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LAMB-SHIFT SOURCES
RELIABLE VERSATILE SOURCES FOR LOW ACCEPTANCE ACCELERATORS

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ABSTRACT

The present performance of Lamb-shift polarized ion sources is reviewed. There are several accelerators where polarized H^+ or D^+ currents of .5 to 1 μA on target are obtained routinely. A systematic analysis of this type of source is attempted, which shows that polarized beam intensities of several microamperes on target should be obtainable in the near future.

INTRODUCTION

Lamb-shift sources are routinely operated in many laboratories for the production of negative polarized hydrogen or deuterium beams. They can deliver these beams either in pure hyperfine states or with pure vector or tensor polarization and they have a small emittance. Although there was considerable effort in several laboratories, progress in the polarized beam intensities from this type of source seems to have been more slowly and difficult in the last years. Sometimes it was also the successful routine operation which impeded further improvement.

There are many excellent review articles on Lamb-shift sources, for example those of T.B. Clegg [1], [2]. Therefore I will only mention the components of this type of source, as shown in Fig. 1. Starting point is a positive ion source including a beam formation system where a H^+ or D^+ beam

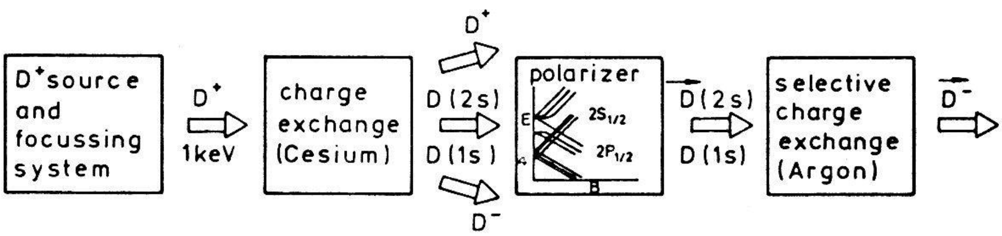

Fig. 1 Schematic drawing ot the components of a Lamb-shift source for negative deuterium ions

is produced with an energy of 500 eV per nucleon. This beam is charge exchanged in cesium vapor to different components of which only the metastable one is useful. The charged particles are deflected out by electric or magnetic fields and the metastable component is polarized by quenching the unwanted hyperfine states to the ground state either by a spin filter or by a Sona transition. The polarized metastable fraction is then ionized in argon gas with a strong preference compared to the - essentially unpolarized - ground state fraction. So a negative beam is obtained with a polarization depending on the relative contribution of the ground state.

REVIEW OF PRESENT PERFORMANCE OF LAMB-SHIFT SOURCES

Since the Vancouver meeting in 1983 some progress has been achieved in several Lamb-shift sources. In the Fukuoka source [3], [4] quenching effects in the cesium charge exchange have been reduced by inserting grounded metal plates in the center of the cell and by improving the magnetic deflection of the charged particles after the cesium, thus reducing the loss of electrons which are needed for space charge compensation. Furthermore, a cryo panel in the argon region was removed because quenching from surface charge up of the frozen argon had been observed. At the Munich source [5],[6] the Wien filter for spin rotation was completed and routine operation at the Tandem was started in Oct. 1984 with two maintenances since then (April and Dec. 1985). The expected reduction of the cesium consumption was not observed due to Cs^+ extraction into the lens system. The polarization from quench ratio was found to be accurate within 1% for hydrogen and too large by 5% for deuterium. Improvement in the Los Alamos source was achieved by removing the rapid spin reversal thus shortening the drift space of the neutral particles (from Cs to Ar) and the Vancouver source has been improved by modifications in the extraction region of the duoplasmatron.

In any Lamb-shift source higher beam currents are connected with lower polarizations. Therefore in Table I polarized beam intensities are given for reasonable polarizations. (Spin filter operation uses one hyperfine state whereas Sona operation uses two for H^- and three for D^- respectively.)

Table I. Performance of several Lamb-shift sources (Jan. 1986)
Given are: polarized negative current from source, polarization from quench ratio, emittance of the source in [cm rad SQR(eV)] (partly estimated), polarized positive current on target

			$\vec{J}^-$[μA]	P	ε	$\vec{J}^+$[μA]
Fukuoka (DC)	H	spin filter	3	.8	1.4	.6
	D	"	2	.65	1.4	.4
Giessen (DC)	H	Sona	1.5	.72	2	1
	D	"	1.5	.5	2	1
LANL (pulsed)	H	spin filter	.8	.8	.3	.2
Munich (DC)	H	spin filter	.5	.83	1	.25
	D	"	1	.68	1	.5
	D	Sona	2.6	.58	1	1.2
Vancouver (DC)	H	Sona	1.5	.72	.7	.6

The Table shows that from Lamb-shift sources polarized beam currents of .5 to 1 μA on target are available in several laboratories.

