SLAC-PUB-3505
November 1984
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CONF-8409162--11

Report on the May 1983 Polarized Electron Source Workshop at SLAC*

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SLAC-PUB--3505

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Résumé - Les travaux ainsi que les conclusions des journées de travail sur les electrons polarisés en 1983 à SLAC sont passés en revue. Sont aussi inclus quelques progrès achevés depuis.

Abstract - The work and conclusions of the 1983 Polarized Electron Source Workshop at SLAC are reviewed. Some mention of progress since that meeting is also included.

Introduction

A workshop on polarized electron sources was sponsored by the International Committee for Symposia on High Energy Spin Physics, and held at SLAC on May 16-19, 1983. This workshop brought together 18 physicists from the fields of atomic physics, surface physics, condensed matter physics, and of course, high energy and nuclear physics. Our goals were to survey the current situation in polarized electron production and electron polarization measurement, and to study ways in which the state of the art in these fields might reasonably be advanced. Our attendees came from four western European institutions, and nine in the U.S. Of these, only eight had as their primary discipline either high energy or nuclear physics. In this brief report, I will review the activities of the workshop and also mention, to the extent I am familiar with it, work accomplished since the time of the workshop.

The workshop opened with a review of the application of polarized electron sources in the areas of high energy and nuclear physics, condensed matter and surface physics, and atomic physics. These discussions will not be reproduced here as they are either well known to readers of these proceedings, or are not germane to the topic of this conference. In a final recommendation session, we prepared a lengthy list of experiments which should be attempted and future directions for new work. Some of these will be covered in the text of this report under the particular sections to which they apply.

Although the meeting was open to, and encouraged, discussion of all types of polarized electron sources, the primary interest of a great majority of the participants was in the GaAs source and other sources of this general type, which employ optical pumping in non-magnetic solids. The GaAs source has seen very wide application to a wide variety of problems in basic and applied physics, and is by far the most commonly employed polarized electron source at this time. In fact, a fairly large number of polarized electron measurements have been made only because of the existence and particular characteristics of this source. Despite all this, the GaAs source delivers only a mediocre polarization and is a demanding source to maintain in operation with a particle accelerator. A large part of the workshop was devoted to a discussion of methods to overcome those weaknesses. No doubt the large emphasis the workshop placed on the GaAs source was due to the presence of physicists from fields other than high energy and nuclear physics, where the low polarization and relatively short operating lifetime of this source is less of a problem than for accelerator based experiments.

Other polarized electron sources which were reviewed included those based upon optical

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

Invited talk presented at the 6th International Symposium on High Energy Spin Physics, Marseille, France, September 12 - 19, 1984.

or magnetic orientation in free atomic beams, and those employing photoemission to release polarized electrons from magnetized solids. None of the techniques employing magnetized solids appear particularly suited as sources for accelerator based physics. Of the atomic beam sources, one, based upon chemi-ionization of an optically pumped helium afterglow, appears capable of being developed to the point where it could deliver a continuous electron beam of about 1 mA with ≈ 90% polarization. Such a source would definitely be useful for some experiments currently considered. This particular type of source is relatively free of many of the troublesome features of other polarized sources (e.g. alkali metal beams, exceptional vacua, difficult optical sources, etc.).

A fair period of time was spent discussing the various techniques which have been developed to measure electron polarization at low energy. Such measurements have, in the past, often been characterized by rather large and uncertain systematic errors, even in circumstances where there was good statistical precision. There is a definite need to have an electron polarization measurement technique which offers high statistical precision in a short measuring time, freedom from systematic uncertainties and spurious effects, and a well known analyzing power, all contained in a sufficiently simple apparatus to permit widespread utilization. Such a method is yet to be invented, although a couple ideas were presented which might well provide such a method in the future.

The techniques to measure electron polarization at high beam energy were not addressed, although the need for better methods in this area is very important, particularly for the coming generation of higher energy machines which plan to utilize polarized electrons: SLC, LEP, and HERA.

The details of the GaAs source were reviewed in a session which covered the operational or near operational sources developed for accelerator applications. These include operational sources at Mainz and Chalk River, and sources under development for the SLC and the MIT Bates linac (this latter source is currently being installed on the accelerator). The physics of producing polarized conduction band electrons in GaAs, and extracting them from the bulk material, received the attention of one session. A session covering the preparation of GaAs photocathodes received a great deal of interest. A large number of the workshop recommendations dealt with producing photocathodes with good quantum efficiencies and long operational life. Increased polarization from sources of the GaAs type received the attention of one session as well.

