Direct Determination of Nuclear Polarization Produced by Beam-Foil Interaction for the Short-Lived β Emitter ^{12}B

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Nuclear polarization P of the short-lived β emitter ^{12}B was produced by the beam-foil interaction and directly determined via asymmetric β decay. For a single tilted foil, at boron energy $E_B = 1.0$ MeV, $|P| = 1.82(14)\%$. This was enhanced to $|P| = 4.69(46)\%$ by stacking four tilted foils. The dependence of P vs E_B was observed for a single tilted foil in the range of $E_B = 0.6$ to 1.3 MeV. The sign of P followed that of the tilt angle and was consistent with predictions from electron-density-gradient models.

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Recently nuclear polarization P of ions ($A \leq 15$) has been produced in an accelerated beam by atomic collisions with metallic plates or carbon foils. In both processes, asymmetric collisions at the final surface created a large orbital angular momentum in the atomic shell which was transferred to the nucleus via the hyperfine interaction as a nuclear polarization. In this way $P \leq 20\%$ of ^{7}Li, ^{13}C, and ^{14}N was achieved by Winter and Andrä[1] and by Andrä *et al.*[2] via grazing-incidence collisions (scattering), and later $P \leq 10\%$ was achieved by Deutch and co-workers[3-5] for full transmitted beams of ^{13}C and ^{15}N through a tilted foil (the tilted-foil technique). However, both techniques observed P *indirectly* by the optical light emitted from the *atom.*

The purpose of the present investigation was to observe P created by collisions through a tilted foil simply and *directly*, from the asymmetric β decay of the polarized *nuclei* themselves. A direct observation of P can test and confirm the results and assumptions made in the previous optical investigations regarding production and transfer of polarization from the atom to the nucleus. Also this method can yield P useful to precision NMR studies on short-lived β emitters[6] and to other applications of polarized nuclei in many possible areas of physics.

In this study, the short-lived β emitter ^{12}B ($I^\pi = 1^+$, $T_{1/2} = 20.3$ msec) was chosen as a first test case because with this nucleus the tilted-foil technique for production of P could be calibrated in the course of the measurements by the large well-known P produced by the nuclear reaction[7] ^{11}B$(d,p)^{12}$B itself. For the tilted-foil technique, the dependence of P vs E_B (the energy of outgoing ^{12}B) and the enhancement of P with increased number of tilted foils were measured. Also demonstrated was a sign change of P by a simple mechanical flip of the foil with respect to the beam direction.

Atomic collisions at the final surface of a tilted foil leave the atom in an anisotropic state since the broken axial symmetry in the collisions results in strong angular-momentum polarization of the electrons. The electron angular-momentum polarization is partially transferred to the nucleus in free flight under the influence of the hyperfine interaction, and the nucleus also becomes polarized.[5,8] In the transfer process to the nucleus, all polarized atomic states in each charge state of the atom may take part.

A schematic view of the present experimental setup is shown in Fig. 1. The β-emitting nuclei ^{12}B were produced by the reaction ^{11}B$(d,p)^{12}$B. The pulsed-beam method was employed in order to separate the β-ray counting period of 20 msec from the beam bombarding period of 20 msec. The ^{11}B target (10 μg/cm^2) evaporated onto a thin carbon foil (10 μg/cm^2) was tilted at 30° relative to the incident beam direction. (See Berry

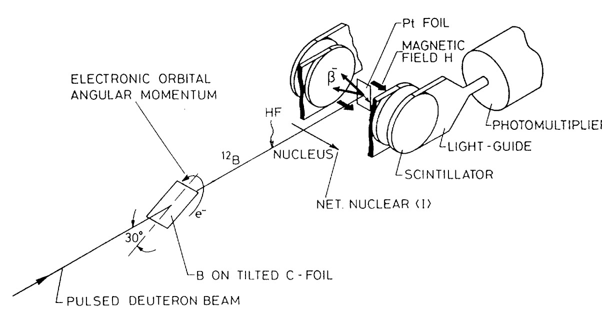

FIG. 1. Schematic experimental arrangement of production and direct detection of nuclear polarization P by beam-foil interaction through a tilted foil. The direction $\vec{I}$, the nuclear spin experimentally found, is drawn in the figure for the tilt angle used and is consistent with the electronic orbital angular momentum predicted from electron-density-gradient models (Ref. 9).

et al.[10] for definition of the angle. The 30° angle is usually referred to as a 60° normal-to-the-surface tilt angle α.) A deuteron beam from the 5-MV Van de Graaff accelerator at The University of Aarhus was used in the energy and current ranges of 1–2.8 MeV and 0.1–1 μA, respectively. To avoid P from the nuclear reaction itself, the ^{12}B ions were collected at a forward angle (0° ± 6°) through the tilted carbon foil, and implanted into a Pt foil (5 μm thick) which was placed 7 cm downstream from the target. In order to preserve P of ^{12}B in the Pt foil, an external magnetic field H_0 of 280 G was applied (anti)parallel to the direction of the produced P.

