LA-UR-80-2274

34c

CONF-800824--21

TITLE: Survey of Methods For Rapid Spin Reversal

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SUBMITTED TO: Fifth International Symposium on Polarization Phenomena in Nuclear Physics, SANTA FE, AUG, 1980

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SURVEY OF METHODS FOR RAPID SPIN REVERSAL^{*}

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ABSTRACT

The need for rapid spin reversal technique in polarization experiments is discussed. The ground-state atomic-beam source equipped with two rf transitions for hydrogen can be reversed rapidly and is now in use on several accelerators. It is the optimum choice provided the accelerator can accept H^+ ions. At present all rapid reversal experiments using H^+ ions are done with Lamb-shift sources; however, this is not a unique choice. Three methods for the reversal of the spin of the atomic beam within the Lamb-shift source are discussed in order of development. Coherent intensity and perhaps focus modulation seem to be the biggest problems in both types of sources. Methods for reducing these modulations in the Lamb-shift source are discussed. The same Lamb-shift apparatus is easily modified to provide information on the atomic physics of quenching of the $2S_{1/2}$ states versus spin orientation and this is also discussed.

INTRODUCTION

Measurement of a nuclear spin- $1/2$ effect usually involves taking part of the data with the spin aligned in one direction and part with the spin aligned in the opposite direction. If the accuracy required is 1%, or perhaps 0.1%, no difficult problems are encountered with the polarized source except perhaps in obtaining accurate spin alignment and measuring the magnitude of the polarization. On the other hand, if the target is unstable as often is the case with a polarized target, then it is useful to reverse the spin frequently.

Rapid spin reversal is a general technique that is useful where there is lack of stability and this may be present in the source, the accelerator, or the target and perhaps in all three. It is plausible that there are many cases in nuclear physics where the application of this technique would make possible measurements that are otherwise impossible. Now it happens that the development work on this technique has been almost entirely associated with parity-violation experiments and in this work the demand for extraordinary stability. Since much of that work has been done on the scattering of polarized protons off of unpolarized hydrogen atoms, consequently the difficulties encountered in these experiments has oriented the development.

Associated with spin reversal one may have modulation problems and those that are coherent with spin reversal are not rejected by the beam amplifier, or the computer - if it is elected to synchronously store the data directly in the computer. Coherent modulation problems involve the position of the beam, the direction of the beam, and the time-varying polarization of the beam. Each of these three

^{*}Presented at the 1978 Annual Meeting of the American Nuclear Society.

modulations have two directions in which to be present. Intensity and focus modulation are also problems and tend to have a related cause. The polarization profile of the beam may have a complex structure. If the polarization profile has a θ component that changes sign coherently, one is in danger of obtaining a false parity asymmetry especially if the analyzing power of the scattering gas or material is large.

One sees two philosophies among the physicists in their approach to dealing with the coherent modulation problems. Those experimentalists who are counter experts tend to treat the source as a black box and design as many methods of measuring the modulations that he can devise for his needs. During a run the measurements on the modulations are accumulated in the computer along with the asymmetry data. Associated measurements are also made on the sensitivity of the asymmetry to each type of modulation. Then in theory it is a simple computer problem in making the corrections for the modulations. While this would seem to be a straightforward process, the sensitivities are not invariant but respond to alignment adjustments and may be difficult to understand. They are certainly time consuming to measure, and one is not sure he is treating all the modulations.

So while the above process is necessary for a good experiment, some like me who are more expert on the source tend to think that the route to a successful parity experiment also depends in an important way upon reducing the coherent modulations to a small value in the source. This is the thrust of this paper.

Rapid spin reversal may not solve all the stability problems unless the beam position and direction is under control. Here again one sees two philosophical approaches. One can build good position detectors or one can build automatic steering systems that will hold the beam accurately on the target.

In association with a program using rapid spin reversal one must be aware that distortion of the polarization profile of the beam can occur both in the source, in the beam transport system and in the accelerator. These may affect the results as mentioned above.

RAPID SPIN REVERSAL WITH GROUND-STATE ATOMIC-BEAM SOURCES

The ground-state source will deliver dc beams of 20A^1 or more of H^+ ions and 100A^2 in pulses spaced far enough apart that the dissociator recovers. So for use on any accelerator that will accept its positive ion output it is the best choice by far for intensity. Even for negative ions this source is giving good performance, for example, the D^- output of the source on the ETH tandem in Zurich exceeds the D^- output of the LANS tandem source by a factor of two. We expect to hear of its performance with H^- ions.