Before leaving this introduction, it is worthwhile to make two remarks. The first is that, although polarized electron sources are usually thought of only in terms of their use with linear accelerators, there is no reason in principle why they cannot be employed with circular machines, at least up to beam energies where the beam energy spread makes polarization problematic. The Bonn University group has successfully accelerated polarized electrons through several resonances, and expect to be able to provide polarized electron beams from their next machine. This work is discussed in a recent preprint by W. Brefeld _et al_. (Bonn University preprint 84-23).

The second remark is that very little polarized electron source development work is being done in high energy and nuclear physics laboratories. Since high beam polarization and large beam intensities are not essential to successful polarized electron experiments in other fields of physics, one cannot expect the development of such source characteristics from experimenters in these fields. To the extent that these source characteristics are required for work in our fields, we will have to do that development.

The GaAs Source

To set the stage for further discussion, let us briefly review the operation of the GaAs polarized electron source. A simplified (though reasonably accurate) view of the band structure of GaAs near the minimum direct bandgap, at the center of the Brillouin zone, is shown in figure 1. Transitions due to photon absorption are vertical lines in this figure. When transitions from the $P_{3/2}$ valence band to the $S_{1/2}$ conduction band are caused by 100% circularly polarized photons, the conduction band electrons

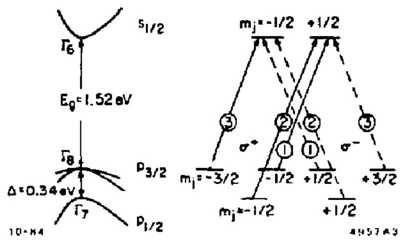

Fig. 1 - The band structure of GaAs near the bandgap minimum is shown on the left. On the right, the relative transition rates between the valence and conduction bands for right (left) circularly polarized photons are shown adjacent to the solid (dashed) lines. For photon energies between E_g and $E_g + \Delta$, only transitions from the $P_{3/2}$ valence band are possible.

have a -50% polarization. This is illustrated in the diagrar of relative transition rates on the right in figure 1, and is a consequence of angular momentum conservation. As the photon energy increases to the point where transitions from the spin-orbit split off $P_{1/2}$ band are allowed, the polarization decreases to zero.

Electrons photoexcited to the conduction band are nominally bound to the crystal by about 4 eV. However, by the addition of monolayer quantities of cesium and oxygen to the GaAs surface, the work function can be lowered to the point where electrons at the bottom of the conduction band can energetically leave the crystal, a condition known as negative electron affinity (NEA). This then completes the basic picture of the GaAs polarized source: optical pumping with a circularly polarized photon beam to produce conduction band electron polarization, and treatment of the crystal surface to lower the work function to the point where conduction band electrons may be emitted. The measured electron polarization from a typical NEA GaAs photocathode is shown in figure 2.

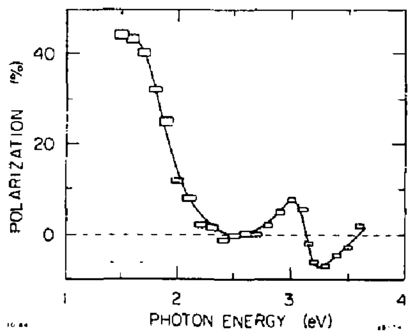

Fig. 2 - Measured electron polarization as a function of circularly polarized photon energy for a typical NEA GaAs photocathode.

As the spin-orbit splitting is sizeable in GaAs (≈ 0.34 eV) the electron polarization is fairly insensitive to the optical photon energy in the vicinity of the bandgap energy. GaAs is a very efficient photoemitter, making it easy to obtain quite large currents of polarized electrons. It is straightforward to reverse the polarization of the optical pump beam, and with it the electron polarization, rapidly and without significantly altering any of the electron-optical properties of the polarized source, thus making it possible to achieve a highly desirable freedom from systematic effects upon polarization reversal. Each of these properties makes the GaAs polarized source most useful.

Not all of the characteristics of the GaAs source are so nice, however. The monolayer quantities of cesium and oxygen which lower the work function must be applied to a crystal which has far less than a monolayer of contamination from any other arbitrary substance. The activated photocathode surface is very susceptible to degradation in the presence of residual gases in the best of vacuum systems. Cesium may desorb from the activated surface, reducing the quantum efficiency as a function of time. Typical operating lifetimes for polarized sources on accelerators are on the order of 10 to 40 hours. Sub-monolayer quantities of some contaminants and/or poor crystal quality or surface morphology readily prevent achievement of good quantum efficiencies. All of these difficulties make the cleaning, handling, and preparation of the GaAs crystals of great importance. Careful cleaning procedures and great attention to detail in vacuum procedures are essential to a successful GaAs polarized source. Finally, the maximum polarization of 50% theoretically, and often 35 to 45% in practice is a real limitation, particularly for those experiments using a polarized target, where radiation damage and/or target heating limit the acceptable beam current.