The angular distribution of the β rays from the polarized ^{12}B in the Pt foil is given as $W(\theta) = (1 - P\cos\theta)$, where θ is the polar angle of the β-ray direction relative to P. The β-ray asymmetry R was determined by the up-down count rates of β rays which were detected by two sets of plastic-scintillation counter telescopes placed above and below the ^{12}B nuclear spin direction: $R = W(\pi)/W(0)$. By correcting the attenuation in R (6.3%) due to the finite solid angle of the β detectors, P of ^{12}B could be deduced as $P = (R-1)/(R+1)$.

The value of P, after passage through a single tilted foil, was examined alternately with and without the magnetic field on the Pt foil for $\alpha = \pm 60°$ and 0° at $E_B = 1.0$ MeV. In Fig. 2, the observed values of P for each measurement are plotted for a typical sequence of runs. The data

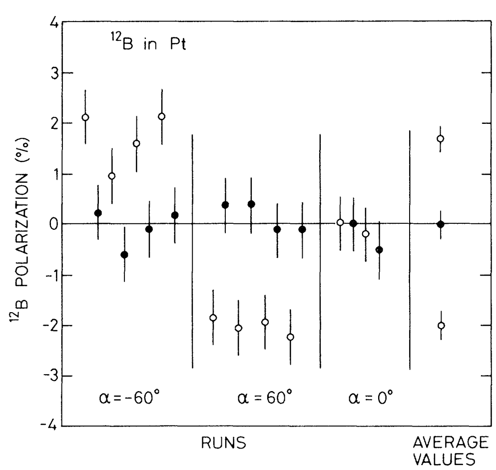

FIG. 2. Nuclear polarization of ^{12}B after passage through a single tilted C foil at outgoing ^{12}B energy $E_B = 1.0$ MeV for a typical sequence of measurements. The open and closed circles represent data with and without the magnetic field, respectively, at ±60° and 0° tilt angles (see definitions in Ref. 10).

with the magnetic field on indicate that the magnitude of P is the same whether the tilt angle α is positive or negative. At $\alpha = 0°$ (no tilt), P disappears whether there is a magnetic field on the Pt foil or not. From the disappearance of P at $\alpha = 0°$, it is concluded that there existed no residual reaction-induced P due to the slightly asymmetric collimation of the ^{12}B beam (0° ± 6°) and/or due to an asymmetric scattering through the nonuniform boron target and carbon foil between +6° and −6°. From a number of similar runs, for a single tilted foil at $E_B = 1.0$ MeV, the average P value was $|P| = 1.82(14)\%$. Not only did these measurements show direct production of P by the tilted-foil technique but they also showed a change of sign of P by a simple mechanical flip of the foil direction with respect to the beam direction. The observed sign of P, as shown in Fig. 1, was found to be consistent with the electronic orbital angular momentum predicted by recent models,[9] which postulate that the interaction of the ion in its rest frame is with electrons with velocity opposite that of the ion-beam direction and negative density gradient across the beam. Remarkably enough, equivalent values of P were achieved even though the normal sequence of the boron target and the carbon foil was reversed, i.e., with carbon the first surface and boron the final foil surface.[11]

For a single foil, P was examined in the range of $E_B = 0.6$ to 1.3 MeV [see Fig. 3(a)]. However, no appreciable energy dependence of P on E_B was found. In this energy range, the main boron charge states are B II, B III, and B IV (all with S atomic ground states) with the higher charge states coming in at higher E_B. Since the observed P of ^{12}B is not correlated with any particular charge state, with the possible exception of B III, it results from an ensemble of many polarized atomic states in every charge state of boron produced by the tilted foil, each transferring its contribution to the nucleus. Furthermore, the polarization's independence of atomic charge state is not masked by the present nuclear reaction used. In fact, the production of the first excited state of ^{12}B* ($E_x = 0.953$ MeV) appears and dominates at higher E_B ($E_B > 0.8$ MeV). Since the nuclear lifetime of the excited state (~0.2 psec) is much shorter than the polarization transfer time (a few hundred picoseconds), there is no contribution from this state to the observed P. This admixture of the nuclear state results only in a 200-keV energy spread of the nuclear ground state of ^{12}B.