ANALYSIS OF LAMB-SHIFT SOURCES

At the Vancouver meeting various details have been discussed which put some limitations on this type of source. Let me try a more systematic analysis to find out which polarized currents might be obtained.

1. Polarized output expected from charge exchange cross sections

Starting at the cesium cell with the wellknown cross sections shown in Fig. 2 and fractional yields shown in Fig. 3 we see that at an energy of 500 eV per nucleon for the incident beam and an optimum target thickness - indicated as "A" - the metastable fraction is almost at its maximum and equal to the ground state fraction $F_m = F_g = .3$. So at this point we are dealing with 2N neutral states of equal intensity (N being the number of hyperfine states).

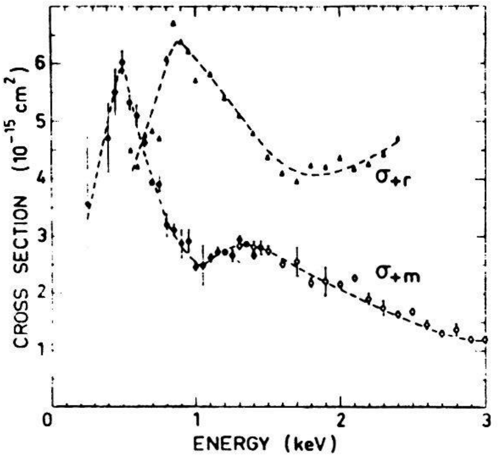

Fig. 2 Cross sections for the production of metastable 2S atoms and radiative 2P atoms from incident H^+ ions in cesium vapor versus energy of the H^+ ions [7]

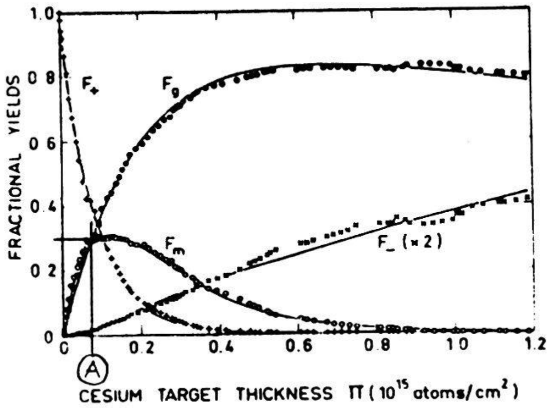

Fig. 3 Fractional yields from incident 500 eV H^+ ions as function of cesium target thickness. F_+, F_m, F_g and F_- are the fractions of the beam in the positive, metastable, ground, and negative state, respectively [7]

At the argon canal for the same particle energy the production of negative ions from metastable atoms is shown in Fig. 4 to be much larger than the production of negative ions from ground state atoms, exhibiting a selectivity $S = \sigma_{m-}/\sigma_{g-} = 50$. The same value for S follows from the independent measurement shown in Fig. 5. From the cross sections given as

$\sigma_{m-} = 5 \quad 10^{-17}$ cm² [7] (production of H^- from metastables),
$\sigma_{m*} = 8 \quad 10^{-16}$ cm² [8] (total reduction of incident metastables),
$\sigma_{-g} = 1.6 \; 10^{-15}$ cm² [8] (collisional destruction of already produced H^-),

and the description of I_m^- in Fig. 5 (x being the target thickness)

$$I_m^- = I_m \cdot \frac{\sigma^{m-}}{\sigma^{-g} - \sigma^{m*}} \left(e^{-\sigma^{m*} \cdot x} - e^{-\sigma^{-g} \cdot x}\right)$$

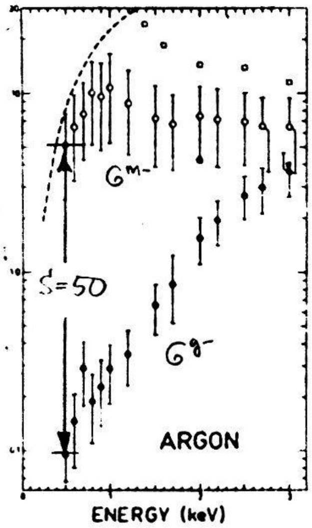

Fig. 4 Cross section for the production of H^- ions from metastable 2S and ground state 1S atoms versus energy of incident particles [8]