Table 1. Typical Operating Characteristics of GaAs Polarized Electron Sources

Beam Polarization	35% to 45%, longitudinal
Beam Current	1 mA continuous to 15 A peak current pulses
Duty Factor	1-2 nsec. pulses to continuous beam
Cathode Quantum Efficiency	0.1% to about 5%
Cathode Operating Temperature	77K to 300K
Source Vacuum	10^{-10} torr.
Operating Lifetime	A few hours to about 100 hours, before in situ recleaning and reactivation is necessary
Optical Source	Typically a dye laser, wavelength between 630 and 800 nm, 100% circular polarization

Table 1 gives a summary of some of the operating parameters of GaAs sources used with particle accelerators. These numbers come from experience with sources at SLAC /1/, Mainz /2/, and Chalk River /3/. Additional sources are under development for the SLC /4/, the MIT Bates linac /5/, and at Nagoya, Bonn University, and Mainz. Perhaps the most novel of the sources under development are those for the SLC and the Mainz microtron. The first is notable for the ability to deliver very short, high current bunches, and the latter is a lovely piece of source engineering. The Mainz microtron source will operate at the high voltage terminal of the injector Van de Graaff, and thus be physically inaccessible. It is both small and light, and incorporates differential pumping to permit connection to the poor vacuum of the Van de Graaff. The Mainz group has also accomplished another impressive feat: the source they use with their linac is regularly removed and re-installed, in alternation with a thermionic gun! The source has been detatched and transported away from the linac under vacuum a number of times.

While each polarized electron gun has its own particular features, figure 3 shows a view of a typical such gun. This one was employed for the SLAC parity violation work a few years ago /6/. The Mainz and Chalk River guns are very similar to this gun. This gun is, in fact, very similar to the thermionic guns used on SLAC, with the major differences being the replacement of the thermionic emitter with a GaAs wafer, the addition of apparatus to activate the GaAs surface, and a means to cool both the GaAs crystal and the inner walls of the vacuum chamber.

Figure 4 displays a complete polarized electron injection system, again as used at SLAC for the parity violation experiment. Most of the first generation of polarized electron injectors were installations of similar complexity. All these complex installations pale by comparison to the very compact and simple source for the Mainz microtron. Operational experience with GaAs sources at a number of laboratories has led to the conclusion that it is not necessary to operate the GaAs at liquid nitrogen (or colder) temperatures to achieve good polarization, and that it is unnecessary to incorporate a Mott scattering apparatus to measure the source polarization. In all polarized electron experiments to date, provision is made to measure the beam polarization at the high energy end of the accelerator. Generally speaking, the high energy beam polarization measurements are as fast and precise as Mott scattering at the source energy, and are thus as good a measure of source performance. Of course, source development work requires some means of polarization measurement in a laboratory setting, and for this Mott scattering is still appropriate.

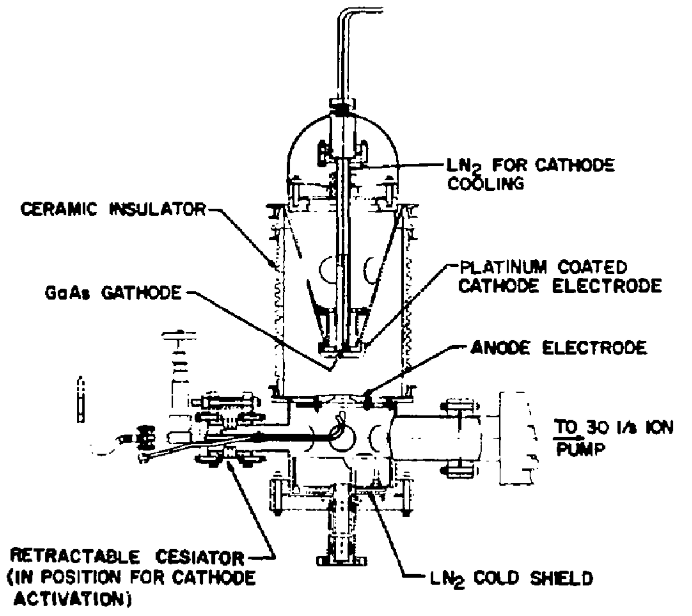

Fig. 3 - The polarized electron gun developed for the SLAC parity violation experiment.

