RECENT ADVANCES IN POLARIZED-ELECTRON EXPERIMENTS

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The field of spin-polarized electrons has rapidly expanded in the past few years. Let me first discuss this with the use of a little table (Fig. 1): One of the processes

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Fig. 1. Electron polarization in various fields of physics.

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from which polarized electrons arise is elastic scattering of an unpolarized electron beam from an unpolarized target. The origin of the polarization is easy to see: The unpolarized primary beam may be considered as a mixture of equal numbers of spin-up and spin-down electrons (e+, e−); the polarization \( P = (N_+ - N_-)/(N_+ + N_-) \) of such a mixture is zero. Owing to the spin-orbit interaction of the incident electrons in the field of the atom one has a scattering potential that is spin-dependent. One therefore obtains a spin-dependent scattering cross section. In other words, different numbers of e+ and e− are scattered into the direction of observation. This means the scattered beam is polarized. Examples may be found in Refs. 1-3. The good agreement between theory and experiment shown there is typical: Owing to extensive experimental and theoretical studies in the past decade, the polarization in elastic scattering is now quite well understood, at least at energies above 100 eV.2,3

On the other hand, polarization studies on inelastic scattering are only at the beginning. Figure 2 shows, for

Fig. 2. Polarization of electrons scattered inelastically from Hg atoms (excitation of the 6^1P_1 state; energy loss 6.7 eV). Experimental4 and theoretical5 values.
various incident energies, the polarization vs. scattering angle of electrons that have excited the $6^1P_1$ level of Hg (energy loss 6.7 eV). The experiments have been done by W. Eitel in my group, the theoretical results are those of Madison and Shelton. Bonham published similar theoretical results last year. Strong polarization effects have also been observed in resonance scattering of slow electrons.

Polarized electrons are an ideal tool for studying exchange collisions, as I will discuss later. I will also talk about a few of the many aspects of spin polarization in ionization processes. You can produce polarized atoms by Stern-Gerlach-type magnets or by optical pumping with circularly polarized light and then eject the oriented atomic electrons by photoionization or by collisional ionization. Polarized electrons produced by collisional ionization of polarized metastables in gas discharges have been used as a diagnostic tool for analyzing collision processes by Walters and his group at Rice University. Another collision process will be discussed by Obyedkov later. One can also obtain polarized electrons from unpolarized atoms by using circularly polarized light for photoionization. I will discuss this Fano effect later on. I will also briefly describe how polarized electrons arise from multiphoton ionization.

There are other aspects of polarized-electron physics which seem not to belong in a conference of the kind we have here: One can extract polarized electrons from magnetized solids. The field of electron-spin spectroscopy, which has been developed by a group in Zürich, yields interesting and even surprising results on the band structure of magnetic solids. Several groups have started to work with polarized electrons in low-energy electron diffraction (LEED). I will later present the first experimental result.

Figure 1 would not be complete if it did not contain the impressive measurements of the electron g factor by means of polarized electrons. This is one of the fields for which the Seattle Physics Department also is well known. Last but not least, experiments with polarized electrons are being prepared at several high-energy accelerators.

From this broad spectrum I am going to pick out a few topics where significant experimental progress has been made during the two years since the last ICPEAC. Let me first describe studies of exchange scattering.

In a conventional electron-atom scattering experiment it is impossible to decide whether the observed electron has suffered a direct or an exchange collision. For this reason
direct and exchange cross sections cannot be measured separately. This is not so if the colliding electrons are distinguishable: If one works with spin-polarized electrons or atoms and if the colliding electrons retain their spin direction during the scattering event, then it is possible to distinguish between direct and exchange scattering. This has been done by Bederson's group\textsuperscript{12} in a well-known series of experiments and by a group at the Joint Institute for Laboratory Astrophysics.\textsuperscript{13} Both groups scattered unpolarized electrons by polarized atoms. This can, of course, only be done with atoms that have unsaturated spins, since only these atoms can be polarized (alkalis, for example). If one, instead, scatters polarized electrons from unpolarized atoms, one does not have this restriction and can use any atoms one wants.

