Measurement of the Magnetic Moment of the One-Neutron Halo Nucleus ^{11}Be

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The magnetic moment of ^{11}Be ($T_{1/2} = 13.8$ s) was measured by detecting nuclear magnetic resonance signals in a beryllium crystal lattice. The experimental technique applied to a ^{11}Be$^+$ ion beam from a laser ion source includes in-beam optical polarization, implantation into a metallic single crystal, and observation of rf resonances in the asymmetric angular distribution of the β decay (β-NMR). The nuclear magnetic moment $\mu(^{11}\text{Be}) = -1.6816(8)\ \mu_N$ provides a stringent test for theoretical models describing the structure of the $1/2^+$ neutron halo state.

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Halo nuclei are weakly bound nuclear systems with an extreme N/Z ratio, which have a neutron (or proton) density that extends far beyond the core of the nucleus. ^{11}Be is the best known case of a one-neutron halo nucleus, and it has been studied quite extensively, mainly using reactions induced by radioactive ion beams.

From interaction cross sections of 790A MeV ^{11}Be nuclei with different targets a large rms matter radius for ^{11}Be was deduced using a Glauber-model analysis [1]. This was taken as an indication for either a neutron halo or a large deformation. Additional information from reaction studies of a 33A MeV ^{11}Be beam yielded the density distribution of the ^{11}Be nucleus [2]. The extended low-density tail could not be explained by deformation, but clearly showed the existence of a halo. Also, the narrow angular distribution of neutrons from dissociation reactions of ^{11}Be supports the assumption of a neutron halo [3].

^{11}Be has two bound states ($1/2^+$ and $1/2^-$), both presenting a halo structure, which are connected by a very strong $E1$ transition [4]. Contrary to what one would expect from the standard shell model, the ground state is not $p_{1/2}$ but a $1/2^+$ intruder state from the sd shell. Various theoretical approaches have been proposed trying to reproduce these peculiar properties. Large-basis shell-model calculations [5–12] do not invariably reproduce the parity inversion ascribed to a combined effect of core excitation to the first 2^+ state, pairing blocking, and proton-neutron monopole interaction [9]. Realistic spatially extended wave functions of both the $1/2^+$ and $1/2^-$ states are needed to explain the strong $E1$ transition [6]. The variational shell model [10], proposed to describe nuclei containing loosely bound nucleons, gives the correct level ordering and the halo structure, but fails to reproduce the $E1$ strength. A good description of all these aspects was recently obtained in a microscopic cluster model [13].

Concerning the structure of the lowered $1/2^+$ state all the model approaches have in common that the main component of the wave function is $|(^{10}\text{Be})0^+ \times \nu 2s_{1/2}\rangle$, whereas the predicted admixture of the core excited $|(^{10}\text{Be})2^+ \times \nu 1d_{5/2}\rangle$ state ranges from 10% to 40%. The magnetic moment should be particularly sensitive to the relative amplitudes of these two components. Thus, in combination with a theoretical analysis, a measurement of the magnetic moment of ^{11}Be would give detailed information about the wave function of the halo neutron.

In this Letter, we report on the measurement of the magnetic moment of ^{11}Be, performed by β-NMR spectroscopy on implanted polarized nuclei. The experimental technique is closely related to the one employed for measurements of the nuclear spin and electromagnetic moments of ^{11}Li [14,15] and of the quadrupole moments of Na isotopes [16]. An isotope-separated 60 keV beam is polarized by optical pumping and implanted into a crystal lattice, where nuclear magnetic resonance signals are observed in the asymmetric angular distribution of the β decay (β-NMR).

The present experiment involves some novel features. (i) An efficient source of radioactive Be$^+$ beams emerged from the development of laser ionization schemes [17] now being widely used at ISOLDE. (ii) The ^{11}Be case constitutes the first application of optical polarization to an *ion* beam instead of a neutralized beam, necessitating efficient optical pumping in the ultraviolet resonance line with the low output power of a frequency-doubled cw dye laser. In addition to that, the first-forbidden β decay to ^{11}B allows no safe prediction of the asymmetry signal to be expected. (iii) The magnetic field at the site of the ^{11}Be sample may be calibrated by performing a similar experiment on a ^{8}Li beam obtained from the same target and surface ionized at the hot walls of the ion source.