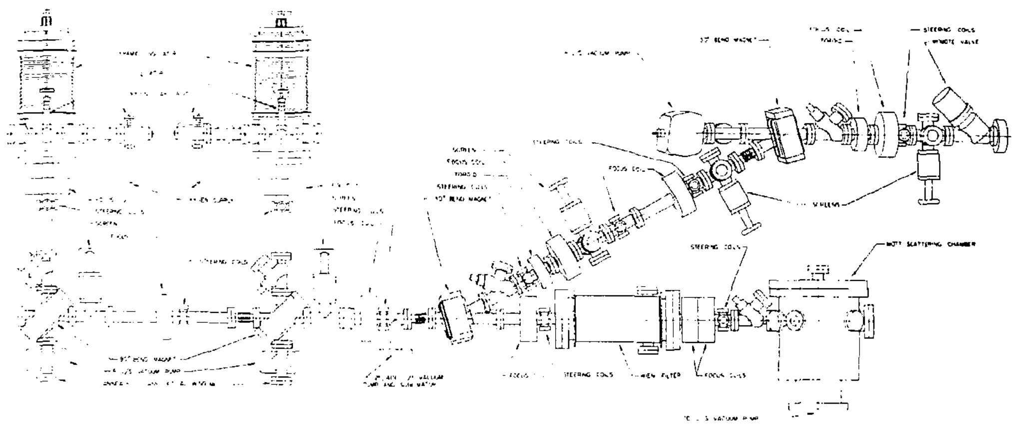

Fig. 4 - The complete polarized electron injection system constructed at SLAC for the parity violation experiment.

Two variations of the basic GaAs source are worthy of note. In the first of these, one employs a semiconductor with the same basic band structure as GaAs, but with a larger direct bandgap. This moves the optical wavelength required to produce the polarized beam toward shorter wavelengths, which may be convenient for some applications. It is quite feasible to produce a polarized emitter which operates at the wavelength of the common helium-neon laser, for example. The Mainz source utilizes a $GaAs_{0.62}P_{0.38}$ cathode which permits operation at a 650 nm wavelength. This is a particularly interesting technique, because in principle, larger bandgap GaAsP photocathodes should be far more stable than those of GaAs. Although GaAsP is commercially available, it is normally n-type, while p-type material is required for photocathodes. Mainz uses n-type material which is converted to p-type at the surface by ion implantation. It may be that the low quantum efficiency of the Mainz source is the result of crystal damage caused by this ion implantation. It would be useful to obtain some p-type GaAsP material prepared by some high quality epitaxial process, to see if good quantum efficiency and good polarization could be obtained from this material. It is not feasible to try to produce a source operating at longer wavelengths than GaAs, as the cathodes become less stable, and it is difficult to obtain negative electron affinity conditions on smaller bandgap materials.

A group at KFA (Jülich) has also experimented with wider bandgap materials, which they grew in their laboratories by molecular beam epitaxy /7/. They observed high polarization from $Al_{0.3}Ga_{0.7}As$, with a bandgap of about 1.75 eV. While AlGaAs is easier to grow than GaAsP, it suffers from having a very reactive surface. It is difficult to prepare good quantum efficiency photocathodes on this material if it has ever been exposed to atmosphere, apparently due to the aluminum oxide which rapidly grows on the surface. The Julich group has solved this problem by a process known as arsenic capping. An arsenic cap layer is grown on the AlGaAs surface in the growth chamber, and protects the surface from oxidation during transfer through the atmosphere. This arsenic layer is readily removed by heating the sample after installation in the polarized source vacuum system. Use of this process may make it possible, in the future, to employ polarized photocathodes of AlGaAs. It is useful to note that both the Mainz and Julich groups achieve good polarization from their cathodes in room temperature operation.

The Jülich group has also reported the highest polarizations to date from GaAs, 49%, or essentially the theoretical limit /8/. This is attributed to the relatively thin layers of GaAs they use. The point is that the electrons have to come from a small depth in the crystal, and have not had a great deal of opportunity to depolarize. At the workshop, Lampel presented a straightforward model for the electron polarization in the bulk GaAs and of the emitted electrons. The model was checked by the actual measurement of both of these polarizations in a very lovely experiment /9/. The results indicate that the spin relaxation constant is about half the bulk recombination constant in the GaAs. This model, and the results obtained are sufficient to indicate a higher polarization from thin GaAs layers, and to also show indirectly that there is no depolarization of the electrons in passing through the cesium activation layer.

Improved Polarization From GaAs Type Sources

Increased polarization from GaAs type sources involves removal of the degeneracy at the top of the $P_{3/2}$ valence band. This may be accomplished by several methods. The application of a uniaxial stress to the GaAs, for example, removes the degeneracy. This has been studied theoretically, and the increased polarization of the electrons in the bulk material observed by measurement of the circular polarization of the recombination radiation /10/. However, the degenerate bands are split by only a few meV per kbar of applied stress. To obtain splittings large enough to enhance the polarization in practical sources, very large stresses are required, often resulting in broken crystals rather than broken degeneracy. It is also difficult to imagine a polarized source which incorporates uniaxial stress along with all of the other requirements in a practical arrangement. This idea has yet to be attempted in a polarized source.