Such an experiment has been performed by Hanne in Münster with Hg atoms.\textsuperscript{14} The idea was, very roughly, as follows: Take a polarized electron beam and fire it at Hg atoms in their ground state. Observe the electrons scattered in the forward direction after excitation of the $6^3\text{P}$ state of the mercury. We chose the forward direction for two reasons. First, there is the maximum of the scattered intensity. Second, the spins of the electrons scattered in the forward direction are not affected by spin-orbit interaction; this has been established in earlier experiments.

The excitation of the triplet state by exchange scattering is illustrated in Fig. 3 which shows that the outgoing

![Diagram](image)

Fig. 3. Excitation of triplet states by exchange collisions.
electron has the opposite spin direction of the incoming electron, if the sublevel $M_S = 1$ is excited. If $M_S = 0$ is excited, the spin directions of incident and scattered electrons are the same. A simple calculation that considers these two processes shows that the ratio $P'/P$ of the initial to the final polarization should be $-1/3$, if exchange scattering were the only way to excite the triplet state. In mercury, however, the spin-dependent forces are not negligible. The excitation of a triplet state can in this case not only occur by an exchange of electrons but also by a direct process, in which the spin of one of the atomic electrons flips during excitation. This affects, of course, the value of $P'/P$ so that a measurement of this ratio yields the extent to which the exchange processes discussed above still contribute to the excitation. This has been studied in a triple-scattering experiment.

Figure 4 is a schematic diagram of the apparatus. Scattering from a mercury-vapor beam, as described at the beginning of my talk, is used to produce a polarized electron beam. The polarized electrons are decelerated to energies between 5 and 15 eV and focused on a second mercury target. From the electrons scattered here an energy analyzer selects those that have been scattered in the forward direction after excitation of the $6^3P$ states of the mercury atoms (energy loss ~ 5 eV). The polarization of these electrons is analyzed by a Mott detector.

![Diagram of the apparatus](image)

**Fig. 4.** Triple scattering experiment for direct observation of exchange scattering by spin flip of polarized electrons in excitation of Hg.$^{14}$
Figure 5 illustrates an experimental result, which shows that at incident energies below 8 eV there are a great number of spin-flip processes. Near 6 eV the aforementioned value of $P'/P = -1/3$ is observed within the experimental error limits. That means that at this energy nearly all the excitation processes of the $6^3P$ levels occur by exchange scattering. On the other hand, the exchange excitation discussed above no longer plays an appreciable role at energies above 10 eV. Figure 6 gives these facts directly for the $6^3P_1$ state. It is the evaluation of a measurement in which the fine structure of $6^3P$ has been resolved.

Needless to say, experiments of this kind are rather delicate and need careful checks in order to ensure that the depolarization observed is not spurious. An essential check of the experiment discussed is shown in Fig. 7. Here the excitation of the $6^1P_1$ level (energy loss 6.7 eV) has been studied in the same apparatus. In the excitation of a singlet state from a singlet ground state no change of spin directions can occur, no matter whether the excitation takes place by a direct or an exchange process. This is observed in the experiment, which shows that no spurious depolarization effects occur.

This exchange experiment contains other interesting points which we are now studying but which I have to skip. All I can do here is to point out that polarized electrons provide a means for direct observation of exchange scattering, a field about which quantitative information is meager.

So far we have been discussing electron scattering by free atoms. Even though this is an atomic collisions conference, I think we should not be so specialized as to ignore an interesting experiment which is connected to surface physics: The group of Walters$^{15}$ at Rice University obtained the very first results on polarization effects in low-energy electron diffraction (LEED). I mentioned at the beginning the high polarization arising in electron-atom scattering. There is no reason why this should occur only in scattering from free atoms. There have been theoretical papers$^{16,17}$ predicting high spin polarization of the Bragg reflections obtained in LEED from solid targets. Whereas in scattering from free atoms the polarization is determined solely by the atomic field, in LEED the scattering process is influenced by several additional factors: The periodicity of the crystal lattice, the surface potential barrier, multiple scattering and inelastic processes. The electron polarization is therefore a sensitive probe of these factors.
Fig. 5. Measured values of depolarization vs. incident energy for $^1S_0 \rightarrow ^3P$.