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The experiment was performed at the ISOLDE facility at CERN. Beryllium isotopes were produced by fragmentation of uranium in a heated UC_2 target exposed to the pulsed 1 GeV proton beam from the PS-Booster synchrotron. They diffused into a tungsten cavity in which resonant laser ionization from the $2s^2\ ^1S_0$ atomic ground state via $2s2p\ ^1P_1$ to an autoionizing state took place [17]. The laser beams used for the two-step ionization process were obtained from copper-vapor-laser pumped dye lasers combined with respectively frequency tripling and frequency doubling. The ions were extracted electrostatically out of the cavity, accelerated to 60 keV, mass separated, and guided to the experiment.

For optical excitation the ion beam was propagating collinearly with a cw laser beam whose wavelength was tuned to the (Doppler-shifted) Be II transition $2s\ ^2S_{1/2} \rightarrow 2p\ ^2P_{1/2}$. About 1 mW of utilizable 313 nm laser light was obtained by intracavity frequency doubling of an Ar^+-laser pumped dye laser running on Sulforhodamine B dye. In a preparatory experiment, fluorescence detection of resonant optical excitation was used to measure the isotope shift and hyperfine structure (hfs) for ^{7,9,10}Be produced copiously from a carbon target. These measurements yield the previously unknown magnetic moment of ^{7}Be [18] and, in particular, the magnitude of the specific mass shift [18], facilitating considerably the search of ^{11}Be resonance frequencies. Beam intensities over 10^9 atoms per second were available for these long-lived or stable isotopes, whereas the ^{11}Be yield was only a few 10^6 atoms per second.

The half-life of 13.8 s is just sufficiently short for a β-NMR experiment which requires the decay of implanted polarized nuclei within the spin-lattice relaxation time. This technique is by far more sensitive than fluorescence detection of optical excitation. Furthermore, a direct NMR measurement of the nuclear g factor is expected to be at least an order of magnitude more accurate than an optical hfs measurement.

Circularly polarized (σ^+) light was used to polarize the Be^+ beam in a weak longitudinal magnetic field which was applied to the optical pumping section of 1.5 m length, kept at a variable electrical potential for tuning the Doppler-shifted laser frequency into resonance. Polarization of the total (electronic and nuclear) spin system was created in several cycles of excitation and decay. In a gradually increasing guiding field the spins were rotated and then decoupled adiabatically while entering the transverse field of the NMR magnet (about 0.3 T). The ions were implanted into a beryllium single crystal placed in the center of this magnet. Electrostatic deflectors were used to compensate the magnetic force. The β decay of the polarized nuclei was detected by two scintillation counter telescopes placed between the thin windows of the vacuum chamber and the magnet pole faces. The β asymmetry is then defined as the normalized difference between the count rates of both telescopes, $A = (N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow)$.

The spin-lattice relaxation time $T_1 = 2.5$ s at 300 K was measured by observing the decay of the asymmetry signal as a function of time after pulsed implantation. Cooling the host crystal to about 50 K slowed down this relaxation by a factor of 5. The time-averaged asymmetry then reached about 1% for optical pumping in the strongest hfs component. In principle, the optical pumping scheme for $I = 1/2$ should provide complete nuclear polarization, but the power density of the ultraviolet laser beam was far below saturation. Taking this into account as well as the relaxation losses, we estimate the β-asymmetry parameter (averaged over all decay channels and β-ray energies) to be at least 20%.

Now the complete hfs pattern was recorded by applying a voltage sweep to the optical pumping section. This already gives a rough value for the magnetic moment, and in addition it gives the sign which, of course, is expected to be negative for the $1/2^+$ neutron state. With this preliminary information the rf scanning range for detecting the NMR signal (around 7.5 MHz) could be restricted to about 5%.

In the NMR experiment the β-decay asymmetry is destroyed by coupling the nuclear Zeeman levels through rf irradiation at the Larmor frequency. Well-saturated resonances were observed and finally narrowed to about 10 kHz by reducing the rf power. The experimental line shapes are influenced by nonstatistical fluctuations of the asymmetry signal mainly caused by power instabilities of the two laser systems: (i) Changes in the output of the frequency-doubled dye laser used for optical pumping directly translate into changes of nuclear polarization, whereas (ii) fluctuations in the laser ion source efficiency result in a variable share between decays of polarized nuclei implanted within the measuring interval of about one half-life and decays of depolarized nuclei remaining from previous intervals. Apart from these fluctuations the NMR spectra at low rf power, of which three examples are shown in Fig. 1, turned out to be well described by a single Gaussian. In order to avoid uncontrolled errors in the determination of the resonance frequency, we took seven independent spectra and used the deviations from the mean value together with the fitting results for evaluating a realistic error. This analysis yields the Larmor frequency of 7.8508(6) MHz.

