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Excitation of Atomic Hydrogen to the Metastable $2^2S_{1/2}$ State by Electron Impact†

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Abstract

The cross section for excitation of atomic hydrogen to the $2^2S_{1/2}$ state by electron impact has been remeasured in a modulated crossed beam experiment in the energy range extending from threshold to 1000 eV. Absolute values for the 2S cross section were obtained by measuring the ratio of the 2S to 2P cross sections and using previous measurements of the 2P cross section, which were normalized to the Born approximation at high energies. The atoms excited to the 2P and 2S states were detected by observing the Lyman alpha photons produced by radiative decay and by quenching in an electrostatic field, respectively. In order to determine the total cross section, it was necessary to consider the polarization of the Lyman alpha radiation emitted in each method of detection. The remeasured cross section is found to be in agreement with the Born approximation above 200 eV. The measured ratios are in reasonable agreement with the ratios that would be predicted by the close coupling theory of Burke et al. The peak value of the cross section curve is $0.168 \pm .020\ \pi a_o^2$ and occurs at 11.6 ± 0.2 eV.

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I INTRODUCTION

Over the past decade considerable experimental effort has been given to the determination of the cross section for excitation of groundstate atomic hydrogen to the metastable $2^2S_{1/2}$ state on electron impact. Although Lamb and Retherford[1] had made a crude determination of this cross section as a minor part of their famous experiments on the fine structure of atomic hydrogen, the first serious attempt to measure the cross section was that of Lichten and Schultz[2] which covered the electron energy range from threshold to 45 eV. While the shape of the cross section curve as a function of electron energy seemed quite well determined, the main feature of the curve being a rapid rise to a peak at 11.7 eV, some problems attended the assignment of absolute values. The surface electron ejection detector used by Lichten and Schultz was difficult to calibrate accurately and on experimental grounds alone the value of the cross section at the peak was determined to be $0.28 \pm 0.14\ \pi a_o^2$. Lichten and Schultz used theoretical arguments to conclude that the true value was probably in the upper portion of this large uncertainty range and assigned the peak value at $0.35\ \pi a_o^2$.

Concurrent with these experiments, Stebbings, Fite, Hummer, and Brackmann[3] were approaching the problem by measuring the ratio of cross sections for excitation to the 2S state and excitation of Lyman alpha radiation. Since the latter cross sections had been measured previously,[4,5] with absolute values having been assigned by normalizing relative cross section data to Born approximation predictions over the energy range 250 to 700 eV, the cross section for excitation to the 2S state could be determined. In the experiment of Stebbings et al.[3] the metastable atoms were detected by applying an electric field which caused Stark mixing of the 2P states with the 2S state and led to emission of Lyman alpha radiation; the Lyman alpha photons were then detected directly. Since only a sample of photons emitted at 90° with respect to the direction of the electric field was detected, it was necessary to assume an angular distribution for the photons produced by quenching in the electric field in order to arrive at total cross section values. The distribution assumed by Stebbings et al. was that corresponding to a polarization fraction, P, equal to unity. With this assumption the data of Stebbings et al. indicated that at high energy the cross section for excitation to the 2S state agreed with the Born approximation, but yielded a value at the peak of the cross section curve of only 0.11 πa_o^2.

Lichten[6] pointed out that the assumed angular distribution was incorrect and argued that the proper angular distribution was the isotropic distribution corresponding to a polarization fraction P = 0. Making this correction increased the values of the 2S excitation cross section as determined by Stebbings et al. by 50%. While this had the effect of placing the peak value of the cross section at 0.16 πa_o^2, just inside the lower experimental limit set by Lichten and Schultz, it removed the agreement with the Born approximation at high energies. The experimental uncertainties at the high energies did, however, just barely overlap the Born approximation values.

Hils, Kleinpoppen, and Koschmieder[7] next attacked the problem by detecting quench radiation photons, taking a relative cross section curve and then normalizing this to the Born approximation for 2S excitation at high electron energies. While the relative cross section curve obtained by them agreed well with the shape of the 2S excitation curve obtained by Stebbings et al.,[3] normalization to the Born approximation at high energies placed the cross section at the peak at about 0.11 πa_o^2.