Fig. 6. Contribution of the exchange processes illustrated by Fig. 3 to the excitation of the $^3P_1$ state. $\sigma^o$ is the differential cross section for excitation by these exchange processes, $\sigma$ is the complete differential cross section for excitation of $^3P_1$. 
Fig. 7. Measured values of depolarization vs. incident energy for $6^1S_0 \rightarrow 6^1P_1$.

Figure 8 gives an example of an experimental result. It has been obtained with a clean tungsten (001) surface in ultrahigh vacuum. The incident angle $\theta$ of the primary electron beam was varied and the polarization of the specularly reflected beam was studied with a Mott detector. The solid

Fig. 8. Polarization of the 00 beam as a function of angle of incidence $\theta$ for two values of the incident electron energy: $\circ$, 69 eV; and $\square$, 82 eV. Dotted line: Calculated polarization for scattering of 100-eV electrons from free tungsten atoms.
lines are experimental polarizations for two different primary energies, 69 eV and 82 eV. The comparison of the 82-eV curve with the corresponding theoretical curve (corrected for the inner potential) for scattering from free tungsten atoms shows little agreement. This is not surprising, since the polarization in scattering from a solid target is influenced by all those factors I mentioned before.

The experimental results have not yet been quantitatively explained. The quantitative theory is certainly much more difficult than in the case of free atoms. But there is no question that polarization experiments in LEED, in conjunction with theories as they are being developed now, are a new promising technique in surface studies. This explains why several labs, among them the National Bureau of Standards, have gone into this field.

Let me now talk about polarized electrons arising from photoionization. This field received a great impact from Fano's discovery that one does not have to photoionize polarized atoms in order to obtain polarized photoelectrons. One can also start from ordinary unpolarized atoms, if circularly polarized light is used for photoionization.18 This Fano effect is caused by the spin-orbit interaction of the photoelectron in the continuum. Spin-orbit interaction has two effects:

1) It can cause a spin flip of the ejected electron during the photoionization process.

2) It leads to a dependence of the photoionization cross section on the direction of the atomic spins relative to the photon spins. In other words: The ionization probability of atoms with spins parallel to the direction of the incident photon spins differs from that of atoms with spin antiparallel to this direction.

Accordingly, if we photoionize an unpolarized atomic beam (i.e. a mixture of equal numbers of spin-up and spin-down atoms) with circularly polarized light, we produce different numbers of e+ and e-, that means, we obtain a spin polarization of the photoelectrons. An example of an experimental result may be found in Ref. 19. It shows the polarization of the photoelectrons from cesium atoms as a function of the wavelength. Near 2900 Å a polarization of 100% was obtained within the experimental error limits. These results together with similar results by Baum, Lubell and Raith20 allow us to say that the Fano effect is fairly well understood for alkali atoms.

In the subsequent research, there were two basic aspects: First, the Fano effect was utilized for building
sources of polarized electrons. Several groups have been successful recently. The group at Bonn has published its result.\textsuperscript{21} By photoionization with a frequency doubled pulsed laser they obtained $3 \times 10^9$ electrons/pulse of 90\% polarization. The second aspect of the further studies is: How about elements other than alkalis, do they yield polarized photoelectrons, too? Again the theoreticians were faster than the experimentalists. The question was answered with "yes" in Leningrad,\textsuperscript{22} Chicago\textsuperscript{23,24} and Belfast.\textsuperscript{25}

In discussing the photoelectron polarization in these cases we must take into account the fact that for many atoms autoionizing transitions play a part in the photoionization process. They may cause a resonance structure of the polarization curve, as is shown in Fig. 9 for the case of thallium, for which the first experimental result has now been obtained.\textsuperscript{26} Dr. Heinzmann will explain this later in more detail. It is an interesting feature that owing to this resonance behavior, one frequently has polarization peaks at those wavelengths where one has maxima of the photoionization cross section. The magic rule for most other polarization phenomena, that polarization maxima are associated with intensity minima, is thus broken. As will be explained in the following talk, polarization measurements in autoionizing transitions yield information on autoionization that is not obtainable from cross-section measurements.