Artificial semiconductor structures, such as GaAs-GaAlAs multilayers, which have a uniaxial variation in the bandgap energy, can also produce highly polarized electrons in the conduction band, as has been demonstrated by luminescence measurements at Bell Labs /11/. However, most of the variation of the bandgap energy occurs in the conduction band, making transport of the highly polarized electrons to the surface very problematic. Experiments at KFA failed to show any enhancement from this effect /12/. At SLAC, experiments on somewhat different material showed a small polarization enhancement at the correct wavelength, but no one has reported any large polarization improvement from multilayer structures to date. In principle, if one could design a multilayer structure in which the bandgap energy variation appeared in the valence band, rather than the conduction band, highly polarized electrons should be produced and easily extracted. No one has prepared such a structure, however.

Perhaps the best method for providing increased polarization from optically pumped non-magnetic solids is to employ a material with a band structure in which the undesirable degeneracy is not present. In principle, band structures exist which should deliver 100% electron polarization. Many members of the II-IV-V_2 family of chalcopyrite semiconductors have band structures which should deliver high polarization. While all members of this family should have a good valence band structure, i.e. no polarization defeating degeneracies as in GaAs, there are different structures for the conduction bands of these materials, some of which are not suited for high polarization. The best candidate material for a highly polarized source from this family is $CdSiAs_2$. Figure 5 compares a simple view of the band structure of this material to that of GaAs, indicating the removal of the valence band degeneracy, and the transition at 1.74 eV which should give high polarization. Unfortunately, this material is not readily available. SLAC has supported growth experiments for this material at the Research Triangle Institute, and the first epitaxial layers of this material have recently been produced. The material grows on an InP substrate, in exactly the correct orientation to produce high polarization. Detailed studies of surface cleaning, cathode preparation, and polarization measurement should begin before too long.

At ETH (Zurich), other chalcopyrites have been measured as candidate polarized electron emitters /13/. They had samples of $ZnSiAs_2$ and $ZnGeAs_2$. The first of these materials has a conduction band structure not well suited to high polarization, while the second material has a band gap too small to give a NEA surface, and thus the presumably highly polarized electrons cannot be emitted. More recently, SLAC has obtained some very high quality samples of $ZnSiAs_2$ and have attempted to reproduce the ETH results. The ETH results along with the SLAC results are presented in figure 6. The ETH samples were small and of uncertain crystalline quality, while the SLAC crystals were grown epitaxially by MOCVD, and were of the correct orientation to produce high polarization. As can be observed in figure 6, these crystals produced lower polarization than the ETH samples. It is worth noting that the quantum efficiency from the SLAC samples was dramatically greater than that of the ETH samples. This may mean that the electrons were able to diffuse to the surface of the crystal from deeper in the material, and thus had a greater opportunity to depolarize. Continued experiments at SLAC are planned to determine if operating with a non-NEA surface could produce higher polarization from these samples.

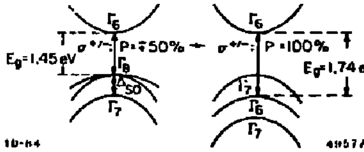

Fig. 5 – Comparison of the band structures of GaAs and $CdSiAs_2$ in the region of the minimum direct bandgap. The valence band degeneracy of GaAs is removed in the chalcopyrite material, and the high polarization transition is indicated.

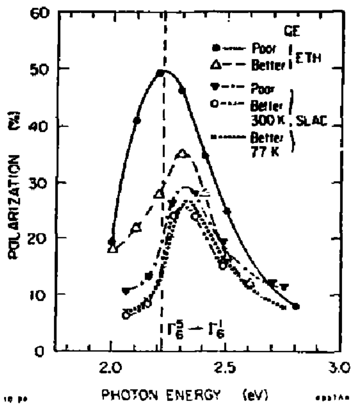

Fig. 6 - Measured polarization from $ZnSiAs_2$ as a function of photon energy. The polarization from several cathode preparations is indicated. The quantum efficiencies of these preparations are indicated qualitatively as "poor" and "better". The SLAC quantum efficiency was much higher than that reported by the ETH group. The location of the transition which should produce high polarization is indicated by the dashed line.

It may also be that further work with $ZnGeAs_2$ could be successful in producing higher polarization. The ETH cathodes were made by applying cesium alone to the surface. It is difficult to produce NEA on this material as its fundamental band gap is quite small, about 1.2 eV, and cesium alone would not be expected to produce NEA. However, techniques are known which can lower the work function to about 1.0 eV, through activation with cesium and fluorine, rather than cesium and oxygen /14/. Polarization measurements should be made on this material treated with cesium and fluorine.

