All three measurements agree satisfactorily with the theoretical value[8]

$$s(\mathrm{H}, n=3)_T = 314.895 \pm 0.025 \text{ MHz}.$$

The success of this experiment in making fine-structure measurements using a fast hydrogen beam indicates that double oscillatory field techniques can be used to select those atoms which live a long time and thus the resonance lines can be significantly narrowed. This will make possible more precise measurements and enable one to resolve some of the disagreements and inconsistencies in the present fine-structure measurements.[1]

We wish in particular to acknowledge the aid of Mr. Robert Brown in constructing the accelerator and for numerous stimulating discussions of the technique. Mr. Mark Silverman contributed significantly to the reduction of the data and to the least-squares fitting program.

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HIGH RESOLUTION PHOTODETACHMENT OF S^- NEAR THRESHOLD*

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A tunable dye laser has been used to measure the fine-structure splitting of the ^2P state of S^- in a crossed-beam photodetachment experiment. These measurements verify photodetachment threshold laws and provide the most accurate experimental determination of any electron affinity.

The vastly increased resolution obtainable with continuously tunable dye lasers over conventional light sources offers a unique opportunity to make precise threshold measurements in photodetachment of negative ions. This paper reports the early measurements of the relative cross section for the process $S^- + h\nu \rightarrow S + e^-$ in the first 1200 cm^{-1} above threshold. These measurements provide the first experimental verification of the theoretical threshold law for p-electron photodetachment, on which some doubt has recently been cast,[1] and the first photodetachment measurement of negative-ion fine structure (the doublet splitting in O^- has been obtained previously be examination of the radiative attachment continuum[2]).

The theoretical threshold behavior of photodetachment cross sections of atomic negative ions is proportional to k^{2l+1}, where k is the momentum of the outgoing electron and l is its orbital angular momentum.[3] In the case of p-electron detachment, the outgoing electron is either s wave or d wave, and the threshold dependence is given by the s-wave contribution. Calculations on O^- photodetachment[4] indicate that the amplitude of the d-wave part is very small in the energy range studied here. Following the discussion in Branscomb et al.[3] the threshold dependence of the S^- photodetachment cross section is expected to be of the form

$$\sigma = \sum_{j=1}^{6} \alpha_j k_j,$$

where k_j is the momentum of the ejected electron in the jth transition. The six photodetachment transitions are those which connect the doublet S^- state with the triplet S state. One expects, therefore, six thresholds as a function of photon energy, each one incrementally $\sigma_j = \alpha_j k_j$.

The effect of the fine structure has been considered previously[3] in O^-, but primarily to establish an upper limit for the broadening of the threshold. In that paper and elsewhere,[1] the strengths of the individual fine-structure transitions have been taken to be the products of the statistical weights of the initial O^- states and

the final O-atom states. We contend that the model is inadequate since the final state also contains a free electron and since one would expect a total angular momentum dependence in the matrix elements.

The experimental apparatus[5] for photodetachment employs a 1-keV mass-analyzed focused beam of S^- ions crossed by the output from a tunable dye laser. Each pulse is approximately 0.3 μsec in duration, and the spectral width (full width at half-maximum) of a group of a few hundred pulses is about 0.1 nm. The dye, Rhodamine 6G, is flash-lamp pumped in an elliptical reflector.[6] The output beam is coupled from a 20%-transmitting mirror; and the energy per pulse is at most 1 mJ, tunable from 620 to 570 nm with a 2160-groove/mm echelle grating blazed at 500 nm. Repetition rates were 5 to 10 sec^{-1}.

The laser beam crosses the S^--ion beam at 90° and is reflected back through the ion beam by a mirror inside the vacuum system. The negative ions are electrostatically separated from the neutral atoms and the ion current is detected at a Faraday cup. The neutrals (at 1 keV) impinge on a 15-stage electron multiplier, whose output is a charge proportional to the number of neutrals incident on the first dynode. A grated integrator gives a high signal-to-noise ratio measure of the cumulative S-atom number.

The laser beam intensity is monitored by using a beam splitter inside the optical cavity to couple out a constant fraction of the cavity power to a thermopile detector. The wavelength of the laser output is determined by calibrating the grating angle with a 35-cm monochromator.

Data were obtained from three distinct groups which span different but overlapping wavelength regions. The three sets are normalized to each other, but the existence of a slowly varying energy-dependent error in the relative cross section cannot be ruled out.

A plot of the relative S^- photodetachment cross section as a function of photon energy is shown in Fig. 1. The existence of well-defined thresholds is clearly indicated. The possibility that some of the mass-32 ion beam is O_2^- is checked by establishing the signal zero below threshold. The upper limit to the zero for these data is two orders of magnitude below the cross-section value at the second threshold. Four of the thresholds (those indicated by arrows) can be identified in an unambiguous fashion because the fine-structure splitting of neutral S is known.[7] The $^3P_2$-$^3P_1$ splitting in S is 396.8 cm^{-1}, almost precisely the separation between the first two and between the second two indicated thresholds in Fig. 1. The separation of the first and third indicated thresholds is thus attributed to the $^2P_{1/2}$-$^2P_{3/2}$ splitting in S^-. The values for these thresholds are estimated visually from the cross section data to within 5 cm^{-1}. The fitting of the data to a threshold law then provides a means to establish the threshold value to within ±1 cm^{-1} on a relative scale.

