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Precise Proton-Polarization Standards Determined with a Lamb-Shift Ion Source Incorporating a Nuclear Spin Filter*

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The polarization of an 8–12-MeV proton beam produced by a Lamb-shift ion source has been determined with 0.4% absolute accuracy by an atomic-beam technique. The procedure, which involves selection of a single hyperfine state of fast H(2s) atoms, is ideally suited to routine monitoring of beam polarization. Absolute p-^{4}He elastic-scattering analyzing powers measured with the calibrated beam are reported, and existing double-scattering data are compared with these results.

The purpose of this Letter is twofold. First, we describe an atomic-beam method for accurately determining the polarization of protons produced by a Lamb-shift polarized-ion source incorporating a nuclear spin filter.[1] Second, we present absolute analyzing powers for p-^{4}He elastic scattering which were obtained with the calibrated proton beam, at several energies and angles coinciding with the most precise existing double-scattering data.[2,3]

In a Lamb-shift polarized-ion source, H(2s) atoms are produced by charge transfer of 500-eV protons in cesium vapor; these are subsequently converted to H^- ions by charge transfer in argon gas. In the Los Alamos apparatus,[4] a nuclear spin filter is located between the cesium and argon cells. This is a resonant interference device which can be tuned (by adjusting its axial field B) to pass only H(2s) atoms with nuclear magnetic quantum number $m_I = +\frac{1}{2}$. These atoms produce a H^- beam which has 100% nuclear polarization, independent of the magnetic field strength in the ionization region. The formation of H(1s) atoms, a small fraction of which convert to H^- ions, contributes a (nominally) unpolarized background beam whose magnitude is about 10% of the total output current.

The procedure for determining the beam polarization (called the "quenching-ratio method") consists simply of measuring the normal output current i and the background current i_B which remains when all H(2s) atoms are quenched to the ground state.[5] The beam polarization is then expected to be $p_Q \equiv (i - i_B)/i$ since the component

$i - i_B$ originates exclusively from H(2*s*) atoms and is thus (nominally) 100% polarized. This method has been used as a routine beam-polarization monitor (1.5% precision) for several years. Considerably greater precision is attainable if several small effects are considered, some of which lead to minor adjustments to p_Q.

There is no proton-induced nuclear reaction or scattering whose analyzing power is presently known precisely enough to check the quenching-ratio method directly. Our testing approach was therefore to use p-^{4}He elastic scattering at 12.03 MeV, 112° lab, as a fixed analyzer for examining *relative* changes in the beam polarization, while pertinent ion-source and accelerator parameters were systematically varied. This is a convenient choice of energy and angle since the p-^{4}He analyzing power is known to approach unity in this region.[6] The observed left-right asymmetry A_{LR} is related to the beam polarization p and the analyzing power $A(\theta)$ by $A_{LR} = pA(\theta)$.[7]

Although the small effects which qualify the p_Q measurement cannot be considered in detail in this communication, we now briefly list their nature and relative significance, along with the corrections and uncertainties they introduce.

(1) Direction of beam quantization axis: The angle β between the beam quantization axis and the direction of incident momentum at the target was set to $90° \pm 1°$ (vertical plane), using a crossed-field spin precessor[5] at the ion-source output. The indicated angular uncertainty includes the effects of (a) misalignment and divergence of the ionization magnetic field at the ion source, (b) unwanted spin precession in the fringe fields of beam-transport magnets,[5] and (c) the earth's magnetic field. Since the component of polarization in the desired direction varies as $\cos\beta$, the effect of the angular uncertanity on p is negligible.[8]

(2) Polarization of the quenched beam: The quenched beam i_B is slightly polarized,[5] the value obtained during the present measurements being $p_B = -0.031 \pm 0.008$. The beam is quenched by greatly increasing the transverse dc electric field in the spin filter. Under these conditions one can argue that the quenched beam would have the same polarization as does the i_B fraction of the beam when the spin filter is set to select $m_I = \frac{1}{2}$ atoms. Comparison of the p_B observed with longitudinal and transverse quenching fields, and direct measurements of the polarization of the i_B part of the polarized beam (using ion-source conditions such that $i/i_B \sim 1.2$), confirm the validity of the argument. Thus, the value of p_Q must be corrected by the amount $p_B(i_B/i) = -0.0031 \pm 0.0008$ since $i/i_B \approx 10$.