The ground-state atomic-beam source is easy to convert to producing a beam of protons with its spin rapidly reversed by the installation of the two rf magnetic-dipole transitions between the sextupole magnet and the ionizer. Actually this is the preferred method of reversing the spin for a real usage since the operation is performed upon the ions in flight and gives no shift in ion position upon reversal. The two transitions used are the $\sigma_{\pm 1}$ which is a 150 G

static field and 1550 MHz rf field and the π_{1-3} which used a 6 G static field and a 10 MHz rf field. These rf fields can be alternated on and off rapidly so this source is simple to adapt for rapid spin reversal. Since a large fraction of these sources already have two rf transitions installed, the use of this technique is generally available.

Let us review briefly the three examples where this source has been or is in use for the parity scattering experiment using polarized protons. One experiment^{4,5} has been performed at 6 GeV/c on the Zero Gradient Synchrotron before this accelerator went out of operation last year. Many of the groups that performed the experiment are associated with the experiment at 15 MeV using the tandem at LANS and also on LAMPF Exp. No. 137 at 900 MeV. The one improvement the parity group requested was the installation of a second rf transition so the polarization could be reversed between pulses which were about 4 seconds apart. Its use was then requested by all groups doing experiments on the ZGS. Since incoherent fluctuations of beam intensity and position were quite large, they masked out any coherent modulations produced within the source. That a number was obtained was due to the counter experts having developed effective monitors for the position, intensity, and polarization of the pulses and also solving a problem involving the production of polarized hyperons that interfered in the experiment. They did make use of some beam steering for they state in their paper⁵ "The horizontal position of the beam centroid at the target was stabilized from pulse to pulse with the aid of a feedback loop". They were fortunate in that the asymmetry at 6 GeV/c is large in comparison to the experimental error that they had. They obtained⁵ $A_2 = (+3.3 \pm 0.7) \times 10^{-6}$.

Two proton-proton scattering experiments on parity violation where the accelerator is a 50 MeV cyclotron are being reported at this conference. One is a SIN⁶ in Switzerland and the other is at Lawrence Berkeley Laboratory⁷. Their preliminary experimental values suggest -3×10^{-7} , but the first number could be 0.0. The intensity achieved through these accelerators and the scattering rate achieved is large enough so statistics should not be a problem and systematic errors will likely be their big error. It is of interest to note that one group has installed fast automatic steering for both position and direction stabilization while the other group is relying upon their expertise with counters and beam scanners to handle the same problem. There is some 50 parts per million of intensity modulation present with spin reversal in this type of source and one group plans to remove the modulation at the target by controlling the intensity at injection into the cyclotron.

FAST REVERSAL IN FAST-SWIFT SOURCES

On many of the fast-swift sources in normal usage, see APPENDIX for a discussion of the LANS source, the spin is reversed by reversing the sign of the current into the spin filter. Again, since the operation is performed upon the electric field it does not change the position of the beam spot, but it does take about 10 microseconds before the current is reversed and the field is then reversed. One method of reversal

have been developed in a program started in 1972.

In the meantime, the capability of rapid spin reversal has been added to two other Lamb-shift sources. One is at the University of Washington⁸ on a tandem Van de Graaff. The other is at LAMPF⁹ in the terminal of one of the three 750 keV injectors. The LAMPF polarized source has to inject H^- ions since the polarized beam must be accelerated along with the intense H^+ ion beam. Another conversion is underway at TUNL¹⁰ and is reported at this conference. There is interest at TRIUMF in adding the capability of rapid spin reversal onto their polarized H^- source, but since the Sena¹¹ method of polarizing the beam was used, a spin filter is required too.

Since I have concentrated on the development of rapid-reversal systems for the LASL tandem Lamb-shift source, I shall primarily discuss my own developments and will refer to the other Lamb-shift source developments as seems appropriate. There have been three essentially different methods developed. In addition, there have been several hardware alterations.

The development of the LASL tandem source has been motivated by the effort to measure parity violation in the scattering of longitudinally polarized protons off of unpolarized hydrogen atoms at 15 MeV. In discussing the properties of the source, it is useful to understand a little about the scattering chamber and its use^{12,13}. The scattered protons are detected collectively by scintillators on the Up, Down, Left, and Right sides of the scattering volume. The light from the scintillators is converted into a pulse-averaged current by four banks of three photomultipliers. The currents U, D, L, and R are summed and balanced against the amplified current intercepted by five insulated plates at the rear of the target chamber. The difference signal is fed into a lock-in amplifier operating at 1000 Hz with its output read once per second by a computer. This signal averaged over a 400 second run is referred to as Y and raw data for the parity experiment is $(Y_F - Y_R)/2$. The subscript F designates that the spin filter field is forward and the subscript R designates that it is reversed.