The possibility that the results of Stebbings et al.[3] were incorrect by virtue of working with an incorrect cross section for 2P excitation next came under scrutiny in the experiment of Long, Cox, and Smith[8] which re-examined the excitation of Lyman alpha. Their experiment considerably improved the precision of the earlier experiments of Fite et al.[4,5] but showed quite good agreement.

The matter rested in this state of confusion until it again came under review by the present authors. Recognizing that questions of angular distributions might still affect both the Lyman alpha and 2S excitation cross section measurements, the polarization of Lyman alpha radiation was measured both for direct electron impact excitation and for 2S quench radiation[9] from which angular distributions may be deduced. The latter measurement yielded the surprise that the radiation does not have a zero polarization as argued by Lichten[6] but in fact has an apparent polarization of -0.30 ± 0.02, which led to a more correct theoretical treatment of the quench radiation yielding P = -0.323.[10] The effect of this negative polarization on the 2S excitation results of Stebbings et al.[3] was to raise them yet another 11%, which at high energies put the Born approximation outside the experimental uncertainties in the results.

Under the circumstances, it became appropriate to repeat the experiment of Stebbings et al.[3] under the improved experimental conditions available a decade later, with a view toward either learning that one or more of the previous experiments on 2S excitation had been in error or discovering some new information on the range of validity of Born calculations. The present paper summarizes the results of these newer experiments.

II. EXPERIMENTAL APPROACH

An atomic hydrogen beam formed in the first of three differentially pumped vacuum chambers was modulated in the second chamber, while the third chamber contained the electron-hydrogen atom interaction region where the groundstate hydrogen atoms were excited to both the 2S and 2P states by impact of electrons in a crossed beam. The atoms excited directly into the 2P states decayed in the interaction region because their lifetime is very short (10^{-9} sec). The longer-lived metastable 2S atoms left the interaction region and entered the quench region where they were subjected to an electrostatic field which produced Stark mixing of the 2S and 2P states resulting in Lyman alpha emission. By measuring the signal from the quench region when the 2S atoms were all quenched-- and then moving the photon counter so that it could observe the signal from the crossed-beam interaction region, a ratio of signals $R_{90} = S_{90}(2S)/S_{90}(L\alpha)$ was obtained. Since the detector observed radiation emitted normal to both the electron beam direction and to the quench field direction, and since the atom beam and the electron beam remained unchanged during the two measurements, the signals were proportional through the same proportionality constants to the cross sections Q_{90}, as defined in the preceding paper.[9] That is

$$R_{90} = Q_{90}(2S)/Q_{90}(L\alpha) . \quad (1)$$

$Q_{90}(2S)$ is the 90° cross section which included direct excitation into the 2S state and cascading into the 2S state from higher excited states.

$Q_{90}(L\alpha)$ is the 90° cross section for the direct excitation of Lyman alpha plus Lyman alpha resulting from cascading. Since the values of $Q_{90}(L\alpha)$ are known from Long et al.,[8] measurement of R_{90} allowed the immediate determination of $Q_{90}(2S)$.

To relate $Q_{90}(2S)$ to the absolute total cross section, Q(2S), use was made of the fact that the Lyman alpha radiation from the quenched 2S state is electric dipole radiation, in which case

$$Q(2S) = (1-P/3)\ Q_{90}(2S) \quad , \qquad (2)$$

where P is the polarization of the emitted Lyman alpha radiation. The value of P has been determined[10] theoretically to be P = -0.323 which is in effective agreement with the experimental value P = -0.30 ± 0.02.[9] Hence, the absolute cross section $Q(2S) = 1.108\ Q_{90}(2S)$.

III. EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic diagram of the experimental apparatus is shown in Fig. 1. The source of the hydrogen atoms was a tungsten furnace heated by joule heating to approximately 2600°K with an internal pressure of up to 2 mm Hg. This produced a hydrogen beam which was 70 to 80% dissociated. Modulation of the beam at 270 Hz was accomplished by using a rotating toothed chopper wheel which enabled ac counting techniques to be used to distinguish between the beam and background signals.