(3) Incomplete spin filter rejection of $m_I = -\frac{1}{2}$ atoms: The resonances of the spin filter can be made sufficiently narrow[9] that overlap between the $m_I = -\frac{1}{2}$ peak and the $m_I = +\frac{1}{2}$ peak is negligible. However, insufficient rf field strength could result in the presence of a long "tail" from the unwanted $m_I = -\frac{1}{2}$ atoms, as indicated by the dashed curve in Fig. 1. That this effect is negligible under operating conditions has been shown experimentally in several ways, the most sensitive being a measurement which shows that the output current varies less than 0.05% as the spin-filter field is swept between 545 and 595 G. We therefore conclude that this effect cannot introduce a correction to p_Q greater than -0.0005 ± 0.0005.

(4) Majorana depolarization: If the field B in the source falls too rapidly between the spin filter (538 G) and the ionization region (10 G), Majorana transitions may occur between the H(2*s*) hyperfine states.[10] This effect was experimentally searched for by increasing the ionization magnetic field by a factor of 7 and reducing the atomic beam diameter by a factor of 3. No change in beam polarization was observed, indicating that within the accuracy of the measurement (0.3% statistics) no flips occur. However, to reduce the effect by at least an order of magnitude, the final 70-G field was retained. It can be calculated that the fraction of nuclear moments which undergo spin flips in the beam-transport magnets is negligible.

(5) Depolarization by electron capture and loss: Depolarization during foil stripping of the H^- beam in the tandem terminal due to the hyperfine interaction is negligible, since the time interval is less than 10^{-5} of a single H(1*s*)-atom Larmor precession period. However, the H^- electron-loss cross sections[11] are such that the terminal

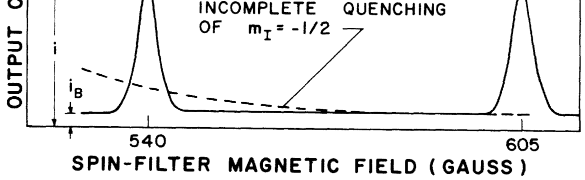

FIG. 1. Polarized source current output indicating the selection of the H(2*s*) hyperfine states.

residual gas ($\sim 2\times10^{-6}$ Torr) is expected to cause a small depolarization. Experiments involving the deliberate introduction of oxygen gas into the terminal showed that this depolarization is 0.001 ± 0.001. The 8–15-MeV H^+ and H^0 electron-capture and -loss cross sections are small enough so that similar depolarization in the tandem high-energy drift regions is negligible.

(6) Current measurement accuracy and polarization stability: Ion-source and beam-transport parameters are stable enough during the 7-sec interval required for the quenching-ratio measurement so that short-term reproducibility of ±0.001 in p_Q is readily attained. An ordinary Faraday-cup and current-measurement device is quite adequate to measure the required current ratio to this accuracy.

(7) Depolarization by collisions in argon: We consider possible depolarization arising from collisions after spin-state selection, but before negative-ion formation. One possibility would involve the formation of excited states ($n>2$) followed by decay back to the H(2s) state; this would not be expected to depolarize the beam because the ~70-G magnetic field effectively decouples the electron and the proton for quantum states with $n>2$. When the ionization field is reduced to low values (10 G), this mechanism, if present, would be expected to depolarize the beam; thus the previously mentioned tests for Majorana depolarization would have detected such an effect. Secondly, we consider the possibility of elastic spin-exchange collisions; these are forbidden at zero degrees for scattering from a spin-0 atom like argon, and impurity-gas partial pressures are negligibly low.

(8) H^--forming collision: Since the H^- ion which is formed in the H(2s)-argon collision has the (ground-state) configuration $(1s^2)^1S$, the nuclear moment is unaffected by the added electron. The only H^- excited state believed to exist, $(2p^2)^3P$, is predicted to be short lived and cannot decay to the stable negative ion.[12]

(9) Polarization enhancement by "beam scraping": The beam component originating from H(2s) atoms, i-i_B, has a smaller emittance than the component which originates from H(1s) atoms, i_B. Thus as the beam passes through the accelerator, the i_B component is preferentially discarded so that the average beam polarization increases. Ideally, p_Q should be measured at the target. However, because of the accelerator energy regulation system, a Faraday cup immediately preceding the energy-analyzing slits is the point closest to the target at which stable measurements can be obtained. The polarization enhancement between this point and the target was determined by comparison of target quench ratios and the Faraday-cup quench ratios to be $+0.0042\pm0.0035$. The ±0.0035 uncertainty, which is the dominant error in the present experiment, arises from the aforementioned interaction with the accelerator energy regulation system; it has been conservatively assigned to include the scatter of all measurements.

Incorporating all the significant corrections and uncertainties in the foregoing list, we find that the corrected on-target beam polarization is $p=(p_Q+0.0002)\pm0.0040$.