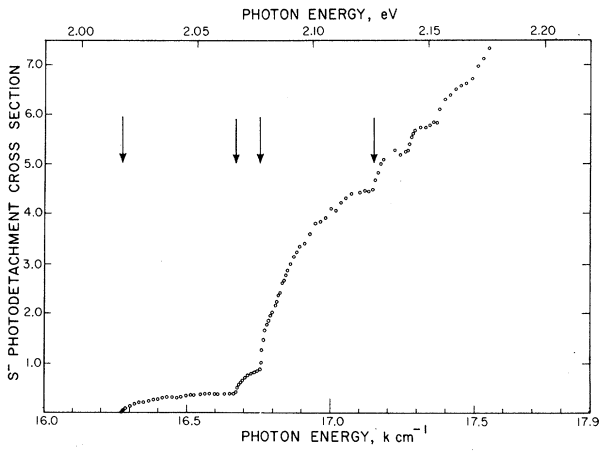

FIG. 1. Relative cross section for photodetachment of S^-. Arrows indicate the thresholds which are discussed in this paper.

The validity of the threshold law is checked by plotting $\ln\sigma_j$ vs $\ln E_j$ for the jth transition, where E_j is the energy of the ejected electron, k_j^2. Above the first threshold, σ_j is obtained by subtracting an extrapolation of the cross section below the jth threshold to about 100 cm^{-1} above it. Based on the energy dependence of the first threshold, the extrapolations are estimated analytic continuations generally slightly flatter than $E_j^{1/2}$ law. These low-energy points can be fitted by making adjustments in the threshold values from 1 to 3 cm^{-1}, well within their uncertainties. The resulting plots are shown in Fig. 2 for the four indicated thresholds. The solid lines are $(\Delta E)^{1/2}$ lines drawn through the plotted points.

Table I lists these four transitions with their identifications and term splittings. The electron affinity of 2.0772 ± 0.0005 eV is to date the most accurate experimental determination for any negative ion. The relative strength is simply the relative value of the coefficient in the expression $\alpha_j k_j$.

The largest significant error in the energy scale of these measurements is in the two-fold transfer of wavelength calibration from spectral lamp to monochromator to grating angle. This

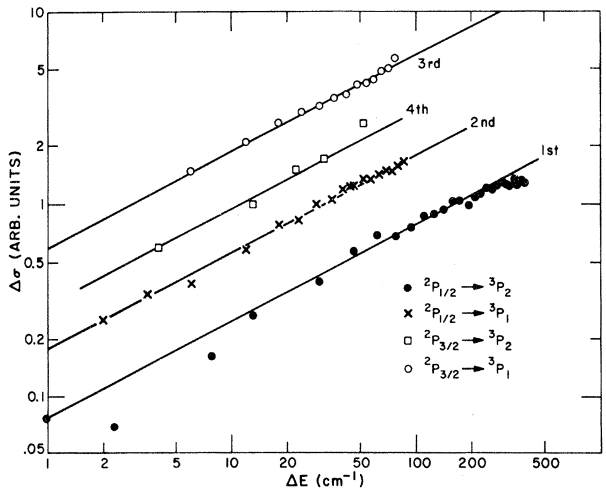

FIG. 2. Functional dependence of each of the four thresholds individually. $\Delta\sigma$ is the increment on the total relative cross section (corresponding to σ_j) and ΔE is the energy above each threshold (corresponding to E_j).

error is estimated to be at most 0.1 nm. No attempt at unfolding the data with the linewidth is made; so the over-all limit of error is estimated at 0.15 nm. Conservatively, this corresponds to an uncertainty of ± 5 cm^{-1} in the absolute energy scale; however, the relative values are considerably better, as indicated by the excellent agreement of our results for the S-atom $^3P_2$-$^3P_1$ splitting with the spectroscopic values. The $^2P_{1/2}$-$^2P_{3/2}$ splitting of 482 cm^{-1} is therefore estimated to be accurate to within ± 2 cm^{-1}. The relative strengths are not precision measurements, inasmuch as there exists some uncertainty about the energy-dependent errors, and since the extrapolation procedure is crude. In addition, the data are rather peculiar near the fourth transition threshold, and this transition strength is at least 50% uncertain. The others are estimated to be correct within 20%.

The experimental results provide two departures from the models for photodetachment previously accepted. Most prominent is the existence of apparent thresholds which are not part of the six transitions connecting $S^-(^2P)$ to S (^3P). These extra thresholds are the three at the highest photon energies and (perhaps) one about 200 cm^{-1} above the first threshold. Based on the limited amount of data, we are not prepared to explain these steps; however, the functional dependence is proportional to $(\Delta E)^{1/2}$ within experimental error. The possibility that the ground state of S^- is not ^2P has been considered, but this does not provide a simple explanation of the

Table I. S^- photodetachment results. Measured splittings (cm^{-1}): (a)-(b), 397; (c)-(d), 397; (a)-(c), 482; (b)-(d), 482.

