Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

Polarized Negative Ions Produced by Charge Exchange Process*

Invited Paper

C. W. Drake, Jr. and R. V. Krotkov

Yale University

This paper will describe a measure of the deuteron tensor polarization of a beam of negative ions produced by charge exchange methods. The polarization is produced by making use of the properties of the metastable n=2 state in hydrogen or deuterium.

That a beam of polarized atoms could easily be produced from a beam of metastable hydrogen atoms was pointed out by Lamb in the first of his well-known series of papers on the hydrogen n=2 fine structure in 1950.[1] The possible use of n=2 state hydrogen atoms was noted by Zoroiskii[2] in 1957. The use of charge exchange to produce intense metastable beams of fast atoms was proposed and seriously worked on by Madansky and Owen[3] in 1959, who used 5 kV protons on H_2 to produce a metastable beam. They attempted to ionize selectively the metastable beam by photoionization but the ions from their metastable beam were overwhelmed by ground state atoms ionizing by collision with the background gas. Alexeff[4] at Zurich in 1960 attempted to charge exchange strip the atoms in H_2 at about 500 eV assuming that the n=2 stripping cross section would be larger than the n=1, however the production of metastables in H_2 was insufficient.

The charge exchange method showed promise when Donnally[5] of Lake Forest College showed that by using cesium as the charge exchange medium large fractions of n=2 atoms could be produced at about 1 kV. This favorable situation with Cs results from the near energy equality of the $H^+ + Cs$ initial system with the final $H(n=2) + Cs^+$ system. This implies a large cross section at low energies where the cross section for making $H(n=1)$ is small.

Donnally[6] also showed that metastable atoms can be selectively charge exchange ionized to negative ions in argon gas in a reaction showing a resonance at 500 volts for hydrogen, 1000 V for deuterium. The process is quite selective, the process for ground state atoms is much less. The choice of the negative ion was made primarily for use in a tandem Van de Graaff. The resonant process $H(n=2) + A \longrightarrow H^- + A^+$ can be qualitatively explained as an energy level crossing between the systems of $H(n=2)+A$ and $H^- + A^+$ as a function of internuclear separation. The levels are actually repulsive in detail but non-adiabatic transitions can be made according to the theory of Landau-Zener.[7] The transition probabilities are velocity dependent giving resonant effects.

An explanation of the method of producing a polarized deuteron beam can best be shown by an examination of the level structure of the n=2 state of hydrogen. Figure 1 shows the $^2S_{1/2}$ and $^2P_{1/2}$ states as a function of magnetic field including the β-e crossing at 575G (the labels are as used by Lamb[1]). In addition there is a $^2P_{3/2}$ level 10,000 mc higher; the $S_{1/2}$ and $P_{1/2}$ are separated by the 1000 mc Lamb shift. A detailed picture including the hyperfine structure is shown at upper right of Fig. 1, as well as a detailed view of the crossing at the lower right. It can be seen that the β-e crossing is at high magnetic field with respect to the hyperfine interaction. If an electric field is applied, S and P states will be mixed approximately proportional to the electric field strength and to an energy denominator proportional to the S-P separation. Therefore near 575 G a small electric field strongly mixes the β-e states but the α state retains its S state character. Since the P states have a lifetime of about 10^{-8} sec as opposed to about 1/7sec for the S state at zero field, the β state atoms are promptly quenched to the ground state leaving polarized metastable atoms.

A diagram of the apparatus is shown in Fig. 2. I.S. is an rf ion source of 1 kV deuterons; L-1 and L-2 are Einzel lenses; Cs is a Cs cell; S are deflecting plates with a small E field to remove charged particles emerging from the cesium cell; P is the 575 G longitudinal field with quenching plates; T is a transition region in which the magnetic field is shimmed to drop approximately exponentially to the 1.8 G field at the argon cell A. It is difficult to bring the

Reprinted from IEEE Transactions on Nuclear Science NS-13 (4), Aug 1966

polarized atoms from the 575 G polarizing field to the low ionizing field without causing non-adiabatic transitions between the α and β state due to the time varying transverse magnetic fields seen by the atom. We estimated these transverse fields due to the longitudinal field gradients and calculated the expected transition probabilities. We tried to minimize the predicted non-adiabatic transitions by a smooth drop.

