The ionizer is now under development. Studies have been made of an electrostatic Pierce-type gun [11] in which the electron beam travels in a direction perpendicular to that of the atom beam and parallel to the long dimension of the ribbonlike beam. The objective was to obtain an electron beam of several hundred ev energy which has a current density of 100 ma/cm^2 and a width approximately that of the atom beam or 0.02 cm. We have found it difficult to achieve this operation with any degree of reliability.

At present we are experimenting with another ionizer [12] which bombards in a direction perpendicular to that of the atom beam propagation and parallel to the short dimension of the beam. The ionizer has a large cathode area (1 cm high by 5 cm long). The design value of the electron current density is 0.5 amp/cm^2 at an energy of 80 ev. The electrons are accelerated through a grid to a collector plate at the grid potential. The atomic beam runs through the space between grid and collector. Advantage is to be taken of the potential minimum due to space charge effects in order to trap the ions and then accelerate them out the exit end of the ionizer. The electric field in the direction of the atom beam propagation is obtained by varying the grid to plate spacing.

3.3 *Acceleration of deuterons and the detection of polarization*

The T(d, n) He^4 reaction with s-wave deuterons provides a convenient and sensitive detector of the polarization of an accelerated deuteron beam [13]. This reaction [14] has a broad resonance centered about 107 keV, and the thick target yield for a deuteron bombarding energy of 150 keV is approximately 4×10^{-6} per incoming deuteron for a 5 Curie T–*Zr* target. The angular distribution, in the center of the mass system, for the outgoing neutrons, when the reaction is induced by deuterons which are partially polarized in the transverse z direction, is given by

$$W(\theta) = (P_1 + P_{-1})(3 \sin^2 \theta + 2) + P_0 (6 \cos^2 \theta + 2) .$$

The angle θ is measured with respect to the deuteron polarization axis in the plane perpendicular to the beam axis, and the quantities P_1, P_{-1}, and P_0 are the probabilities for the deuteron to have $m_I = +1$, -1, and 0, respectively. For the completely polarized deuterons, the anisotropy $W(90°)/W(0°)$ will be 2.5. However, as discussed in section 3.2, before acceleration one expects 11 times as many unpolarized D_2^+ as polarized D^+. With a terminal voltage of 150 kv on the accelerator, the ratio of the thick target yields for D^+ and D_2^+ is approximately 1.5 since the D_2^+ are accelerated only to 75 keV. The expected asymmetry with this D_2^+ background, as well as with the background of D^+ in magnetic substates other than the desired one (see section 3.2), then becomes $W(90°)/W(0°) \simeq 1.08$. Solid angle effects and scattering will tend to reduce this somewhat.

The accelerator column consists of seven spinnings separated by ceramic insulators 3 inches long. It was kindly provided by Drs. N. HEYDENBERG, G. TEMMER, and J. WEINMAN of the Department of Terrestrial Magnetism Laboratory in Washington, D.C. The deuterons are focussed into the accelerator column from the ionizer by a single electrostatic lens.

Plastic scintillators are used for neutron detection. They have an intrinsic efficiency of approximately 10% for the 14 MeV neutrons produced in the $T(d,n)He^4$ reaction. The spectrum produced by the recoil protons has a reasonably sharp cut-off at maximum energy. With appropriately chosen bias levels the counter can be made quite insensitive to gamma rays below a few MeV.