In any event, emitted electron polarizations in excess of 50% from optical pumping in non-magnetic solids has yet to be observed . It does appear that all the avenues for higher polarization from sources of this type have not been exhausted, and several promising lines of work are still underway. The difficulties are present, however, as indicated by the offer of Prof. H. C. Siegmann of ETH. He has offered a case of champagne and plane tickets to Zurich to the first person to produce 70% polarization by this method, and to come to Zurich to reproduce the results!

Techniques For Preparation Of Photocathodes

In a session which aroused great interest and provoked much discussion, Prof. W. Spicer of Stanford reviewed for several hours the techniques for photocathode preparation, and the extent of quantitative knowledge about activated cathode surfaces. As can be imagined, quantitative and structural knowledge about surfaces having sub-monolayer quantities of materials is difficult to obtain. Much of Spicer's work was done in conjunction with Varian, and as such, was proprietary, and thus was not discussed. However, published work by Spicer's group on activated GaAs photocathodes was presented and discussed /15/. Much of the information on the preparation of these surfaces is still empirical. An excellent recent review of NEA photocathodes is contained in the article of Escher /16/.

It was suggested that preparation of cathodes with cesium and fluorine might give better results than the more standard cesium and oxygen preparation. At SLAC, we have subsequently prepared a number of photocathode activations on the same sample of GaAs, using both of the above techniques. Preparation with fluorine consistently gave a higher quantum efficiency than preparation with oxygen. In addition, cathodes activated with fluorine showed about one order of magnitude less sensitivity to elevated pressures of CH_4 and CO, compared to the oxygen activations. The view was expressed at the workshop that CH_4 was a very bad contaminant gas for these photocathodes, as it could be the source of carbon contamination, which is known to be bad. The experiments to date at SLAC do not bear this out. Both oxygen and fluorine activated cathodes showed the least sensitivity to CH_4, greater sensitivity to CO, and very great sensitivity to CO_2. Work is underway to reproduce these results on additional GaAs samples prior to publication. Cathode activation with fluorine rather than oxygen may represent a significant improvement for polarized source work, if these results prove to be reproducible.

Atomic Beam Polarized Sources

Three types of polarized sources employing atomic beams were discussed. The first of these used a beam of oriented Li^6 atoms which are photoionized by unpolarized light from an arc lamp. This source has been employed at SLAC for several experiments on the scattering of polarized electrons from polarized protons, and has been thoroughly described in the literature /17/. One development for this source would be to pump the Li^6 atoms with circularly polarized resonance radiation, again followed by ionization by unpolarized arc lamp light. In principle, this could produce somewhat higher beam polarization, about a factor of ten greater beam current, and the great advantage of optical polarization reversal, rather than the magnetic reversal required in the present version of this source.

A second type of atomic beam source has been developed for accelerator applications by the Bonn University group. It utilizes the photoionization of alkali metal beams by circular polarized light of a wavelength which gives high electron polarization through the Fano Effect. Two of these sources have been developed at Bonn, one using cesium, and one rubidium /18,19/. Sources of this type are capable of the highest beam polarizations developed for accelerator work.

The third source discussed has never been used with an accelerator. It is based upon the chemi-ionization of optically pumped helium metastables /20/. This source is able to deliver quite a high beam polarization if enough optical pumping power is provided, and should be able to deliver continuous beam currents of up to 1 mA. Currents of this size are possible from the Li^6 source and the Fano source only on a pulsed basis, due to the optical sources required for the ionization. An additional advantage of the helium chemi-ionization source is relative simplicity. Alkali metal beams and good vacuum systems are not required. While 1 mA is not a large current by contemporary standards, there are polarized electron experiments under consideration which could profit from such a source. This source is shown schematically in figure 7. Basically, microwaves are used to produce a beam of 2^3S helium metastables, which are then optically pumped by a near infrared laser. Chemi-ionization of these pumped metastables liberates the polarized electrons.

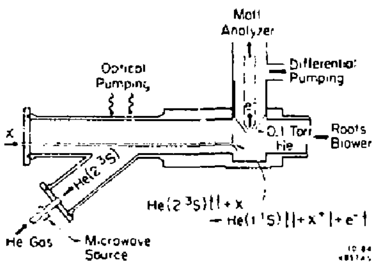

Fig. 7 - The helium chemi-ionization polarized electron source.

The operational characteristics of these three sources are given briefly in Table II, where the results actually achieved with each of these sources is noted, along with the parameters which the workshop concluded could be reached with a maximal development of each of these source types. In general, these sources deliver much higher beam polarization and much lower beam current than the GaAs sources, and are in general more complex installations than the current generation of GaAs sources. For those experiments where the beam current is limited by other considerations, as in polarized target experiments, these sources may be very useful.