During a run we obtain information on horizontal polarization by reading (U-D) by a lock-in amplifier and also on vertical polarization by reading (L-R) with another lock-in. If the average value or offset in Y, $(Y_U + Y_R)/2$, is significantly different from zero, it is a matter of concern for it indicates a difficulty within the source. This problem will be discussed again.

Since the asymmetry values appear to lie in the vicinity of $(-1.5 \text{ to } 0.0) \times 10^{-7}$, and the current on the target with the LASL source is about 200 nA and the fraction of the beam scattered is not large, we are discussing a very difficult experiment.

The three methods used to reverse the polarization at 1000 Hz and the successful improvements are now discussed.

RAPID REVERSAL METHOD A

The first method, proposed by R. Smith¹⁴, used reversal of the field direction in the spin cell. (The method is related to a method used in the field for flipping the spin of slow neutrons.¹⁵) The

sign of the 6 G field in the argon cell was alternated at 1000 Hz using a square-wave current supply. In one direction the field diminished smoothly from the 540 G value in the spin filter to the 6 G value in the argon cell so the spins of the atoms were not reversed. In the other direction of the argon field, there was a zero or a change in the sign of the longitudinal field about 8 cm ahead of the argon cell. Now as Sona¹¹ first pointed out, state 1 atoms will pass by a zero without a change in the sign of their spin in space. However, we wanted the spins to turn around so it was necessary to provide a transverse field to adiabatically guide them around. The field provided was a dc field inasmuch as its perturbation during the forward phase was small. While this method did reverse the spin, it was accompanied by large coherent modulations of all types, especially position modulation.

RAPID REVERSAL METHOD B

About a year later R. Mischke¹⁶ suggested that we should leave the argon field steadily on in its reversed direction and turn on and off the transverse magnetic field located about the Sona zero. While this meant rebuilding, the revision was soon completed.¹⁷ At the same time a transverse electric field was added to compensate for the quenching induced by the motion of the metastable atoms through the transverse magnetic field with $v/c = 1/1000$. We also realized that each time the transverse field was turned on it should have the opposite sign, since in theory that would largely transform the frequency of the position modulation to 500 Hz and consequently it would be ignored by the lock-in amplifier at 1000 Hz. These changes required

Fig. 1 This is a drawing of the source made in 1976 and shows it with reversal method B and the 20 K refrigerator.

an extensive revision of the electronic system by Potter.¹⁸ A feature of the method was that if the argon field was turned on with the same sign as present in the spin filter, then there could not be any spin reversal yet most of the modulations would still be present. This provided a control experiment.

This method of reversal was installed at about the same time on the polarized source at the University of Washington⁸ and it is still in regular use there.

In the summer of 1975 a 20 K helium-cycle refrigerator was installed as shown in Fig. 1; this drawing is from a paper¹⁹ delivered in 1976. This cooled copper surfaces at both ends of the argon cell to a low enough temperature to pump argon readily. It doubtlessly reduced the argon pressure in the reversal region considerably and eliminated many H^- ions from being formed there. This was important as they would have improper spin orientation and would have contributed to position modulation also. The argon cell was rebuilt at the same time and its magnetic shielding was much improved.

The refrigerator has been in regular use on the parity experiments since then. However, in making the method C revision, now to be discussed, I realized that it was only important to cool the front end of the cell. Isolation was provided by a 3-cm-diameter copper tube 8 cm long at 20 K and such additional pumping is provided inside the box of the reversal region by 150 sq cm of copper at 20 K.

RAPID REVERSAL METHOD C

In a run early in 1977 in connection with tests on Y where the scattering gas was helium with its 400 times greater analyzing power than hydrogen, we became concerned that the polarization profile of the beam was affected by the Sona zero. We had experimental results that suggested that such an effect was present and it is easy to see from theoretical arguments that a polarized atomic beam about 25 mm in diameter in passing by a Sona zero might acquire a $\hat{z}$ component of polarization. If, for example, the $\hat{z}$ component was proportional to the radius and if it reversed coherently, then the experiment was in danger from a false asymmetry effect. This is clear when one notices that the effect would reverse sign with the field in the spin filter so $(Y_L - Y_R)/2$ could be given a contribution from this effect. We had no satisfactory system in operation in the scattering chamber for detecting such an effect. This was a serious concern, so it was decided to redesign and rebuild the reversal region in a manner that would assure us that the effect could not be present.

