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PHOTODETACHMENT IN MAGNETIC FIELDS

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Résumé. - Le comportement près du seuil de la section efficace de photodétection des ions atomiques négatifs est décrit et illustré à l'aide des résultats expérimentaux obtenus sur S. L'effet de l'interaction avec l'état final est discuté. La situation est comparée à la photoionisation d'atomes neutres dans un champ magnétique. Des résultats récents, concernant le photodétection de l'ion moléculaire SeH⁻ dans un champ magnétique sont présentés et commentés.

Abstract. - The behavior of the photodetachment cross section, near threshold, for atomic negative ions in a magnetic field is described and illustrated with data on photodetachment of electrons from negative sulfur ions. The effect of the final state interaction is discussed and the photodetachment of atomic negative ions in a magnetic field is compared to photoionization of neutral atoms in a magnetic field. New data on the photodetachment cross section of a molecular negative ion, SeH⁻, in a magnetic field are presented and discussed.

A striking and interesting example of the differences between negative ions and neutral atoms is provided by a comparison of atomic photodetachment in a magnetic field to atomic photoionization in a magnetic field. A description which ignores the final state interaction between the neutral atom and the departing electron compares rather well to experimental data on photodetachment from negative sulfur ions while the cross section for photoionization in a magnetic field is obviously strongly influenced by the coulomb attraction between the resulting ion and the departing electron. Of course, this situation is also true in the absence of the magnetic field as shown clearly by Wigner many years ago. He demonstrated that for production of pairs of non-interacting particles the cross section near threshold should vary as $k^{2l+1}$ where $k$ is the relative wave vector and $l$ is the angular momentum in the final state. Final state interactions which fall off faster than $r^{-2}$, i.e. faster than the centrifugal potential, do not change the shape of the cross section near threshold although they can affect the absolute magnitude and the range over which the asymptotic behavior is valid. However the stronger coulomb potential washes out the effect of the centrifugal potential and produces a cross section which is finite at threshold even for higher angular momenta.

The behavior for negative ions is easily understood in terms of the golden rule which says the cross section is proportional to $|<f|V|i>|^2 \rho(E_f)$ where $V$ is the perturbation causing the transition between initial and final states and $\rho(E_f)$ is the density of final states. For energies near threshold and distances on the order of the size of the initial bound state, $kr << 1$ and the free particle final state wavefunctions are proportional to $(kr)^l$. Since $\rho(E_f) \sim k$, the cross section varies as $\sigma \sim k^{2l+1}$ in agreement with the Wigner prediction. This kind of behavior has been verified in a number of cases.
Application of a magnetic field changes the final state wavefunctions from free particle to cyclotron wavefunctions. If the field is weak enough, the final state wavefunction is not modified very much in the region of space where it overlaps the initial state wavefunction. Explicitly, starting in a bound p orbital we still find that the transition matrix element is independent of energy to first order just as in the absence of the field. However, the density of states changes significantly. By constraining the electron to a single cyclotron or Landau level, we have reduced the three dimensional continuum to a one dimensional continuum. Thus $\rho(E_p) \sim 1/k$ and $\sigma \sim 1/k$. Of course, there is now an infinite number of thresholds corresponding to transitions to successively higher cyclotron levels and in the limit where the magnetic field is too small to permit resolution of the individual cyclotron levels a sum over the individual cross sections recovers the Wigner prediction.

The only experimental data to date on photodetachment of electrons from atomic negative ions in a magnetic field is that obtained for negative sulfur ions. In order to apply the ideas of the basic description above to the actual data, some complications have to be introduced. First the motion of the ions in the magnetic field during photodetachment leads to broadening effects from Doppler and motional Stark shifts. Second, the various Zeeman sublevels in the negative ion and neutral atom lead to a number of thresholds for a single cyclotron level and these thresholds need to be included with appropriate frequencies and relative amplitudes. This is described in detail in reference 1. An example of the agreement obtained between theory and experiment is shown in Figure 1.

![Figure 1](image_url)

**Figure 1.** Photodetachment data for S$^-$ ions near the $^2P_{3/2} \rightarrow ^3P_2$ threshold. The fraction of ions surviving illumination is plotted as a function of light frequency (with an arbitrary zero). The data shown here are for light of $\sigma$ polarization at 1.07 T. The data points are plotted together with a curve predicted by the theory described in the text.

The description outlined gives rather good agreement with photodetachment experiments where motional effects add significant broadening. It seems likely that such a simple description could fail to produce such good agreement if the resolution were not limited by the motional broadening. One obvious omission from
the theory is the effect of final state interactions. Since the longest range interaction falls off at least as fast as $r^{-3}$ for photodetachment of electrons from atomic negative ions, there is no significant modification of the shape of the threshold in the absence of the magnetic field. However, the magnetic field constrains the electron to remain close to the atom (in two dimensions) and might enhance the effects of the final state interaction. In order to get an idea of the effect of the final state interaction, assume that the motion of the electron is dominated by the magnetic field and that the electron-atom interaction is given by a potential $V(r)$. The effect of $V(r)$ in directions perpendicular to the field is assumed to be small and $V$ can be treated as a perturbation, but for motion along the field we must consider the effect of the potential completely and not as a perturbation.