A. Electron Gun, Collector, and Interaction Region Module

The electron gun (see Fig. 2) was patterned after one of Simpson and Kuyatt[11] and used a tungsten-ribbon filament. The energy of the electrons was provided by biasing the cathode negatively with respect to the grounded interaction region module. Throughout the course of the experiment, the electron current was monitored to ensure that it remained constant to within 1% during the measurement of the ratios of the quench and directly excited signals for each selected energy. To prevent electrons from entering the quench region where they could produce bremsstrahlung at surfaces and countable uv radiation from residual gases which would appear as noise, (1) Helmholtz coils were used to provide a magnetic field of 60 gauss parallel to the electron beam in the interaction region and (2) the electron gun was enclosed in a cylindrical enclosure with a small aperture in one end to permit electrons to enter the interaction region and open at the other end for the electrical leads for the gun components.

One of the main considerations in the design of the electron collector was to minimize the possibility of electrons being ejected from it and following the magnetic field lines back into the interaction region. This effect could produce an abnormally high value for R_{90} at higher energies (where the cross section for excitation of H(2S) is small) if secondary electrons with low energy (where the H(2S) cross section is large) were getting back into the interaction region, re-crossing the atom beam and exciting H(2S). The collector was made up of a central collector and an outer collector as shown in Fig. 2. The central collector was a wedge-shaped cavity such that electrons entering along the electron beam axis would strike the collector surface at an angle of incidence of 36°. The outer collector was cylindrical in shape with its axis along the electron beam axis so that it would collect only the electrons on the outer fringes of the electron beam, allowing the central and larger portion of the beam to pass through and be collected by the central collector. To hinder the back scattering of secondary and primary electrons from the collectors they were biased at +45 V and located far back where the magnetic field from the Helmholtz coil was small. Measurements of the magnetic field at the positions of the collectors revealed that the outer collector was subject to a field of 2 to 9 gauss and the central collector, being further removed, was in a field less than 2 gauss.

Typical electron currents used ranged from about 50 μA for electron energies above 50 eV down to about 25 μA for energies below 20 eV. The central collector collected from 75 to 80% of the electron beam with the remainder collected by the outer collector. It is probable that not all the measured electron current passed through the atom beam and the gun would not have been suitable for measuring relative cross sections. However, in the present experiments the only requirement is that the same current of electrons passed through the beam irrespective of whether directly excited Lyman alpha radiation or quench radiation was being observed, and the gun was suitable for making the ratio measurements here described. Both the Lyman alpha and quench signals varied linearly with electron currents for the currents used. The Stark quenching of metastable 2S atoms by the electron space charge in the electron beam of 30 μA near threshold (where this effect would be most pronounced) was estimated to be less than 0.1%.

The interaction region module was a cylinder whose axis was parallel to the electron beam as indicated in Fig. 2. It had a smaller diameter than the outer electron collector and was sufficiently long so that the effect of penetration of electric fields from the collectors into the interaction region would be to quench less than 10^{-6} of the H(2S) atoms leaving the interaction region of the two beams. Apertures in the module were made to (1) permit free passage of the incoming and outgoing hydrogen beam and (2) allow the photon counter to see the entire region of electron-hydrogen atom collisions with there being no chance for Lyman alpha photons to be reflected into the counter from a surface of the interaction region module. The size of the exit aperture from the interaction region was chosen so that atoms which were scattered through angles up to 25° in the horizontal plane and 15° in the vertical plane would enter the quench region in view of the counter. To prevent premature quenching of the 2S atoms in the interaction region by stray fields, all surfaces in that vicinity were gold-plated in the same bath and grounded. The electron gun and collectors were similarly gold-plated in the same bath to minimize contact potential differences.

The electron gun, collectors and the interaction region module were designed such that the photon counter could not see any surface that could be bombarded by electrons.

B. Quench Plates

After passing through the interaction region, the atoms entered a region in which an electrostatic field could be established to quench the metastable 2S atoms and cause them to radiate Lyman alpha photons. The quench field was provided by four parallel plates as shown in Figs. 1 and 2 with the plates being placed close to the interaction region in order to (1) minimize the loss of 2S atoms by collision quenching in the residual gas and (2) quench the 2S atoms before they have time to spread out due to the angular scattering which occurs when the hydrogen atoms are excited. The beam passed between the central two plates which were biased symmetrically above and below ground. The outer two were potential image plates used to reduce the fringe fields at the edges between the central plates. Reduction of the fringe fields helped ensure that quenching of the 2S atoms would occur in a very concentrated region which would be in the field of view of the photon counter (see Sec. IV for a discussion of the region of quenching).