A possible solution seemed to be to place the reversal field in a region which is sufficiently shielded so that no other magnetic field is present. The spin could now be processed in a manner that does not generate a $\hat{z}$ component. Then if we can solve the problem of getting the beam from the spin filter into the shielded region and again back out through the magnetic field in the argon cell without creation of a $\hat{z}$ component, we would have a solution to the entire problem.

To provide an adequately shielded region, 100 gauss was required. This was provided by using the spin filter forward "B"

from the position in the vacuum case shown in Fig. 1. Then using mu metal to form a shielded region for the transverse field device, a space 11 cm long in which the stray field was less than 0.06 G was constructed. Since it takes a 11-G-cm field to precess the spin of a 500 eV hydrogen atom by 180° , the region seemed close to being ideal. A coil located at the front end of this region provides correction for the small effect observed on the spin by the stray field.

Let us now consider the problem of getting the spin from the 540 G field in the spin filter into the mu metal box with zero field on its interior. The field is decreased exponentially in 16 cm from the spin filter to a value in the range of 1 to 5 G in front of the reversal box. This presents no problem since spins stay aligned adiabatically; however, we can calculate from the divergence theorem that those atoms on the outside a 25-mm-diameter beam will have their spins tipped outwards by 10° . That gives a trivial decrease in polarization since $\cos 10^\circ = 0.985$. The tricky step to understand is the passage from the low field in front of the box into the zero field inside the box since that involves a diabatic transition. It was elected to place a magnetic grid at the opening into the box. It is a simple calculation to determine the effect on the spin of an atom in passing from a 3 G field into the zero field on the inside. If it goes through a 2.4-mm hole one can see that those atoms that pass through on the outside of the hole will have their spins precessed the most but the magnitude is quite small.

A 25-mm-diameter pattern of hexagonal holes was fabricated into a 2-mm thick disk of mu metal. Diametrically across the center hole of the disk was bored a simple 25.4-mm hole. Either the grid or the hole could be rotated so the beam could pass through while the source was in operation with 100 kV potential on it by a shaft through the vacuum wall. With the Wien processor set so the polarization was transverse at the target chamber and with helium gas in it, it was a simple matter to optimize the polarization. The main adjustment was the field from a coil just in front of the box. With the grid at the opening the optimum field was 3 G, but with the hole in the disk at the opening the optimum field was 1 G. Curiously, the polarization was 2% greater with the 25.4-mm hole there. So one wonders why he should accept the 13% loss of intensity produced by the grid of hexagonal holes?

Any θ component of polarization present in the atomic beam is cleared out by the magnetic field in the argon cell and to increase the clearing we have been using a 12 G field there. The transverse component of the spin of metastable atoms is precessed until they are transformed into a H^- ion--up to 18 revolutions if it travels the full 33 cm of the cell. The result is that any transverse or θ component of spin is well cleared out.

There remains the small possibility that a θ component can be produced on atoms that are transformed into H^- ions near the front end of the argon cell. This effect is easily counteracted by taking one half of the data with the argon field in one direction and the other half with the spin in the other direction. Fortunately, the sign of this field relative to the sign of the field in the spin filter is completely arbitrary and it makes less than 0.1% difference

in the polarization measured. We are now confident that no θ component of polarization is introduced into the H^- beam.

There are three small coils surrounding the 8-cm-long copper tube at 20 k between the reversal region and the argon cell. It has been observed that the introduction of a small field in any one of these coils slightly increases the polarization measured in the target chamber if the field is of the same sign as in the argon cell.

A drawing showing the TUNL source revised so as to produce a H^- beam with the fast reversal of the spin is shown in Fig. 2 of a paper submitted by T. B. Clegg et al.¹⁰. A drawing of the LAMPF source which contains many of the features just described has been submitted by E. P. Chamberlin et al.⁹.

FABRICATION OF THE TRANSVERSE-FIELD DEVICE

The generation of a transverse magnetic field at 1000 Hz with a clean square-wave profile requires fabrication of a device with quite special properties. An associated complication in its design is the need of generating a longitudinal magnetic field at the same location at times for experiments not requiring fast reversal. I have developed one design and E. P. Chamberlin has developed another design and it is in use in the LAMPF source. My design was also influenced by the desire for a device capable of precessing the spin of atoms up to 10 revolutions for studies in atomic physics.