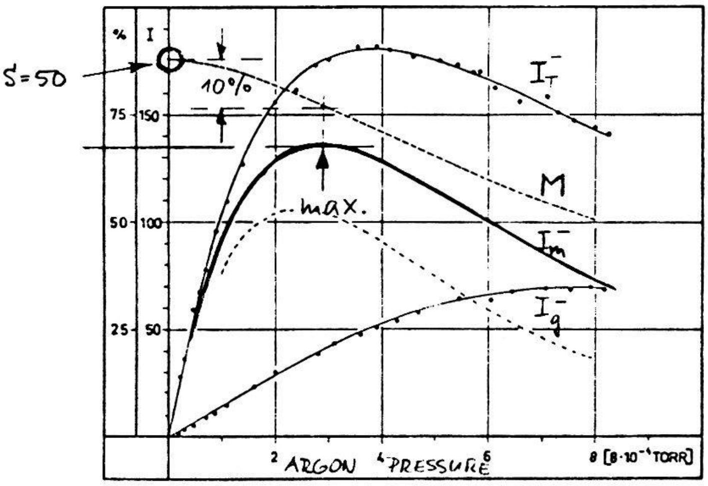

Fig. 5 Measured: total negative beam I_T^- and ground state contribution I_g^- from 500 eV incident neutral beam versus argon pressure. Deduced: negative beam from metastables $I_m^- = I_T^- - I_g^-$ and relative metastable contribution $M = I_m^-/I_T^-$

we calculate the maximum obtainable fraction of polarized H^- from metastables to be $I_m^-/I_m(\max) = 1.5\%$. It is further shown in Fig. 5 that at this maximum indicated as "max" the relative metastable contribution M is 10% smaller than in the low intensity limit. For the selection of one hyperfine state this relative metastable contribution is equal to the polarization. The polarized beam $\vec{I}^-$ per useful positive beam I_{Cs}^+ incident in the cesium cell and the corresponding polarization P in this case are therefore

$$\frac{\vec{I}^-}{I_{Cs}^+} = F_m \cdot \frac{1}{N} \cdot \frac{I_m^-}{I_m} \cdot \frac{1}{P} = \begin{matrix} 1.5 \cdot 10^{-3} & \text{for } H^- \\ 1 \cdot 10^{-3} & \text{for } D^- \end{matrix}$$

$$P = \left(1 - \frac{2N-1}{1 \cdot S+2N-1}\right) \cdot .9 = \begin{matrix} .80 & \text{for } H^- \\ .74 & \text{for } D^- \end{matrix}$$

Experimental values of polarization agree in case of hydrogen and are smaller ($\approx$.65) for deuterium, so some loss of the selected state is involved in the later case. The result was obtained without any background reduction which in turn would improve the polarization.

In multiplying these numbers it has been implied, that

- the phase space volume of the metastable beam from the cesium cell is fully accepted by the argon canal
- the spin selection is perfect
- there is no depolarization or quenching of the selected state
- there is no negative beam contribution from the cesium to the polarized beam
- there is no molecular positive beam incident in the cesium cell

2. The phase space volume which can be transmitted

Let me come back to the first of the above implications. If we have cesium and argon canals with exit and entrance apertures seperated by some distance as shown in Fig. 6 there are some trivial relations for the

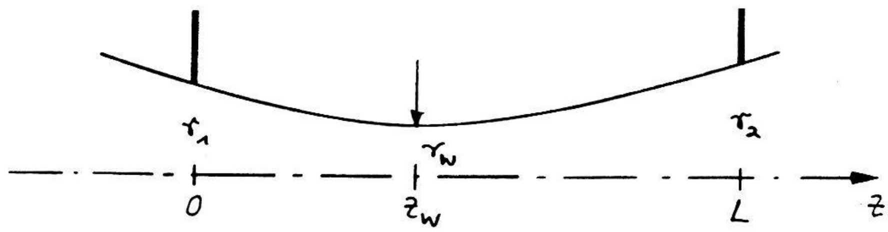

Fig. 6 Neutral drift space from cesium to argon canal. r_1, r_2 and L being aperture radii and the distance between them

maximum emittance $\varepsilon = r_w \cdot r' \cdot SQR(E)$ which can be transmitted and the corresponding waist position z_w, waist radius r_w and maximum asymptotic slope r'

$$\varepsilon_{max} = \frac{r_1 \cdot r_2 \cdot SQR(E)}{L}, \quad Z_w = \frac{r_1^2 \cdot L}{r_1^2 + r_2^2}, \quad r_w = \frac{r_1 \cdot r_2}{SQR(r_1^2 + r_2^2)}, \quad r' = \frac{SQR(r_1^2 + r_2^2)}{L}$$

These are of course valid only if ion optics is perfect, that means if the geometry of the phase space volume is prepared correctly. The above waist position is always in between the relevant apertures so for transmitting ε_{max} we need a convergent metastable beam emerging from the cesium cell. Since the intensity is proportional to ε^2 one can easily loose a lot of beam in this area.