Table II. Characteristics of Atomic Beam Polarized Electron Sources

Source Type	Results Achieved	Possible with Maximum Development
Photoionization of oriented Li^6	2×10^9 e/pulse P = 85% 180 pps magnetic reversal	2×10^{14} e/pulse P ≈ 90% 180 pps optical reversal
Fano Effect	3×10^9 e/pulse P ≈ 93% (Cs); 1 pps P ≈ 67% (Rb); 50 pps optical reversal	1.5×10^{11} e/pulse P ≈ 93% (Cs) 180 pps optical reversal
Chemi-ionization of helium metastables	P ≈ 70-80%, 1 μA CW P ≈ 40%, 50 μA CW optical reversal	1 mA CW, P ≈ 90% optical reversal

Two final points need to be made regarding atomic beam sources. We have not so far mentioned the emittance of the source because the GaAs sources have both excellent emittance and very small energy spread, and have no difficulty in meeting the acceptance specifications of accelerators. This is not necessarily true of atomic beam sources. Those which have a magnetic field in the region from which the electrons originate will have an enlarged emittance. Those with a significant electric field over the volume from which the electrons originate will have a substantial beam energy spread. These effects can be very important. For example, at SLAC, the linac accepted the same fraction of the beam from the GaAs source that is accepted from the normal thermionic guns, while it did not accept this fraction from the Li^6 source, which had both a larger emittance and a substantial beam energy spread. The helium afterglow source is believed to have an emittance about as good as that of the GaAs source.

The second point concerns the importance of optical reversal of the source polarization. Even in experiments which do not explore small parity violating asymmetries, such as in polarized electron - polarized proton scattering, the experimental asymmetries are generally quite small after two polarizations, useful target content, backgrounds, kinematic depolarizations, and the real physics asymmetry are all considered. The systematic effects associated with a magnetic polarization reversal scheme, no matter how carefully controlled, are a real limitation. Optical polarization reversal is much to be desired.

Polarized Electrons from Magnetized Materials

Polarized electrons may be emitted from magnetized materials by either field or photoemission. Examples include polarized electron photoemission from Fe, Co, Ni, and EuO, and field emission from EuS coated tungsten needles. To date, field emission has required operation at LHe temperature, and has delivered only very small currents without destruction of the emitter. This technique was not discussed. Photoemission from EuO has delivered modest pulsed currents of reasonable polarization, but is no longer pursued as a polarized source. Photoemission from metals like Fe, Co, and Ni is characterized by: (1) emitting materials which are durable and stable; (2) the need to flip a magnetic field to effect polarization reversal; (3) a quantum yield near threshold, where polarization is the highest, which is quite low (ca. 10^{-6} e/photon); and (4) the need for quite high photon energy (ca. 5 eV). The work function of these metals may be lowered by the addition of cesium, but this does not improve the yield significantly, although it does ease the photon energy requirement. Photoemission from the 110 face of Ni crystals has recently been shown to give essentially 100% electron polarization, but in the face of the many disadvantages of a source of this type, this lofty polarization seems not so significant. It was the essentially unanimous opinion of the workshop participants that electron emission from magnetized materials is not a very suitable source technology.

Electron Polarization Measurement

One session was devoted to a discussion of methods for electron polarization measurement at typical source energies of tens of volts to about 100 kV. The important area of electron polarization measurement at high energy was left undiscussed. The following polarization measurement techniques were discussed: (1) Mott scattering; (2) polarized low energy electron scattering; (3) absorbed current detectors; (4) excitation of atoms with polarized electrons, followed by a determination of the electron polarization by optical measurements of the atomic decay radiation; and (5) correlations in polarized electron bremsstrahlung.

Mott scattering is still the technique most commonly employed for measurement of electron polarization, although the difficulties and weaknesses of the method are well known. Separation of elastically and inelastically scattered electrons requires that a target thickness extrapolation be done. The thinnest targets available, gold foils a few hundred angstroms thick (if self-supporting) are not thin enough to be unimportant; if thinner, non-self supporting foils are used, corrections for the foil support are needed. It was emphasized that the theoretical form of the foil thickness extrapolation was not known, and that this effect alone gives about a 5% absolute uncertainty to all Mott scattering measurements.

A Mott scattering apparatus employing a new geometry was described /21/. This apparatus permits the use of lower voltages than normally employed with Mott scattering (20 to 40 kV versus the more normal 100 to 120 kV), and gives excellent discrimination against inelastically scattered electrons. Another advantage is that the apparatus is operated at ground potential. The instrument has a good figure of merit. A Mott analyzer based on cylindrical geometry, and incorporating several of the good features of the better spherical geometry has been described earlier by the same group /22/. No doubt Mott scattering, with all its problems, will continue to be used in the future, and analyzers of the sort described in these reports will likely be the designs of choice for future work.