For an evaluation of the nuclear g factor it is necessary to calibrate the magnetic field at the position of the implanted sample. This can be done in an elegant way by measuring the Larmor frequency of ^{8}Li in the identical NMR setup. A ^{8}Li beam is produced by surface ionization from the same target. The technique is similar to the one described for ^{11}Be, but optical pumping of lithium requires some modification of the apparatus, to be achieved within a few hours. A beam of neutral atoms was obtained by charge exchange on sodium vapor produced in a heated cell to which the Doppler-tuning potential was applied. The laser (operated on DCM dye) was tuned to the $2s\ ^2S_{1/2} \rightarrow 2p\ ^2P_{1/2}$

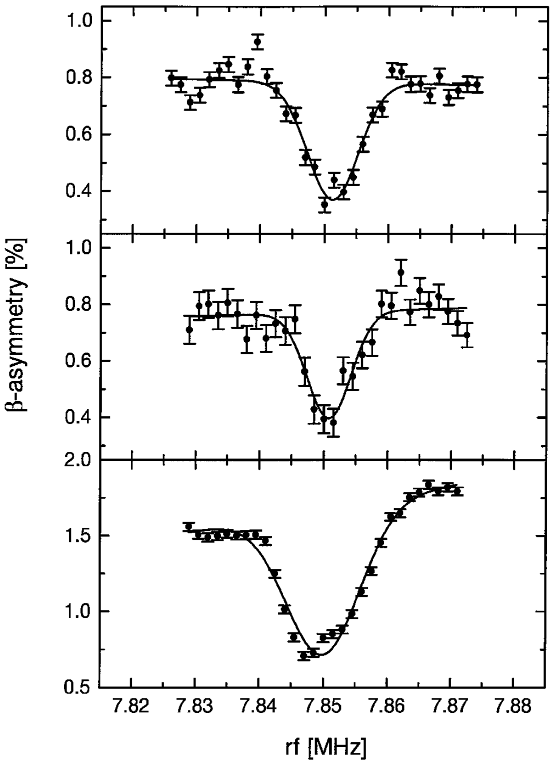

FIG. 1. Examples of β-NMR signals of ^{11}Be nuclei in a beryllium host crystal.

resonance line at 671 nm. ^{8}Li with the spin $I = 2$ might be subject to a noticeable quadrupole interaction with the unknown electric field gradient of the implantation site in the beryllium lattice. This would result in a splitting or in an unresolved asymmetric shape of the NMR signal, corresponding to the occupation distribution over the m_I levels achieved by optical pumping. The resonance structure (Fig. 2) was found to be well reproduced by a single Gaussian of 3 kHz width. The maximum displacement of the resonance center from the Larmor frequency was estimated from simulations of the line shape in comparison with the experimental curve. This gives the error for the deduced Larmor frequency of 1.9301(5) MHz.

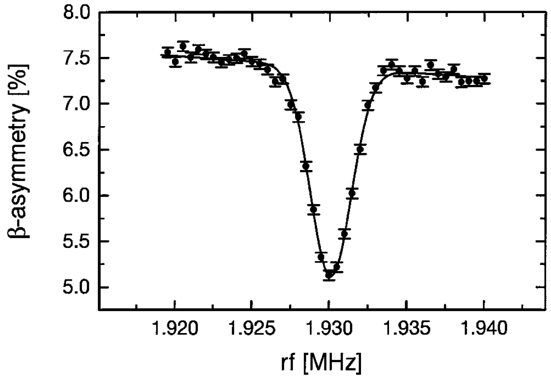

FIG. 2. β-NMR signal of ^{8}Li nuclei in beryllium serving for calibration of the magnetic field.

Different positions of the implanted spot on the crystal could involve slightly different values of the magnetic field used for ^{11}Be and for ^{8}Li. Field inhomogeneities over the 12 mm diam of the crystal were measured with an NMR probe to be smaller than 10^{-4}. On-line checks for ^{11}Be were performed by moving the 5 mm ion beam spot over the crystal with no measurable effect on the Larmor frequency. During the two days of data taking, field drifts of the order 5×10^{-5} were monitored with a Hall probe. Apart from the changeover from the original to the calibration setup their influence on the resonance position is largely included already in the averaging over the results of the individual measurements.

Using the reference value for the magnetic moment of ^{8}Li [19], $\mu(^8\mathrm{Li}) = 1.653\,560(18)\ \mu_N$, we obtain the magnetic moment of ^{11}Be, $\mu(^{11}\mathrm{Be}) = -1.6816(8)\ \mu_N$. The difference in the diamagnetic corrections for Be and Li, though practically negligible, has been taken into account. The quoted error includes an uncertainty from the Knight shift. This shift is known to be very small for Be in beryllium [20], and it can be estimated for Li in beryllium to be less than 2×10^{-4} from the systematics of results for the ^{8}Li spin-lattice relaxation obtained in similar systems [21].