3. Emittance increase from positive beam to polarized beam

Both charge exchanges in the Lambshift source increase the emittance of the beam:

$$\varepsilon_+ \underset{\text{cesium}}{<} \varepsilon_{metast.} \underset{\text{argon}}{<} \varepsilon_{\rightarrow} =: \varepsilon_{accelerator}$$

and the emittance of the polarized beam should be equal to the acceptance of the accelerator.

Let me start with the argon charge exchange. In Giessen [10] emittances have been measured for the polarized beam and for the negative beam coming from the cesium cell (without any argon). The result is $\varepsilon_{\rightarrow} \geq 1.2 \cdot \varepsilon_{F^-}$ for different magnetic fields in the argon region. Since the emittance of the negative fraction is certainly larger (two step process) than that of the metastable fraction, we conclude that in the argon charge exchange the emittance is increased by more than 20% (for 4 cm diameter). Our observation in Munich is $\varepsilon_{\rightarrow} \approx 2.5 \cdot \varepsilon_+$ (for 3 cm diameter at cesium and 4 cm diameter at argon) which means that the emittance increase in the cesium is ten times larger than that in the argon. The reason for this is that the cesium cell is not a good drift space. At the Vancouver meeting these large Cs^+ densities have been discussed [11] which are 100 times larger than the H^+ densities. They would produce quench fields of the order of 10 kV/cm at beam surfaces if they were not space charge compensated by electrons. As can be shown by beam transport calculations including space charge (space charge from gas ions can be simulated by choosing a proper beam intensity) imperfections in this compensation of the order of 10^{-3} are sufficient to cause considerable emittance blow up by the residual radial field (particles not flying on straight lines are charge exchanged at different places). So not only the macroscopic quenching but also the emittance treatment requires an excellent space charge compensation in the cesium cell. Due to the different velocity of the negative ions and the Ar^+ ions the effect of emittance increase is also present in the argon cell in a less severe manner.

Microscopic quenching in the cesium plasma has also been discussed in Vancouver [11] with the actual result that with increasing positive beams it might become a problem. J. Benage [12] has looked into this problem by solving all the rate equations which determine the different populations. He gives the maximum positive current density that may enter the cesium cell to be 20 mA/cm². For a 3cm diameter beam this gives I_{max} = 140 mA which could deliver 200 μA of polarized H^- per hyperfine state. But one must be careful. Since the local production rate of Cs^+ density is proportional to the positive current density times the density of neutral cesium vapor - both local -, one must avoid useless positive current being injected into the cesium cell as well as the production of high local cesium vapor densities. From this point of view the positive beam diameter should be large and the neutral cesium vapor density should be constant over a certain length.

As mentioned above A. Isoya has solved the problem in a different way [13]. Since the time for a Cs^+ ion to become neutralized is proportional to the distance it has to travel to a surface (no volume scattering!) he has installed grounded baffle plates in the center of his cell where the vapor density is highest.

4. Positive ion sources and beam formation

As mentioned above a large diameter convergent H^+ or D^+ beam with an energy of 500 eV per nucleon and an emittance considerably smaller than the acceptance of the accelerator is needed for optimum performance of a Lamb-shift source. There have been two different approaches toward this goal.

One has a large diameter multi aperture extraction with a short accel decel system coming quickly to a 500 eV per nucleon beam. The space charge is compensated by electrons from the extraction system itself, sometimes in addition by electrons from heated wires. An example is the Fukuoka quartz capillary source which delivers 100 mA of 95% H^+ with an estimated emittance of 2 cm rad SQR(eV). ECR-sources are also an example of this scheme. They have been tried in Karlsruhe and Vancouver. The result in both cases was that the polarized negative beam from the Lamb-shift source was not larger than with the previous positive ion source. It is not clear to which extent insufficient brightness or imperfect ion optics are involved. There is a new attempt at Tsukuba [14] with a large ECR source using a frequency of 2.45 GHz and a magnetic field of B = 1 kG.