The LAMPF uniform transverse field has been produced by a winding of a special shape on the surface of a cylinder. Conducting lines have been produced by photochemical means on the surface of an insulating sheet and it was then wrapped on the surface of a cylinder. A difficulty I see in this approach is that magnetic shielding is required outside of the cylinder and eddy currents will be induced and cause a slow change in the field unless the shielding is distant from the cylinder.

The tandem-source transverse-field device was made with a sequence of rectangular toruses of commercial sheet 0.1 mm thick, a well outgassed material similar to mu metal. These were separated by G-10 fiber-glass plastic 2.5 mm thick. By careful adjustment of the winding the field was made uniform over the cross section of the atomic beam to 2%. The eddy current problem is small enough that the reversal is 97% complete in 20 nsec as has been determined by use of a standard inductance as a pickup coil. (This was hooked to a special operational amplifier whose circuit²⁶ includes positive feedback that can be adjusted to neutralize the resistance of the pickup coil. The reversal field pattern can now be observed on an oscilloscope.) While eddy current is not a problem in this design, hysteresis has been a bigger problem than anticipated and the use of a small compensating dc current is clearly indicated when the display of the polarization signal is observed on an oscilloscope.

COHERENT POSITION MODULATION AND BEAM STEERING

Coherent position modulation is now used from signals out of four insulated quadrants that the beam strikes at the rear of the

target chamber. In the last run no correlation with the source could be demonstrated and this represents progress because it has been a troublesome problem in the past.

Beam steering, while not a direct topic of this paper, probably will play a role in any experiment where rapid spin reversal techniques are required--it certainly does in the parity experiment.

During the entire series of runs the target chamber has been located so the beam passes directly from the tandem Van de Graaff into it. Beam stability was considered much more important than energy stability so the energy analyzing magnet was bypassed.

A fast steering system was installed quite early. It holds the beam accurately in both position and direction. Moreover, 1000 Hz signals can be introduced into the system to determine the sensitivity of Y to either position or direction modulation.

Position steering is applied magnetically by coils on the outside of a glass pipe located about 50 cm downstream from the quadrupole lens at the high energy end of the tandem. The steering signals are obtained from the four insulated quadrant plates located on the rear end of the target chamber. The system holds the beam in position at the target chamber to a few microns.

Direction steering is accomplished by electric dipole fields applied to the beam just before it enters the tandem and near a focal point in the beam. The signals are obtained from four insulated jaws located near the same high energy quadrupole. They have recently been given more isolation from the magnetic steering coils so there is no longer any cross talk to the insulated jaws.

COHERENT POLARIZATION MODULATION

Fortunately, polarization modulation is not a large effect in the 15 MeV experiment since the analyzing power of the chamber filled with hydrogen is only about 0.1%. Therefore, we normally make adjustments on the source with it filled with helium for then we have the benefit of analyzing power of 40%.

To accurately maintain spin alignment with the beam during a parity run we now use a specially developed precision regulator²¹. These regulators hold the current into both the precessor magnet and the inflection magnet to one part in 10,000 during a run.

We did have a problem with distortion of the polarization across the profile of the beam that occurred in the 30 cm of space between the Wien precessor magnet and the 58° inflection magnet. The spin of a H^+ ion is necessarily orientated about 40° from the beam direction in this region so the longitudinal field components generated by the pole edges produced distortion of the polarization. The stray field effects were balanced out by a setting of the precessor that gave both spin alignment at the target and the fields on the pole edges were of the same sign and about the same magnitude.

Rapid-reversal method C allows tests to be made on the sensitivity of Y to transverse polarization without disturbing the adjustment of either the precessor or the beam transport line through the tandem. If the current in the argon cell is turned off, the magnetic shielding in the argon cell is sufficient that the spin of a hydrogen atom is

Fig. 2 Oscilloscope display of the analog signals on polarization from the target chamber. The upper trace is the (L-R) analog signal or the vertical polarization. The lower trace is the (U-D) analog signal or the horizontal polarization. The overshoot pulses on the leading edge is an artifact of the special circuit used to separate these currents out of the normally summed currents. Note that the width of the lines are small indicating excellent statistics.

only slightly perturbed in traveling through the cell. If one adjusts the current into the spin reversal device so that the spin is flipped between $+90^\circ$ and -90° , then one has a transversely polarized beam at 1000 Hz as is displayed in Fig. 2. Adjustment of the small current into any one of the sequence of three field coils surrounding the 8-cm-long copper tube at 20 K can easily change the polarization direction from horizontal to vertical. This current had been adjusted when the picture of Fig. 2 was taken so that the polarization was all in the vertical direction. In the usual adjustment of the source before a run, one sets 10-turn potentiometers to provide the correct current for both vertical and horizontal polarization. This allows selection of the polarization direction by a switch in the control room. Another switch turns off the argon field and other switches select the reversal patterns. By the use of four switches it is a simple matter to check the sensitivity of Y to coherent polarization modulations in both directions and return to running.