To illustrate the reduction of fringe fields by the two outer image plates a field plot was made in an electrolytic tank for a representative case as shown in Fig. 3. In this case the four parallel plates were biased symmetrically above and below ground with a grounded plate in front of the parallel plates to simulate the grounded interaction region module. The rapid dropping off of the electric field as one leaves the region between the plates is shown by the fact that the electric field at point A is 0.38 of its value at point B (which is in the uniform field region). The lifetime t of an H(2S) atom in an electrostatic field E (in volts/cm) is given by [12]

$$1/t = 2780\ E^2\ \text{sec}^{-1} \quad . \qquad (3)$$

Hence, the lifetime of an H(2S) atom at point A is nearly 7 times longer than its lifetime in the uniform field between the plates (represented by point B) which indicates the rapid decrease in the efficiency of the guarded quench plates to quench H(2S) atoms in its fringe fields.

C. Photon Detection System

To detect the Lyman alpha photons given off by de-excitation of the 2P and quenching of the 2S states of the atoms, an iodine-vapor-filled ultraviolet photon counter[13] was mounted on a trolley so that it could be moved to view either the interaction region of the two beams or the quench region. The position of the counter on the trolley was such that its field of view would be perpendicular to the plane containing the electron and hydrogen atom beams. An oxygen filter was mounted on the front of the counter in order to strongly attenuate the ultraviolet radiation produced by electron collisions with background gases, while transmitting the Lyman alpha radiation. When the Lyman alpha from the quenched H(2S) atom was being observed, a shutter was used to block out the directly excited Lyman alpha radiation from the region where the electron beam and the atom beam crossed.

D. Use of a Quadrupole Mass Spectrometer

A quadrupole mass spectrometer was used to (1) determine the dissociation fraction of the hydrogen beam, (2) calibrate the energy scale for the electrons, and (3) measure the energy distribution of the electron beam. The spectrometer was positioned beyond the quench region so that the hydrogen beam could be sampled. It was necessary to turn off the magnetic field from the Helmholtz coil during the sampling of the hydrogen beam for H_1^+ and H_2^+ in order to allow the ions to drift undeflected into the mass filter.

The dissociation fraction D of the hydrogen beam was obtained by measuring the H_1 and H_2 particle fluxes in the beam, S_1 and S_2, which were ionized in the interaction region by 100 eV electrons. Then knowing the ionization cross sections for atomic and molecular hydrogen, Q_1 and Q_2, at 100 eV it was straightforward to obtain the dissociation fraction from [4]

$$D = (1 + \sqrt{2}\, Q_1 S_2 \,/\, Q_2 S_1)^{-1} \quad . \qquad (4)$$

The electron energy was calibrated by observing the appearance potential for ionization of atomic hydrogen which is known to be 13.6 eV and the energy distribution of the electron beam was determined by plotting the second derivative of the ionization cross section in the threshold region versus the electron energy. The best least squares fit for the experimental electron energy distribution was found to be

$$f(V) = AV^{1.05} e^{-5.25V} , \quad (5)$$

where V is the energy in eV above the onset of the distribution and A is a constant. The procedure of taking the second derivative of the ionization cross section near threshold is valid if the cross section is linear with excess electron energy. The deviations from linearity for the ionization cross section very near threshold that were studied by McGowan and Clarke[14] are sufficiently small that the linear approximation is good to the needed accuracy here.

E. Procedure for the Ratio Measurements

The experimental procedure used to measure the direct excitation and quench signals is as follows. The $S_{90}(L\alpha)$ signal was measured by positioning the counter directly beneath the interaction region (position B in Fig. 1). The quench field was kept off during this measurement.