	Transition	Threshold (cm^{-1})	Threshold (eV)	Relative strength
(a)	$^2P_{1/2} \rightarrow {}^3P_2$	16 273	2.0175	1
(b)	$^2P_{1/2} \rightarrow {}^3P_1$	16 670	2.0667	2.3
(c)	$^2P_{3/2} \rightarrow {}^3P_2$	16 755	2.0772 $\pm$0.0005 (electron affinity)	7.6
(d)	$^2P_{3/2} \rightarrow {}^3P_1$	17 152	2.1264	3.9

experimental results.

The other new result is more quantitative. We find that the relative strengths of the first two transitions are completely different from those assumed by previous workers.[1,3] We have attempted to make transition-strength predictions based on the quantum numbers which one assigns to the final-state complex composed of the S atom plus a free electron. Electric dipole selection rules and *LS* coupling allow only two terms to be associated with the final-state complex of the atom + s-wave electron. The d-wave contribution and interference terms are assumed to be negligible near enough to threshold that only the $E_j^{1/2}$ threshold law is observed experimentally. In that case the final states are just $^2P_{1/2}$ and $^2P_{3/2}$ (the same as the initial S^- states), and transitions are allowed from both S^- states to both of these final states. But these states do not have energy as an eigenvalue; i.e., the three states which are energetically separated ($^3P_{2,1,0}$ + s electron) are linear combinations of these two complexes. We have

$$^3P_2 + s = a_1{}^2P_{3/2},$$

$$^3P_1 + s = a_2{}^2P_{3/2} + b_2{}^2P_{1/2},$$

and

$$^3P_0 + s = b_1{}^2P_{1/2}$$

since total angular momentum must be conserved. The coefficients a_i, b_i are simply the fractions specifying the combinations of "states" to be related to the observed energies. The allowed Pauli states one obtains by coupling an s electron to each of the three atom states correspond to those obtained from an unweighted linear combination of complexes; so a_1 is arbitrarily set equal to a_2 and $b_1 = b_2$ (all the coefficients are $\frac{1}{2}$). Then the strengths for transitions from the initial states to the final states (of the complex) are obtained from Condon and Shortley[8] and

Table II. Relative transition strengths for ^2P-^3P photodetachment.

Transition	Previous assumption	This work	Experimental
$^2P_{1/2} \rightarrow {}^3P_2 + s$	1.0	1	1
$^2P_{1/2} \rightarrow {}^3P_1 + s$	0.6	3	2.3 ± 0.5
$^2P_{1/2} \rightarrow {}^3P_0 + s$	0.2	2	not observed
$^2P_{3/2} \rightarrow {}^3P_2 + s$	2.0	5	7.6 ± 1.5
$^2P_{3/2} \rightarrow {}^3P_1 + s$	1.2	6	4 ± 2
$^2P_{3/2} \rightarrow {}^3P_0 + s$	0.4	1	not observed

divided equally between the two competitors in each case. The strengths predicted in this way are compared in Table II with the observed and statistical strengths.

It is clear that the predictions using this "complex final-state" model are in substantially better agreement with the experimental transition strengths of the first two transitions than the statistical weight results. These arguments attempt to emphasize the importance of treating the final state in photodetachment as the atom + electron complex. We would hope that this work will provide incentive for a proper treatment of the bound-free transition strengths in fine structure.

We are deeply indebted to Dr. L. M Branscomb for his encouragement and help during the early portions of this program and to Dr. J. L. Hall for many discussions of the experimental results.

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ROTATION OF TOKAMAK EQUILIBRIA*

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It is found that resistivity causes the self-consistent Tokamak equilibria to be unstable towards rotation about the magnetic axis. The growth rate is $\sim 2\pi^2 \eta R^2 \beta / \iota^2 a^4$, with η the resistivity, $R(a)$ the major (minor) radius, and ι the rotational transform. This is comparable with the skin penetration rate $\sim \eta / a^2$ of the poloidal field. We employ simple magnetohydrodynamic theory with resistivity, without considering possible stabilization by other dissipative effects. The quantities η, β, and a/R are regarded as small. Our result agrees with one obtained previously in the case of an externally fixed field.

Recent theoretical studies of toroidally confined, low-β plasmas have shown that resistivity can drive the plasma unstable with respect to rotation about the magnetic axis.[1-4] Previous calculations have applied only to the case of externally produced confining fields, β being assumed so small that Ampère's law could be ignored. In view of the current interest in self-consistent toroidal equilibria with a driven toroidal current, as in Tokamak geometry, it is important to extend the stability analysis to this case. We treat these equilibria by means of the isothermal magnetohydrodynamic (MHD) equations, with a small scalar resistivity providing the only source of dissipation. In fact, as has been shown by Stringer,[5] Galeev,[6] and others, the effects of ion viscosity and electron thermal conductivity are dominantly stabilizing for most