COHERENT INTENSITY AND FOCUS MODULATION

There are still two bothersome coherent modulations present: one involving intensity and the other apparently involving the focus of the beam. They are discussed together because their cause seems to be related. The intensity modulation at times has been observed to be in the range of several hundred parts per million and that struts the

capability of the compensation system used in the experiment.

The main cause of the intensity modulation that we have now appears to be coherent space charge modulation. Electrons are released in the argon cell by collisions of the atomic beam with the argon atoms, but the electrons are confined by the magnetic field of 12 G so their escape is largely from the ends. The escape route back through the reversal region is modulated off and on by the presence or absence of the reversal magnetic field. The sign of the modulation observed in the lock-in amplifier indicates that the presence of the electrons increases quenching.

Associated with this type of space charge modulation one must expect focus modulation. The space charge must be expected to affect the trajectories of the H^- ions formed at the various places along the argon cell. The sign and magnitude of the focus modulation must be expected to depend upon the ratio of the two dc voltages that affect the focus at the first aperture the beam passes through. At the optimum focus the coherent modulation should be zero.

Unfortunately, we do not have a good detector for focus modulation. The offset in Y or $(Y_F + Y_R)/2$ does at times have an unreasonably large values and one can understand why the scintillators on the side of the scattering volume should be sensitive to the diameter of the beam. On the other hand, the parity asymmetry is $(Y_F - Y_R)/2$ and focus modulation does not affect that result. If there are erratic changes in focus modulation there might be an effect on the result.

An effect that produced a sizable offset in Y was observed late in 1976 during a test where helium was being used in the scattering chamber. The effect was traced to 6 keV electrons originating upon or near the accel electrode inasmuch as the effect went away when magnetic deflection of the proper magnitude was used. The transverse field coils were located on the downstream side of the separation wall; unfortunately, the coils do not show in Fig. 1. The 1.3-mm-id tube does show and the effect went away when the magnetic field was sufficient to deflect 6 keV electrons into it. The field required for 180° rotation of the spin deflects these electrons by 7.5° and that would largely keep them out of the argon cell.

The electron current from the accel electrode can obviously produce a tiny θ component of field within the argon cell during the 0° phase of the reversal current. The spins of the H^- ions are given this θ component since the spins of the atoms are adiabatically in alignment with the net field direction upon conversion to H^- ions. This suggests that the offset value of Y is very sensitive to a θ component of polarization. Note that one sign of a θ component increases outscattering and the other sign decreases it.

There have been measurements in Exp. No. 137 at LAMPF at 800 MeV that suggests the presence of an offset in Y . Their target has as high an analyzing power as does helium at 15 MeV. While the reversal is by method C in the LAMPF source, they have kept the sign of the argon field to always be the same as in the spin filter field so they may be seeing such an effect. While what I have just said does not prove that they do have such an effect, it does suggest tests that need to be made. It probably does not explain the "focus modulation" problem that we have been having at the tandem but again it suggests

tests. The reflection of the electrons produced inside the cell does affect the net current within the cell, but since we observed the effect with hydrogen in the chamber it is doubtful if we could have seen such an effect.

RECENT EFFORTS ON REDUCTION OF THE MODULATIONS

An effort was made during the last run to reduce the modulations by using double frequency on the spin reversal and consequently double frequency in the detection. This was developed by Potter²² who deduced from the theory of Walsh Functions²³ that it would be useful in reducing errors that are due to incoherent sources. So we made runs in which we had 137 Hz spin reversal along with the 1000 Hz, and an equal number where we used 1000 Hz alone. Alternating reversal is used at both frequencies, for example spin rotations of 0° , $+180^\circ$, 0° , -180° , 0° , etc. are used. It is possible to operate in this manner for $\pm 360^\circ$ precession and 0° precession are equivalent as far as the effect upon the spins of the atoms. There was no noticeable difference in coherent position modulation or coherent polarization modulation. The use of the two frequencies did give a significant reduction in intensity modulation and in the offset in Y. The escape of electrons should have been cut in half by the use of two frequencies since one half of the 0° phases have been replaced by $\pm 360^\circ$ phases.