The argon cell A is followed by a 90° electrostatic analyzer, a 130 kV accelerating tube and a tritium-titanium target. The nuclear tensor polarization of the deuterons can be measured by the neutron asymmetry between counters at 0 and 90° with respect to the polarization axis when the $T(d,n)He^4$ reaction is used.[8] The ease of this reaction is the reason for using deuterons.

The polarization is transferred from the atoms to the nucleus in a weak field through the hyperfine interaction. A tensor polarization parameter P_{33} of -1/3 results at zero magnetic field from a pure α beam. The D^- ion is in $^1S_0$ state so no hyperfine interaction exists to perturb the nuclear polarization.

The instrumental asymmetry was measured by increasing the magnetic field in the argon chamber to 50 G, reducing the deuteron polarization to effectively zero. With no Cs or A in the cells and with all fields off, the positive ion current at the target was 1.5×10^{-7} A or 1.8×10^5 cpm in either counter.

It should be noted that we did not try to get a high positive beam. We were only interested in getting sufficient signal to measure easily.

The current of negative ions due to metastables was obtained by taking a quenching curve as shown on Fig. 3. The characteristic quenching voltage is 39.6V. It can be obtained from theory and geometry and is computed to be 40V. As a measure of the metastable current we took the difference between the counting rates at quenching voltages of 0 and 200.

At a fixed cesium temperature the metastable signal as a function of argon pressure is shown in Fig. 4. The peak occurs at 15×10^{-3} torr/cm of argon.

Figure 5 shows the dependence on Cs pressure. The solid curve is the negative ions due to the total metastable signal α's and β's, the dot-dash is that from the α's only, and the dashed is an indication of the ground state beam.

The peak counting rate corresponded to a deuteron current of 4×10^{-9} A on the target or about 2% of the positive ion current measured at the target with no cesium, argon or deflecting or quenching fields. At this intensity the tensor polarization was -0.19 ± 0.01. The error is one standard deviation from counting statistics. This number includes the effect of negative ions made by ionization of ground state atoms. If the asymmetry is taken after subtraction of the counting rate which is obtained with the quench field at 200 volts, the resulting tensor polarization is that possessed by those deuterons which became negative via the metastable atoms. The tensor polarization is -0.23 ± 0.01. The ratio of these two polarizations is consistent with that expected from a measurement of the counting rate with all metastables quenched.

It was found that the measured values were insensitive to Cs and A pressure over charge in Cs and A pressure great enough to give a factor of two drop on the signal. The tensor polarization of -0.23 for those deuterons made via metastables is to be compared with the expected value of -0.33. It was found that turning off the exponential shim fields reduced the polarization to essentially zero. This is consistent with estimates of the depolarization induced by the fringing field of the solenoid. However it appears that either our practical approximation to an exponentially decreasing field was inadequate or that our numerical estimates of the depolarization introduced by this field are unrealistic. Neither of these can be ruled out.

We are now doing experiments using rf methods to select a particular hyperfine state which produces higher polarization and permits high field ionization and thus eliminates the non-adiabatic transition problem.

It should be said also that Cs is an efficient converter of incident deuterons into negative ions; at 1 keV as much as 25% of the positive ion current is converted into negative ion current at 18×10^{-3} torr/cm of Cs.

---

* Research supported in part by the U.S. Atomic Energy Commission.

References

1. W.E. Lamb and R.C. Retherford, Phys. Rev. 79, 579 (1950).

2. E.K. Zoroiskii, Zh. Eksperim i. Teor. Fiz. 32, 731 (1957). English Transl.

Soviet Phys. JETP 5, 603 (1957).

3. L. Madansky and G. Owen, Phys. Rev. Letters 2, 209 (1959).

4. I. Alexeff, Helv. Phys. Acta. Supplm VII, 134 (1961).

5. B.L. Donnally, J. Clapp, W. Sawyer, and M. Schultz, Phys. Rev. Letters 12, 502 (1964).

6. B.L. Donnally and W. Sawyer, Phys. Rev. Letters 15, 439 (1965).

7. L. Landau, Physik. Z. Sowjetunion 2, 46 (1932); E.C.G. Stückelberg, Helv. Phys. Acta 5, 369 (1932); C. Zener, Proc. Roy. Soc. A137, 696 (1932); D.R. Bates, ibid A257, 22 (1960).