The magnetic moment should reflect the composition of the ^{11}Be ground-state wave function. Most experimental information [1–3,22] has been found to be consistent with the assumption of a well-developed one-neutron halo state of essentially $s_{1/2}$ nature. The large variation in theoretically calculated amplitudes of the $|(^{10}\mathrm{Be})2^+ \times \nu 1d_{5/2}\rangle$ admixture [5–12] must be due to particularities of the models, e.g., in the construction of a p-sd cross-shell interaction or in the ways of incorporating the features of weakly bound halo structures. Nevertheless, the predictions for the magnetic moment are generally close to $-1.5\mu_N$ [10,11,23].

Using recent empirical interactions for the p-sd region [8] and free-nucleon g factors, Brown [23] obtained $-1.58\mu_N$ with the WBP interaction and $-1.49\mu_N$ with the WBT interaction. In both calculations the $|2^+ \times d_{5/2}\rangle$ component contributes about 20% to the ground-state wave function. The calculated moments, being already smaller than the experimental value, are further reduced to about $-1.2\mu_N$ by taking an effective value of $0.78g_s^{\mathrm{free}}$ for the g_s factor of the neutron as obtained from a fit to thirteen magnetic moments of p-sd-shell nuclei. (The fit for the effective g factor crucially depends on the magnetic moment of ^{15}C used also by Suzuki *et al.* [25] as a representative of a well-bound spherical $s_{1/2}$ system.) In comparing this with the experimental value, one may conclude that the $1/2^+$ halo state is of even purer $s_{1/2}$ character (with a Schmidt value of $-1.91\mu_N$) than the particular interactions predict. A previous shell-model calculation by Millener [24] based on the Millener-Kurath interaction [5,6] and using the free-neutron g_s factor gave $-1.71\mu_N$, a value which is very close to the experimental result. Compared to other calculations, the enhanced value of the magnetic moment can be traced to a larger $|0^+ \times s_{1/2}\rangle$ parentage (82% compared to 74% of the WBP calculation) in the wave function. However, as long as the quenching of g_s for halo states cannot be calculated reliably (see below), the agreement may be regarded as fortuitous.

Suzuki *et al.* [25] based their prediction for the magnetic moment on variable relative amplitudes of the $|0^+ \times s_{1/2}\rangle$ and $|2^+ \times d_{5/2}\rangle$ components, and they included corrections for the influence of meson-exchange currents. By analyzing the situation in ^{15}C they assumed $g_s^{\mathrm{eff}} = 0.85\, g_s^{\mathrm{free}}$. The prediction of $-1.5\mu_N$ for a 40% component of $|2^+ \times d_{5/2}\rangle$ is then consistent with the situation suggested by the variational shell model. However, the experimental value of $-1.68\mu_N$ is incompatible with the range of predictions reaching the maximum (negative) value of $-1.62\mu_N$ for a pure $s_{1/2}$ configuration. On the other hand, the variational-shell-model results [10] seem to be in accordance with recent preliminary data [26] on the transfer reaction $p(^{11}\mathrm{Be},\, ^{10}\mathrm{Be})d$. In contrast to $^{10}\mathrm{Be}(d,p)^{11}\mathrm{Be}$ reaction data [22], the spectroscopic factors for the channels to the 0^+ and 2^+ states of ^{10}Be suggest a strong $|2^+ \times d_{5/2}\rangle$ component for ^{11}Be.

As we have shown, we may interpret the magnetic moment as compared to the shell-model calculations in support of a pronounced (and relatively pure $s_{1/2}$) halo state. The halo structure will reduce core polarization compared to equivalent configurations in other nuclei. This also means that shell-model calculations not accounting for the exotic spatial structure of the ^{11}Be wave function will implicitly overestimate the quenching of the g_s factor. Presumably, the shell-model predictions of about $-1.5\mu_N$, compared to the experimental value of $-1.68\mu_N$, are influenced by this effect. Thus a coherent description of the ^{11}Be nucleus will depend on further theoretical investigations quantifying these arguments.

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Note added in proof.—A recent final analysis [27] of the transfer reaction cross sections of Ref. [26] is consistent with a 16% core polarization admixture in the ^{11}Be ground state wave function. This is no longer in obvious contradiction to our result.

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