This has suggested an idea on eliminating the modulations by eliminating the 0° phases entirely. We can do this at 1000 Hz alone and the precession sequence could be $+360^\circ$, $+180^\circ$, -360° , -180° , etc. One suspects that the success of such a cycle depends mostly upon the escape of the electrons from the argon cell being equally blocked by the 180° phase as by the 360° phase.

Another idea in reducing these effects is to locate an electrical grid between the spin reversal device and the 20 K pumping surface. A bias of -10 to -20 volts will keep the electrons from escaping from the argon cell but the associated fields will introduce some quenching. The quenching will not introduce a coherent component into the intensity since the axial magnetic field is close to zero at this location.

QUENCHING OF METASTABLE ATOMS VERSUS SPIN ORIENTATION

We have observed interesting effects upon the quenching of the metastable atoms after they have undergone spin precession. The quenching is introduced into the source by a transverse dc field located at the front end of the argon cell. The electrodes are formed out of an aluminum cylinder 5 cm in diameter and 2.5 cm long that has been cut into quadrants. It is easy to produce either a horizontal or a vertical field by application of about 200 volts across a pair of opposing electrodes, enough so about one half of the beam is quenched. The intensity of the H^- ion beam from the source that is coherent with spin reversal is observed with a lock-in amplifier. In making the observations it is useful to ramp the magnitude of the 1000 Hz alternating reversal current. We produce graphs of the effects on a plotter by connecting the output of the lock-in to the Y axis and a signal proportional to the ramped reversal current to the X axis. The

graph displays the difference in intensity at X revolutions to the intensity at 0° where X is continuous from 0 to perhaps 10 revolutions, but we usually use about 4 revolutions.

If the 12 G axial field of the argon cell is also present at the quenching plates, one sees a large effect depending upon the orientation of the spin relative to this field. This is easily explained because when one calculates quenching, one finds a term in the denominator that depends upon the energy difference between the levels as seen as a function of the magnetic field in a Breit-Rabi diagram. The observed effect is useful in making adjustments upon the source in that it can be done without further acceleration of the beam; however, interpretations of the observations are not as easy as in the case of the target chamber filled with helium and bombarded with 15 MeV polarized protons.

If one turns the magnetic field about the electric field plates to zero he sees that there still are significant effects present although of lower amplitude. These depend upon whether the spins of the atoms are parallel or normal to the electric field that is doing the quenching. In general, this happens twice per revolution. Curiously, the effect is present in state 2 with twice the amplitude and with the opposite sign as in state 1. The effects in both state 1 and 2 have been explained by Ohlsen²⁴ on the basis of the transitions that are allowed in the different directions of the electric field relative to the spin orientation and van Dyck²⁵ has verified the observed graphs with computer calculations based on Ohlsen's explanation. However, there are small differences between $n + \frac{1}{2}$ revolutions and $n + 3/2$ revolutions where $n = 0, 1, 2$, etc.. These have not been explained although they are clearly visible. One can speculate that they are due to the interference of the $2P_{3/2}$ into the $2P_{1/2}$ amplitude in quenching but no one has made this difficult calculation.

A third effect shows up in these graphs; however, it shows up more clearly where the transverse polarization observed in the target chamber is plotted against the spin rotation. The percentage of the polarization decreases with each successive 180° rotation starting with 90° until it passes through zero near $3\frac{1}{2}$ revolutions and starts to build up again. Apparently in the spin reversal device of the length chosen to be used in this source, the protons spin falls 90° behind the electron spin by $3\frac{1}{2}$ revolutions and then builds up in the opposite phase as the number of revolutions is increased a little more. This effect has also been verified by computer calculations by van Dyck and is related to effects reported by van Dyck et al.²⁶ at this conference.