The other approach has a small diameter single aperture extraction with a subsequent controlled diameter magnification at energies higher than 500 eV per nucleon. The linear part of the space charge forces is compensated by lens forces and the deceleration to the correct energy is made close to the cesium cell. This scheme is tried in our Munich RF-source which delivers 2.8 mA of 95% D^+ with an emittance of .4 cm rad SQR(eV).

It is interesting to note that the brightness I^+/ε^2 is not very different for the Fukuoka and the Munich source.

5. Over all performance

The polarized negative beam from a Lambshift source can be written as

$$\vec{I}^- = I^+_{source} \cdot \underbrace{\boxed{\frac{I^+_{Cs}}{I^+_{source}} \cdot \text{Loss}}}_{=:\ \text{LS-efficiency}} \cdot \left(\frac{\vec{I}^-}{I^+_{Cs}}\right)_{\text{theor.}}$$

where the second term is the useful fraction of the positive beam incident in the cesium cell, the third term represents any losses in the selected state and the last term is the one calculated above from charge exchange cross sections. From the observed polarized beam, the extracted positive beam and the calculated term we can determine what here is called "LS-efficiency". It is given in Table II for the above mentioned sources. The efficiency is rather small in most cases and it seems that low brightness of positive beam, imperfect ion optics and poor transmission of the neutral driftspace are the limiting factors. In the Munich source there is a substantial contribution from the charge density in the positive beam being not as constant as desired with the effect of imperfect space charge compensation.

Table II. Source efficiencies for different sources

	LS-efficiency
Fukuoka	.02
Giessen	.05
LANL	.09
Munich	.3
Vancouver	.07

CONCLUSION

It is of course impossible to make a precise statement about what polarized negative beam can be obtained from a Lamb-shift source. Since the maximum emittance which can be transmitted through the neutral driftspace for geometrical reasons (apertures of charge exchange cells, length of polarizer, deflection of charged particles after cesium !) is about $\varepsilon_{max} = 1$ cm rad SQR(eV) this type of source is mainly suited for low acceptance accelerators. Having in mind the emittance increase in the cesium the question is reduced to how much positive beam can be produced with $\varepsilon \approx .5$ cm rad SQR(eV) If we assume a maximum LS-efficiency of .66 the above equation becomes

$$\vec{I}^- = I^+_{source}(\varepsilon = .5 \text{ cm rad eV}^{1/2}) \cdot 10^{-3}$$

for hydrogen (one hyperfine state). It shows clearly that further progress is strongly related to the construction of a high quality positive ion source and a beam formation which prepares the metastable beam from the cesium cell to be fully accepted by the argon canal. A few microamperes on target should certainly be obtainable in the near future.

It should also be kept in mind that compared to other schemes where ECR-sources and high intensity lasers are used, a Lambshift source is a cheap and versatile source, very well suited for routine operation at a Tandem accelerator.

REFERENCES

[1] T.B. Clegg, Proc. of Conf. on Polarized Proton Ion Sources, Ann Arbor 1981, AIP Conf. Proc. 80 , (1982) 21

[2] T.B. Clegg, Proc. of Conf. on Polarized Proton Ion Sources, Vancouver 1983, AIP Conf. Proc., 117, (1984) 63

[3] A. Isoya et al., Proc. Int. Ion Engineering Congress (1983) 269

[4] A. Isoya et al., Proc. of the Sixth International Symposium on Polarization Phenomena in Nuclear Physics, J. of the Phys. Soc. of Japan 55 (1986) 1054

[5] P. Schiemenz, Proc. of Conf. on Polarized Proton Ion Sources, Vancouver 1983, AIP Conf. Proc. 117 (1984) 78

[6] P. Schiemenz et al., Proc. of the Sixth International Symposium on Polarization Phenomena in Nuclear Physics, J. of the Phys. Soc. of Japan 55 (1986) 1056

[7] P. Pradel et al., Phys. Rev. A 10 (1974) 797

[8] F. Roussel et al., Phys.Rev. A16 (1977) 1854

[9] L. Friedrich Ph.D. Thesis, Karlsruhe 1968

[10] A. Hofmann et al., Proc. of the Sixth International Symposium Polarization Phenomena in Nuclear Physics, J. of the Phys. Soc. of Japan 55 (1986) 1058

[11] T.B. Clegg, Proc. of Conf. on Polarized Proton Ion Sources, Vancouver 1983, AIP Conf. Proc. 117 (1984) 103

[12] J. Benage, LANL report LA-UR-85-4463

[13] A. Isoya, contribution to this conference

[14] Y. Tagishi, Annual Report of Tandem Accelerator Center of University of Tsukuba (1984) 9