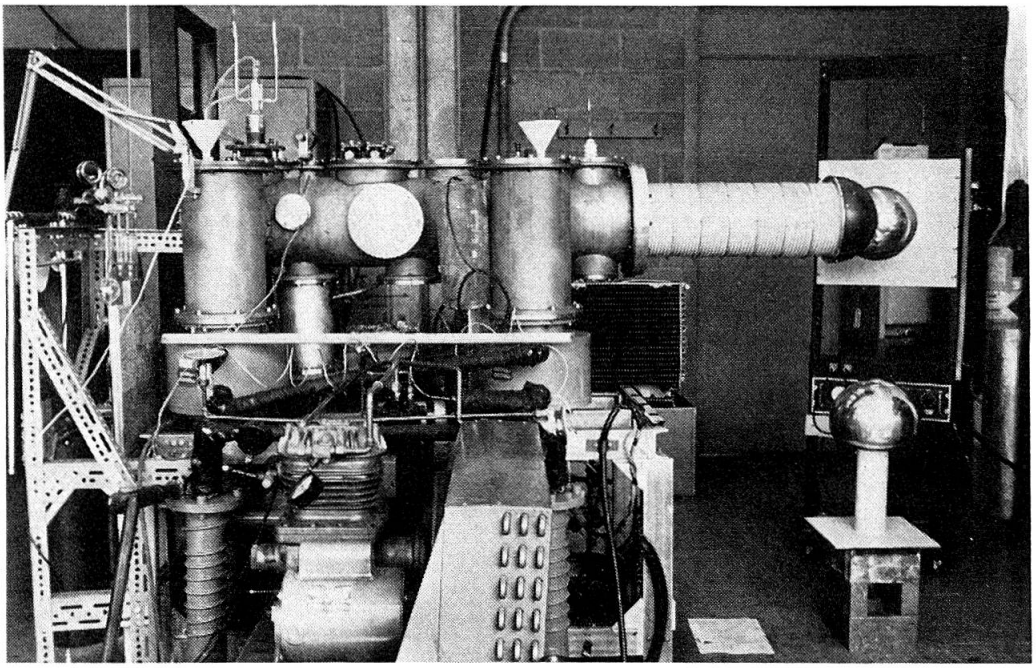

Figure 14
Photograph of entire apparatus

Acknowledgements

We are particularly indebted to Drs. N. HEYDENBERG, G. TEMMER, and J. WEINMAN of the Department of Terrestrial Magnetism, Carnegie Institution, Washington, D.C., for supplying the electrostatic accelerator tube and for encouragement and collaboration. It has been our mutual intention to install the polarized ion source in their Van de Graaff accelerator.

REFERENCES

[1] W. GERLACH and O. STERN, Ann. Phys. *74*, 673 (1924); W. GERLACH and O. STERN, Z. Phys. *8*, 110 (1921–1922).
[2] P. KUSCH and V. W. HUGHES, *Encyclopedia of Physics* (Springer, Berlin 1959), Vol. XXXVII/1, p. 41.
[3] P. KUSCH and V. W. HUGHES, *Encyclopedia of Physics* (Springer, Berlin 1959), Vol. XXXVII/1, p. 51.

[4] P. KUSCH and V. W. HUGHES, *Encyclopedia of Physics* (Springer, Berlin 1959), Vol. XXXVII/1.
[5] N. F. RAMSEY, *Molecular Beams* (Oxford: Clarendon Press, 1956).
[6] W. L. FITE and R. T. BRACKMANN, Phys. Rev. *112*, 1141 (1958).
[7] H. S. W. MASSEY and E. H. S. BURHOP, *Electronic and Ionic Impact Phenomena* (Oxford: Clarendon Press, 1952), p. 247.
[8] H. E. NEWHALL, Phys. Rev. *62*, 11 (1942).
[9] I. I. RABI, Phys. Rev. *49*, 324 (1936).
[10] A. G. PRODELL and P. KUSCH, Phys. Rev. *88*, 184 (1952).
[11] J. R. PIERCE, *Theory and Design of Electron Beams* (D. Van Nostrand Co., New York 1949), p. 167.
[12] K. R. SPANGENBERG, *Vacuum Tubes* (McGraw-Hill, New York, 1948), pp. 248–265.
[13] A. GALONSKY, H. B. WILLARD, and T. A. WELTON, Phys. Rev. Letters *2*, 349 (1959).
[14] J. B. MARION and J. L. FOWLER, *Fast Neutron Physics* (Interscience Publishers, Inc., New York 1960), Vol. IV/1, p. 90 and p. 692.