8. A. Galonsky, H.B. Willard and T.A. Welton, Phys. Rev. Letters 2, 349 (1959).

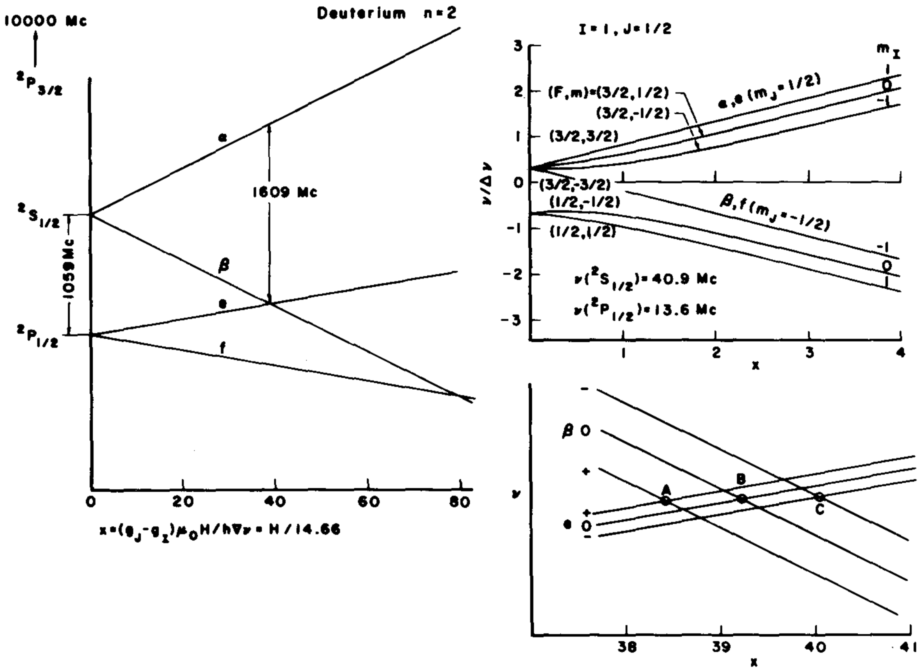

Fig. 1. The energy levels of the n=2 state of deuterium as a function of magnetic field. On the right are the details including the hyperfine structure of the zero field and β-e crossing region.

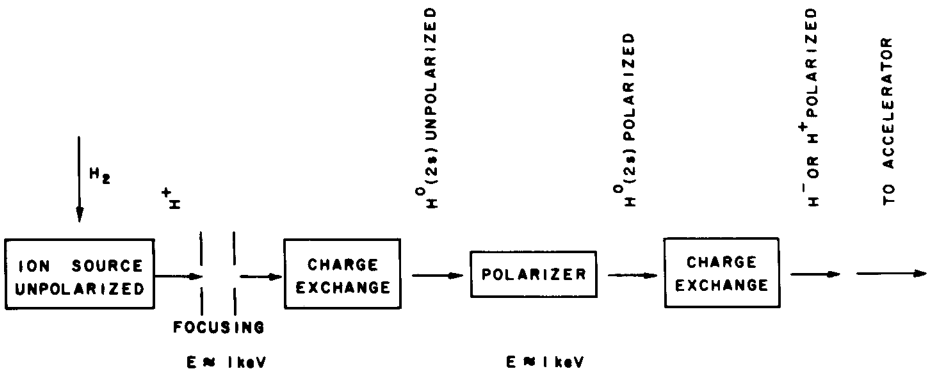

Fig. 2. Diagram of the apparatus.

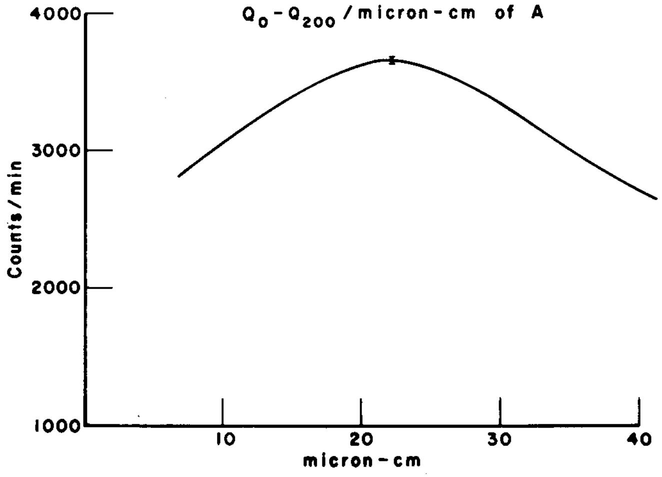

Fig. 4. Pressure dependence of the matastable beam on argon pressure in the argon cell.