A polarized low energy electron diffraction analyzer was described. While such an analyzer has a very high figure of merit, tungsten, the only crystal employed to date for such an analyzer, requires an UHV environment and frequent cleaning of the crystal. As with other low energy electron processes, one expects great sensitivity to the details of the crystal surface. Were a stable crystal surface which could be used in a less demanding vacuum system to be found, this method would be more attractive. This detector is described in a paper by Kirschner and Feder /23/.

The ultimate in polarimeter simplicity is the absorbed current spin detector. The net current absorbed by a sample placed in a polarized electron beam depends on the electron spin through either the exchange interaction in a ferromagnetic material, or the spin-orbit interaction in a high Z material. The effect is considerably enhanced at those energies where the secondary yield crossover occurs; i.e. where the number of backscattered and secondary electrons equals the incident beam current. In fact, there are two secondary yield crossovers, one for each spin, such that at a particular energy, only electrons of one spin orientation induce an absorbed current. The figure of merit for detectors of this type may be very high. This type of detector has been analyzed in detail by Pierce et al. /24/. These detectors do have some problems in their application. They are clearly a low energy instrument, making their use difficult with polarized sources of interest as injectors for accelerators. Secondary emission is a surface sensitive process, requiring good vacuum conditions and stable surfaces. There is the unpleasant possibility that the electron beam incident on the surface can change the surface conditions, and thus the analyzing power, of the detector, particularly at beam currents in use with accelerators. The technique appears very useful in a small laboratory devoted to studying polarized electron physics.

Electron polarization may be measured optically by exciting atoms with polarized electrons and measuring the circular polarization of the resonance recombination light. This method, applied to zinc atoms, was used for the measurements of Eminyan and Lampel, noted earlier /9/. The advantage of this method is the possibility of an absolute polarization measurement. While it is unlikely that this technique would be adopted as a standard laboratory procedure, it could be usefully employed to calibrate other polarization analyzers which have a higher figure of merit. In an unpublished contribution, Tim Gay suggested the use of helium atoms as the analyzing target. There are a number of advantages to the use of helium, and the numbers determined by Gay indicate that the measurement should be feasible.

Finally, the possibility of using polarization correlations in the bremsstrahlung of polarized electrons was reviewed. While theory and measurement are in agreement, it appears that there are no advantages in the use of this difficult technique.

Summary

The following conclusions and suggestions for further work seem most likely to be of benefit to polarized electron sources for accelerator applications.

(1) The GaAs source has proven so useful that attempts to overcome the two weaknesses of this source, mediocre polarization and short operational lifetimes, are worth vigorous pursuit. One may obtain some polarization improvement by the use of thin emitting layers, as done at Jülich, with possibly some loss in quantum efficiency. To obtain much higher polarization will require a source with no GaAs-like degeneracy at the top of the valence band. This might be achieved with a multilayer structure which placed most of the bandgap variation in the valence band. Other materials possess band structures which have the correct band structure to give high polarization directly. $CdSiAs_2$ appears to be a very desirable candidate material. First samples of this material are now coming available for cathode preparation. Another candidate material is $ZnGeAs_2$, if the work function can be lowered sufficiently by the use of cesium and fluorine activation. The preparation of many of these special materials might be materially aided by the availability of a molecular-beam-epitaxy system in the polarized electron community. The success of the arsenic capping technique indicates that materials grown in these systems may be removed and transported. It should be possible to resolve the poor operating life problem with the appropriate attention to cleanliness and surface preparation. The fact that long lived cathodes are prepared commercially gives hope that a solution exists.

(2) Atomic beam sources offer the highest electron polarizations. Until such time as a solid state source reliably delivers a highly polarized beam, the atomic sources will have an important role, particularly in experiments where their limited current can be tolerated. [illegible] ity is the primary disadvantage of these sources. Only sources which have optically reversed polarization should be developed. The helium chemi-ionization source appears capable of development to a very useful level, and is the least complex of sources of this type.

(3) Polarized electron emission from magnetized mater is is not a suitable source technology for accelerator based applications.

(4) The Mott polarimeter is likely to remain the "industry standard" for accelerator based electron polarization work. Polarimeters with spherical (and cylindrical) geometry offer a number of advantages for these polarimeters. For a source development laboratory, other simpler methods may be the most useful for fast, non-absolute measurements. The use of optical polarization measurement techniques, with their possibility for absolute polarization measurement should be pursued, particularly as a way to calibrate other polarization analyzers.

(5) Techniques for polarization measurement at high energy, although not discussed at the workshop, need study and development.

Work Supported by the U.S. Department of Energy

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