In Fig. 2, we show the uncorrected p-^{4}He analyzing power at 12.03-MeV proton energy for several angles near 112° lab. The uncorrected value for 112° lab is 0.9968 ± 0.0011, where the uncertainty represents counting statistics. Including the corrections for finite detector acceptance angle ($+0.0014$) and false asymmetries (0.0000 ± 0.0010), and the above-noted beam-polarization correction, this analyzing power becomes 0.9980 ± 0.0043. The uncertainties have been combined quadratically and apply to the absolute value.

Although it is possible that additional phenomena affecting the beam polarization have been overlooked, the sum of any such effects must either be small or must enhance the polarization, since otherwise analyzing powers greater than unity would be implied for some of our data. We therefore tentatively conclude that the quenching-ratio method permits polarization measurements to be performed with ±0.004 absolute accuracy when the noted corrections are incorporated.

By using the calibrated polarized beam, p-^{4}He

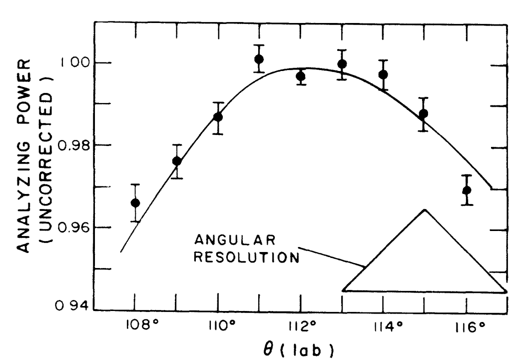

FIG. 2. p-^{4}He analyzing power at 12.03 MeV. Only statistical uncertainties are indicated. The curve was calculated with the optical potential of Satchler *et al.* (Ref. 13).

TABLE I. ^{4}He$(p,p)^4$He analyzing power.

θ_{lab}	θ_{cm}	p_Q	A_{LR}/p_Q	This Work $A(\theta)$	Other Work $A(\theta)$
			E_p = 11.93 MeV		
45.77	56.26	0.8985	-0.4018±0.0024	-0.4019±0.0035	-0.417±0.010[a]
60.77	73.57	0.8990	-0.5995±0.0023	-0.5999±0.0038	-0.605±0.018[a]
75.57	89.80	0.8991	-0.7753±0.0034	-0.7761±0.0049	-0.772±0.024[a]
94.27	108.92	0.8991	-0.0386±0.0083	-0.0384±0.0101	
109.97	123.75	0.8988	0.9860±0.0036	0.9871±0.0057	
112.47	126.02	0.8996	0.9976±0.0033	0.9988±0.0055	
115.07	128.34	0.8975	0.9778±0.0023	0.9789±0.0051	0.985±0.035[a]
159.97	164.95	0.8993	0.2345±0.0028	0.2345±0.0035	
			E_p = 9.89 MeV		
45.77	56.24	0.9018	-0.4402±0.0021	-0.4404±0.0034	-0.444±0.009[a] -0.413±0.022[b]
60.77	73.55	0.9031	-0.6364±0.0029	-0.6368±0.0044	-0.648±0.019[a] -0.626±0.030[b]
75.57	89.78	0.9018	-0.7684±0.0029	-0.7691±0.0047	-0.775±0.024[a] -0.761±0.036[b]
99.97	114.41	0.9027	0.5248±0.0063	0.5262±0.0088	0.482±0.032[b]
111.97	125.55	0.9035	0.9878±0.0028	0.9889±0.0052	
115.07	128.33	0.9054	0.9911±0.0027	0.9921±0.0052	0.994±0.033[a]
			E_p = 7.89 MeV		
45.77	56.23	0.9089	-0.4789±0.0022	-0.4791±0.0036	-0.476±0.008[a] -0.479±0.019[b]
60.77	73.53	0.9078	-0.6580±0.0029	-0.6584±0.0045	-0.659±0.016[a]
75.57	89.76	0.9071	-0.7032±0.0032	-0.7038±0.0047	-0.692±0.020[a]

[a] From Ref. 2. [b] From Ref. 3.

elastic-scattering analyzing powers were determined at several energies and angles corresponding to the most precise existing data obtained with double-scattering techniques. The results are presented in Table I, where now $A(\theta) = A_{LR}/p$. The column p_Q is the beam polarization measured by the quenching-ratio method, with no corrections noted. The A_{LR}/p_Q are the raw analyzing powers computed on line, with the indicated errors due to counting statistics only. The $A(\theta)$ are the p-^{4}He analyzing powers adjusted for the beam-polarization corrections and finite-detector geometry [using $A(\theta)$ predictions from Satchler *et al.*[13]]. The errors are quadratic combinations of statistical errors and all other uncertainties of the measurement.

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