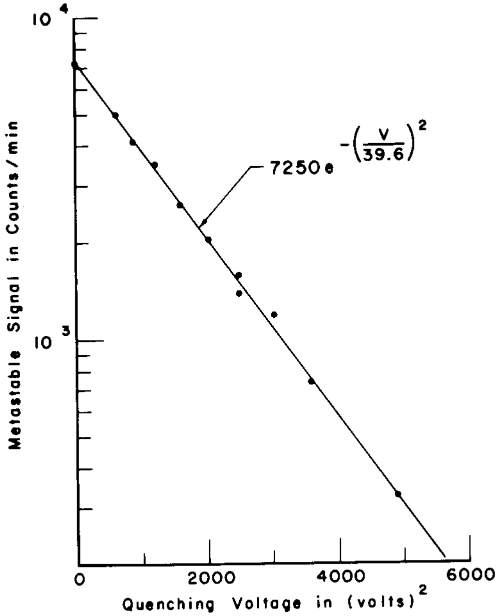

Fig. 3. Metastable quenching curve. The expected dependence on quenching voltage is const. x exp $(-V^2/Q^2)$ where Q is computable from theory and geometric factors. The computed value is Q=40 volts.

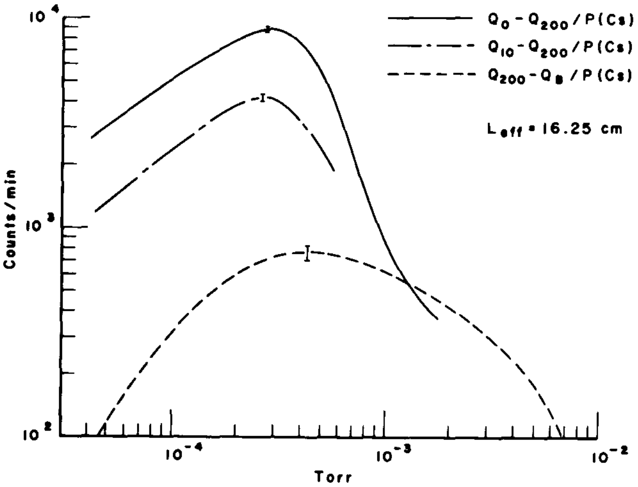

Fig. 5. Pressure dependence of the metastable and quenched beam on cesium vapor pressure in the cesium cell.

DISCUSSION

CRADDOCK: Please comment on the intensity of the beam, the conversion coefficients in the gas cells, and the possibility of improving the intensity.

DRAKE: It is difficult to say which is which. There seems to be about 10% efficiency in both the gas cells. The possibility of increasing the intensity depends on how conservative you are.

In our apparatus, which was strictly a laboratory apparatus for measuring the polarization and not intended as a working ion source, we could easily increase the intensity a factor of 10. This is a matter of increasing the positive ion current, presuming the ratio would stay the same, up to a point. I don't see any reason why we couldn't increase the intensity by a factor of 100. Then difficulties occur. With more elaborate apparatus, such as is being constructed at Los Alamos by Joe McKibben, a factor of perhaps 1000 is possible.

At some point, where the positive ion current is about 100 μA, one runs into difficulty in which the fields, due to the charge, begin to quench the ions. Then, more elaborate procedures of charge neutralization and so forth must be considered; we haven't thought of this, much.

CONZETT: Can currents of positive ions be polarized by this method in the same amounts, or even larger amounts, as negative ions?

DRAKE: It doesn't seem that way yet. There hasn't been a good charge-exchange process tested to convert the polarized metastables into positive ions. It has to be a process that selects the metastable atoms over the ground states, such as the inverse of the pickup process, that is, by the use of Cs^+. But Cs^+ gas is hard to come by. There are probably others that we don't know of, yet.

Reprinted from IEEE Transactions on Nuclear Science NS-13 (4), Aug 1966