A FALSE PARITY ASYMMETRY EFFECT IN BOTH TYPES OF SOURCES

In the study for this paper, I have become aware of an effect that is present in both the ionizer of the ground-state source and in the argon cell of the Lamb-shift source. It has to do with the fact that in general the ions are formed from the atomic beam at some finite radius to the axis of the solenoid. The ions in crossing at the end of the solenoid have to cross lines of force with their number being proportional to the field strength times the radius. (A spherical

phenomenon in regard to the emittance of an ion beam generated in the same manner has been discussed by Ohlsen et al.²⁶⁾ The crossing of the lines of force will impart a θ component to the polarization in the profile of the beam and this may generate a false parity asymmetry as has been explained above. Reversing the field in the ground-state ionizer does eliminate the effect upon the results since both the spin and the radial lines of force are reversed at the same time. This is also true in the Lamb-shift source if the argon field is reversed at the same time as the spin filter, but if the averaging procedure recommended in method C is followed the effect on the results disappears. It would seem likely that the θ profile would be well scrambled if the beam is sent, for example, through a 50 MeV cyclotron. On the other hand, if the experiment on parity were attempted again on the 12 MeV tandem at the ETH in Zurich attention would have to be given to this problem. The practice on Exp. No. 137 in use of the LAMPF source has been such that this problem needs to be considered there too.

CONCLUSION

The technique of rapid spin reversal is effective in solving stability problems both in the ground-state source and the metastable-state source. The much greater intensity of the ground-state sources has resulted in greater intensity on targets where the accelerator can accept H^+ ions. Both sources have coherent intensity and perhaps coherent focus problems. The problems remaining on the Lamb-shift source seem solvable and the author hopes to see this done soon in spite of his retirement. There is much work to be done in nuclear physics using these techniques and I suspect the parity experiments will proceed for some time and by different groups before the results needed will be obtained to tie down the parity asymmetries.

ACKNOWLEDGEMENTS

The author acknowledges help and support from R. Hardekopf and G. Ohlsen. J. Potter developed essentially all of the electronics used in the source for rapid spin reversal with the assistance of T. Lopez. The experimental group on the parity experiment have made contributions. The present groups are: D. Nagle, R. Mischke, C. Hoffman, D. Bowman, R. Carlini, and J. Potter at LASL, H. Frauenfelder, V. Yuan, and R. Harper at the Univ. of Illinois; and J. Zyskind at Cal. Tech.. The earlier contributors are noted in references 12 & 13.

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APPENDIX, NORMAL OPERATION OF THE TANDEM LAMB-SHIFT SOURCE^{19,20}

The source as shown in Fig. 1 can easily be adjusted to operate in the normal manner. The axial magnetic field is diminished in a smooth manner from the 540 G present in the spin filter to 6 G in the argon cell with both fields of the same sign. The use of the 20 K pumping is not required and the spin reversal system is turned off.

A beam of protons at 500 eV, from a duoplasmatron and a -6 kV accel-decel system, is sent through a cesium vapor curtain. In it according to Pradel et al²⁹, at optimum density about 1/3 of the protons become metastable atoms, about 1/3 become ground-state atoms, and most of the rest remain protons. 1% or so of the protons are transformed into H^- ions, much more if the cesium is denser.

The beam is next sent through a tube about 15 cm long with its inside diameter tapered from 10 mm to 15 mm. It has a few volts negative bias which peels off the electron space charge. The electric field produced by the proton space charge causes the proton beam to blow up and impinge into the tube. The associated quenching is small since the field is small. The beam that emerges is largely atomic with an estimated equivalent current of 100 μA and approximately equally divided between metastable atoms and ground-state atoms.

The beam next passes through the spin filter³⁰. This device quenches, or causes decay to the ground state of essentially 100% of three of the four states in the $2S_{1/2}$ atomic beam with the fourth being transmitted at 80 to 90% efficiency. State 1 is transmitted at 540 G and state 2 at 604 G. The metastable beam now has an estimated equivalent current of 10 μA with 100% polarization and the ground-state beam is 90 μA . The unpolarized H^- ions formed in the cesium and the remaining H^+ ions are deflected out of the beam by a transverse electric field which is essential to the operation of the spin filter.

In the argon cell about 4% of the metastable atoms make collisions that form H^- ions and these are 100% polarized. However, over 0.05% of the ground-state atoms form H^- ions and these are about 3% polarized in the opposite direction³⁰ and are scattered at much larger angles in formation. The 500-eV H^- ions are now accelerated to about 7 keV through a lens that focuses them on an aperture, usually one 1.8 mm id. This scrapes off some of the polarized beam but a much larger fraction of the unpolarized beam.

The body of the source is normally operated at 100 kV and the H^- beam is sent through a Wien processor before being inflected into the beam line of the tandem with a 58° magnet. If the source is working well, the output may be 400 nA at 86% polarization measured in the cup in the middle of the processor and 270 nA at 80% polarization measured in a cup that the accelerated beam can strike.