The $S_{90}(2S)$ signal was obtained in the following manner. First, a measurement of the total signal from the quench region was made by positioning the counter below the region of maximum quenching (represented by position A in Fig. 1) and applying a quench field sufficient to quench all the 2S atoms in view of the photon counter (refer to Sec. IV for a discussion of the study made to ensure that all the 2S atoms were quenched in view of the counter). The shutter was used to shield the counter from photons originating in the interaction region. Next, an observation of the signal from the quench region was made with the quench field off so that the background ac signal could be determined. This background signal was caused by Lyman alpha photons escaping from the interaction region and by collisional quenching of the 2S atoms by background gases present in the experimental chamber. The photons produced by collisional quenching should be included in the $S_{90}(2S)$ signal since the photons originated from 2S atoms. A correction must be made to account for the photons escaping the interaction region and entering the counter. Knowing the approximate collision quenching cross sections for various background gases, Q_i, as measured by Fite et al.,[15] the number densities of the background gases, n_i, as determined with the quadrupole mass spectrometer used as a residual gas analyzer, and the beam path length, L, that the detector can effectively view (see Sec. IV) one can calculate the fraction F of 2S atoms that are collision quenched by using the formula

$$F = \sum_i n_i Q_i L. \quad (6)$$

It was found that for normal experimental operating conditions with the quench field off, 0.7% of all the 2S atoms are collisionally quenched in view of the counter. Having determined the ac background signal arising from collisional quenching, it was straightforward to determine the modulated signal caused by Lyman alpha photons from the interaction region. The $S_{90}(2S)$ signal was then obtained by subtracting the ac background signal, due to escaping photons entering the counter, from the 2S signal observed with the quench field on. Typically, the escaping photon contribution was about 4% of the total signal.

The above cycle would be repeated a minimum of two times for each determination of the ratio of the quenched signal to the direct excitation signal. From 5 to 10 determinations of the ratio at each energy were made on different days with different experimental conditions, such as, electron current and hydrogen beam densities, to ensure reproducibility of results.

In addition to the correction for the background signal it was necessary to correct the observed count rates at both counter positions for the residual H_2 in the beam and the effect of saturation of the photon counter. The signal attributed to the molecular hydrogen in the beam was determined by measuring the signal due to H_2 at a temperature T_o (both $T_o \sim 300°K$ and $T_o \sim 1200°K$ were used) where the dissociation fraction of the beam was zero and then calculating the signal expected at the temperature T where the ratio measurements were made and the dissociation fraction D was measured.

The loss of counts resulting from saturation of the photon counter was determined by measuring the dead time of the counter (500 μsec) and making an allowance for this effect in the observed count rates. Typical count rates for the direct excitation signal on the scaler which records the beam signal plus background signal were 20 counts/sec which required a 2% correction due to saturation of the counter. Since the quench signals were generally at least a factor of two smaller their corrections due to saturation were always less than 1% of the total count rate.

IV. RELATIVE EFFICIENCY OF THE DETECTION SYSTEM

Because of the very short lifetime of the hydrogen atom in the 2P states, the source of the directly excited Lyman alpha radiation could be only the small region of intersection of the electron and atom beams. The source of the 2S atom quench radiation signal, on the other hand, is the broader region of the quench field. In order to make a comparison of the two signals it was mandatory to ensure that the photons from the two separate source regions are detected with equal efficiency by the photon counter system.

This assurance was gained in a three-step process. First, a pair of slits of width 1.5 mm and length 1.1 cm were placed above the photon counter with the long dimensions perpendicular to the direction of the atom beam. The lower slit was located immediately above the center of the LiF window of the oxygen filter and the upper slit was located 4.1 cm above the lower slit. The atom beam was approximately 4.5 cm above the upper slit. The counter with the pair of slits was moved along under the beam interaction region and the extent of the region from which directly excited Lyman alpha photons originated was mapped. After correction for penumbra effects it was determined that the region appeared to be 4 mm long, in satisfactory agreement with the 3.2 mm length expected on the basis of the electron beam geometry. Since the atom beam was 4 mm wide at the beam interaction region, the source of Lyman alpha radiation as viewed by the photon counter was effectively a square of 4 mm on a side located approximately 10 cm above the photon counter.

The second step was to remove the slits from the photon counter assembly and again move the counter below the beam interaction region. It was found that the signal remained constant to within the statistical uncertainty of the recorded counts (2%) over a distance of traverse of the photon counter of 2.5 cm. Since the photon counter had cylindrical symmetry, it was established that the photon counter could "see" with constant efficiency a circle of 2.5 cm diameter at a distance of 10 cm.