Consider the case when the electron is detached to the ground cyclotron state. Following Landau and Lifshitz\textsuperscript{7} we write the wavefunction as the product of radial and axial parts $\psi(r) = R_0(\rho)\chi(z)$, substitute in the Schrödinger equation, multiply by $R_0(\rho)$ and integrate over $\rho d\rho$ to obtain

$$-\frac{\hbar^2}{2m} \chi'' + \bar{U}(z)\chi = \varepsilon \chi$$

where $\varepsilon = E - 1/2 F_m$ and

$$\bar{U}(z) = \int_0^\infty V(\rho^2 + \rho^2)^{1/2} R^2_0(\rho) \rho d\rho$$

If we start with a 3 dimensional well of depth $V_0$ and range $r_0 << a_F$, we find an effective one dimensional potential of depth $U_0 \sim V_0 (r_0^2/a_F^2)$, where $a_F$ is the cyclotron radius. Thus the effective depth is reduced by the ratio of the time the electron spends in the well to the time it spends out of the well.

If we start with a well a few eV deep and 1Å wide, there is an effective well depth on the order of 1 GHz at 1.0 T. This is comparable to the motional broadening in the previous experiments. Note that the effective depth increases linearly with applied field.

The potential well modifies in two ways the otherwise free electron motion in one dimension. First, any one dimensional well, no matter how shallow, has at least one bound state. Thus applying the magnetic field creates a new bound state. (This result is known\textsuperscript{7} and implies the existence of a bound negative ion state for ground state helium in the presence of a magnetic field.\textsuperscript{8} The ground state of helium has a negative electron affinity in the absence of a magnetic field). Unfortunately the binding, if real, is on the order of kHz for our effective potential and the bound state would be very difficult to observe in this case. A second effect of the potential well is to reduce the spatial density of the continuum states in the vicinity of the well for electrons near zero energy. This occurs over a range of energies comparable to the well depth and could be observable in precise experiments. Clearly this effect is correlated with the presence of the bound state since with energy resolution large compared to the effective well depth, the effects of the potential should be unobservable.

If the assumptions in the discussion above are valid, then the final state interaction could be visible in more precise data and would provide a rare look at atomic physics in one dimension. Of course a careful analysis would have to include a realistic atom-electron interaction.

It seems clear that a reasonably good description of photodetachment from atomic negative ions in a magnetic field can ignore the final state interaction or perhaps treat it in some perturbative fashion, at least for magnetic fields attainable in the laboratory. However, this is clearly not the case for photoionization in a magnetic field. The difference is due to the long range character of the coulomb potential. If we start with a very strong magnetic field, the behavior of the photodetachment cross section near the threshold will be
substantially influenced by the final state interaction if $a_H$ is comparable to atomic dimensions. If the field is reduced and thus the radius of the cyclotron orbit is increased, it appears the magnetic field effects alone will eventually determine the shape of the cross section. As the magnetic field is reduced the energy of the ground cyclotron level is reduced in proportion to $1/a_H^2$. Since the longest range interaction between the neutral atom and the electron falls at least as fast as $1/r^3$, the magnetic energy will dominate at sufficiently small values of magnetic field. This argument should apply for any final state interactions which fall off faster than $1/r^2$.

This suggests that a particularly interesting case intermediate between atomic photoionization and photodetachment from atomic negative ions would be a system where the final state interaction varied as $1/r^2$. Indeed, even in the absence of a magnetic field this is an interesting case since as the strength of the interaction is increased from zero to a large value the photodetachment cross section for a given $\lambda$ varies from the Wigner form to one which is finite at threshold and therefore similar to that observed with an attractive Coulomb interactions. Molecular negative ions provide candidates for observing this type of behavior due to the interaction between the molecular dipole moment and the electron. Indeed, thresholds with onsets sharper than the Wigner prediction for $\lambda=0$ have been recently observed in rotationally resolved photodetachment from $\text{OH}^-$ and explained in terms of the interaction between the electron and the molecular dipole moment.

We have very recently made measurements on the photodetachment of electrons from SeH$^-$ in a magnetic field of about 1.3T. The basic experimental technique is similar to that used for measurements on negative sulfur ions. The SeH$^-$ ions are created by dissociative attachment of electrons to H$_2$Se, stored in a Penning ion trap, subjected to illumination by light of a selected energy, and counted by measuring the currents induced on the trap electrodes while driving the ion motion. The fraction of ions surviving illumination by a fixed number of photons is plotted as a function of optical frequency. An example of the results obtained in the present experiments is shown in Figure 2. Five separate thresholds of the

![Figure 2](image)

**Figure 2.** Photodetachment data for SeH$^-$ in the vicinity of a threshold. This data was taken with a resolution of 0.2 cm$^{-1}$ at a field of 1.3 T.
type shown have been observed. This is only the second molecule for which the rotational structure in the photodetachment cross section has been resolved. The apparent scatter of data points in Figure 2 is much larger than the noise level and in fact is due to an oscillatory variation in the ion signal which appears generally in the data. This oscillatory structure is shown more clearly in Figure 3 where a finer scan was taken in the vicinity of another threshold. The experimental resolution for these results is on the order of 0.2 cm$^{-1}$. The oscillatory structure is highly reproducible and appears to be at or very close to the electron cyclotron frequency.

While no analysis of the effect of a magnetic field on molecular photodetachment has been carried out and while it is not clear that the analysis done for the zero magnetic field case can be readily extended to included magnetic fields, it is clear from the data on SeH$^-$ that there is a substantial effect due to the magnetic field. The most striking feature of the data is the way in which the ion number oscillates without damping even far from a threshold. This is in sharp contrast to the S$^-$ case where the oscillation damps out in a few cycles due to motional broadening and overlapping Zeeman split thresholds. It is possible that other sources for the oscillation should be considered, but it is unlikely that anything other than direct interaction of the departing electron with the magnetic field could have such a striking effect in the photodetachment data. Despite our limited understanding of the effects of a magnetic field on molecular photodetachment, it seems clear that it will prove to be an interesting and challenging problem.

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