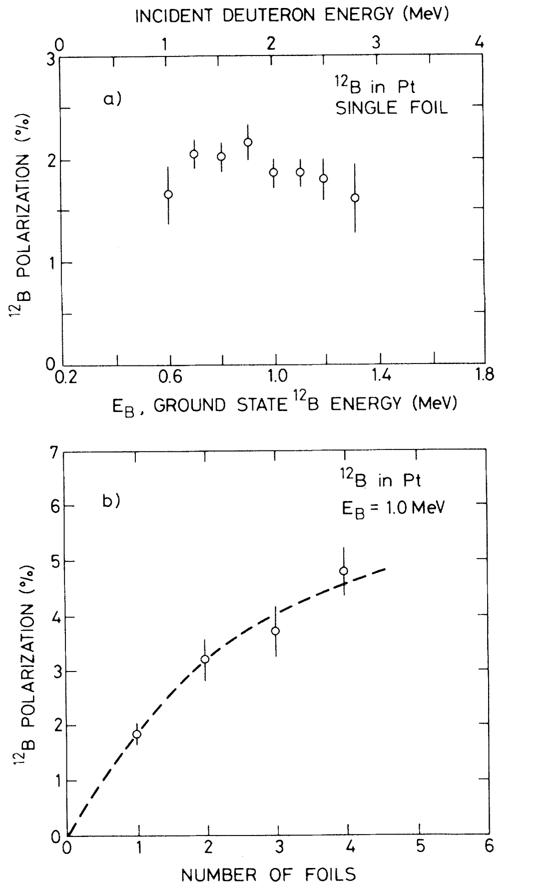

FIG. 3. (a) Nuclear polarization of ^{12}B after passage through a single tilted C foil as a function of ^{12}B energy E_B. (b) Enhancement of nuclear polarization in ^{12}B for a sequence of tilted foils. The target is boron evaporated onto the first foil. The dashed line corresponds to an enhancement according to a geometric progression.

The amount of P was built up by a system of multifoils.[1,5,12] Up to three extra tilted carbon foils (each 10 μg/cm^2 placed 1 mm from one another) were added in sequence at $|\alpha| = 60°$, with the first foil 1 mm behind the target foil. The data are displayed in Fig. 3(b) and portray a beautiful enhancement of P from an original value of $|P| = 1.82(14)\%$ with one foil to $|P| = 4.69(46)\%$ with four foils. This is about $\frac{1}{3}$ of the maximum P produced by the nuclear reaction in the best geometric setup. It appears that even more stacked foils would increase P further, up to some saturation value.[1]

The transit time of ^{12}B between two foils (0.5 nsec) is about the average polarization transfer time from the atom to the nucleus because P for each tilted foil is enhanced according to a geometric progression.[1] This time is also shorter than the lifetimes of many atomic excited states of boron. Therefore, in the present case, for boron atoms with S atomic ground states, the transfer of polarization to the nucleus can also come from polarized atomic excited states. In fact, the atomic ground states of B II and B IV are both $^1S_0$. Therefore, the atomic polarization produced can only be maintained and transferred by atomic excited states, although in B IV, the metastable $1s2s\,^3S_1$ may also be a source of long-lived "ground state" for polarization transfer. On the other hand, in the case of B III, for which the population is ~45% over the entire present range of E_B energies, the ground state is $^2S_{1/2}$, which may be polarized by repopulation (feeding) from polarized non-S excited states and transfer the polarization to the nucleus. The nucleus could be polarized directly from the excited states as well. These suppositions regarding excited-atomic-state polarization transfer are in agreement with the present result of a smooth P vs E_B dependence. A large integrated polarization contribution to the nucleus from polarized excited atomic states in every charge state would mean a general applicability of the beam-foil technique to a wide range of beam elements and energies.

In conclusion, with this direct method to determine P, a quantitative test can be made of the indirect (optical) methods for determining and calculating P by beam-foil or grazing-incidence techniques. This kind of test is essential for the quantitative understanding of the mechanisms responsible for polarization transfer between atoms and nuclei. In addition, the present investigation has demonstrated in a direct way a remarkably simple method to polarize the spin of a nucleus, enhance P without loss of intensity, and even change the sign of P. This may open up the use of new probe nuclei for precise measurements in a wide range of physics areas. In particular, the present technique can expand the region of utility of NMR studies[6] in which the preparation of polarized or aligned β emitters is essential. Note that only a 1% effect of P is enough to determine hyperfine frequencies to 1 part in 10^4 by use of the NMR technique. The alignment of β-emitting nuclei by beam-foil techniques would also serve the same purpose.

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