![Graph](image)

Fig. 9. Polarization of electrons produced by photoionization of Tl atoms with circularly polarized light. Experimental results and values predicted on the basis of experimental cross sections.
Another possibility for producing polarized photoelectrons is multiphoton ionization. This process, in which several photons are absorbed simultaneously, occurs if one works with high-intensity light sources like lasers. Figure 10 shows the simplest example I can think of. It has been suggested by Farago and Walker. Take an atom like thallium in a \( \Pi_{1/2} \) ground state and consider a two-photon process with, say, circularly polarized \( \sigma^+ \) light. Then you have the selection rule \( \Delta m_j = +1 \). This means that in Fig. 10 the arrows go upwards to the right. By the first absorption process with a suitable wavelength, you reach the sublevel \( m_j = 1/2 \) of an \( S \) state; no other transitions are allowed. Since for an \( S \) state \( m_j = m_s \), the excited state has the spin-orientation quantum number \( m_s = +1/2 \); in other words, the excited atoms are totally polarized. These totally polarized atoms are ionized by absorption of the second photon so that totally polarized electrons are to be expected.

This is by no means an exceptional case. By playing around with selection rules, energy levels, and the number of photons you can easily find innumerable other transitions which yield polarized electrons. It seems, however, that quite a few problems come up when one tries to verify these predictions experimentally: P. Lambropoulos has shown that the polarization may be strongly affected by high intensity effects of the radiation field. Preliminary experimental results have been obtained with sodium in JILA and with cesium in Münster. They verify that electron polarization is obtained by multiphoton ionization. For a quantitative test of the just-mentioned intensity effects of the laser light these measurements must be improved.

![Graph showing polarization and energy levels](image)

**Fig. 10.** Polarized photoelectrons by two-photon transition in trivalent atoms.
Let me conclude with another digression into solid-state physics. After we had made the Fano-effect experiment with cesium atoms we were curious enough to try the same with a cesium surface: We evaporated our cesium beam on a substrate, under the dirty conditions of normal high vacuum, and measured the polarization of the photoelectrons produced by circularly polarized light. It turned out that even under these conditions we obtained a polarization.\textsuperscript{30} (See Fig. 11.) It was only 5%, but the polarization maximum was now in the experimentally convenient visible region — not in the uv as with free atoms — and the intensity from this dense solid target was much higher than that obtained with an atomic beam. Other alkalis gave similar results. The subsequent work at Münster by Koyama and Merz showed that the polarization is due to spin-orbit splitting of the energy bands.\textsuperscript{31} This occurs in many solids so that many materials should yield polarized electrons in photoemission.

![Graph](image)

Fig. 11. Polarization of photoelectrons from solid cesium produced by circularly polarized light.\textsuperscript{30}

This has been demonstrated for the case of GaAs by the aforementioned group in Zürich.\textsuperscript{32} Figure 12 shows the result they obtained in ultrahigh vacuum. The shape of the polarization curve can be easily explained by the well-known band structure of GaAs. For the many materials whose band structure is less well known, electron-polarization measurements provide information on the acute problem of energy-band splitting in solids.

I did not emphasize in this report the aspect of polarized-electron sources since I have reviewed this area at an earlier conference.\textsuperscript{33} Rather I have tried to show that from
Fig. 12. Polarization of photoelectrons from GaAs + CsOCs at T < 10 K produced by circularly polarized light.32

experiments with polarized electrons interesting things can be learned in quite different fields of physics. A less condensed survey on the physics of polarized electrons will appear early in 1976.34

REFERENCES