The third step was to replace the slits above the photon counter and map out the source of the 2S atom quench radiation along the length of the hydrogen atom beam, at various settings of the quench field. These measurements were made using high electron energies (several hundred eV) for which it is known[3] that the excited atoms are deflected only slightly in the excitation process. Under these circumstances the excited atoms were confined to a width of about 6 mm, slightly more than the width of the groundstate atom beam at the quench region, and the quench radiation came effectively from a line source. It was determined that more than 99% of the quench radiation emanated from a length along the beam of 1.3 cm when the quench field was set at 100 V/cm. At the same field setting the signal dropped to zero beyond a point between the quench plates (thus ensuring that all atoms were quenched by the field) and a zero signal was found between the interaction region module and the quench field plates (thus ensuring that no quenching was occuring in the interaction region module due to quench field penetration).

Since the counter response was known from step (2) to be flat over a circle of diameter 2.5 cm and since for high electron energies the quench radiation source lay entirely within this circle, direct comparison of signals at high electron energies gave direct ratios of Q_{90} cross sections for 2S and Lyman alpha excitation.

At lower energies substantial momentum is transferred from the exciting electron and the excited atoms tend to fan out over an appreciable angular range. From the angular distributions reported by Stebbings et al.[3] and from the geometry used in the present experiment it was determined that with the 100 V/cm quench field less than 1% of the atoms could be quenched outside the 2.5 cm diameter circle over which the photon counter response was flat.

We thus conclude that at all energies the photon counter detected with equal efficiency to within 1% the radiation coming from the 2P excitation and the 2S quench radiation.

V. RESULTS AND DISCUSSION

The experimentally determined values of R_{90}, the ratio of the observed quench signal to the direct excitation signal are shown in Figs. 4 and 5, along with the standard deviations from the mean values for the accumulated data. Above the n=3 excitation threshold the observed signals are not entirely those resulting from direct excitation of the 2S and 2P states, but also include contributions due to cascading from higher excited states. Q(2S) and Q(2P) as defined are the total cross sections for excitation into the 2S and 2P states which includes cascade effects. Long et al.[8] have indicated that the cascade contribution to population of the 2P states is about 2%, and Lichten and Schultz[2] have established that the total cross section for excitation into the 2S state is of the form

$$Q(2S) = Q(1S\text{-}2S) + \gamma Q(1S\text{-}3P) \quad , \qquad (7)$$

where γ is a constant and Q(1S-2S) and Q(1S-3P) are the total cross sections for direct excitation of hydrogen atoms in the 1S state to the 2S and 3P states, respectively. Hummer and Seaton[16] have subsequently shown that the appropriate theoretical value for γ is 0.23.

The experimental results predicted by the Born approximation, shown for comparison in Fig. 4, were obtained from the Q(2S) and Q(2P) Born total cross sections by using the experimental values of the polarization[9] to calculate the $Q_{90}(2S)$ and $Q_{90}(2P)$ cross sections and then determining the ratio

$$R_{90} = Q_{90}(2S) \;/\; Q_{90}(2P). \qquad (8)$$

It can be seen that the Born approximation is in good agreement with the experimental data above 200 eV.

In Fig. 5 the ratios measured in the near threshold region are compared with the ratios predicted by the best theoretical results of Burke and his collaborators,[17-19] who have used the close coupling approximation to calculate the Q(1S-2S) and Q(1S-2P) cross sections. They used the 6-state (1S,2S,2P,3S,3P,3D) close coupling approximation[18] above 11.6 eV in order to display the resonance structure in the vicinity of the n=3 excitation threshold, whereas an approximation using three states (1S,2S,2P) plus 20 correlation terms[19] was used below 11.6 eV. In the belief that the latter approximation gave superior absolute values, the results from the 6-state calculations were renormalized to agree with the results of the 3-state-plus-correlation calculations at 11.6 eV. Since their calculations extend only up to the threshold for excitation of the n=3 level of the atom, no correction for cascade effects is necessary in comparing theory with experiment.

It is necessary to take into account the energy distribution of the electrons in the electron beam, however. Our procedure was (1) to fold the known electron energy distribution into the cross sections given by Burke et al. for both 2S and 2P excitation, in order to arrive at predicted experimental total cross sections and (2) to use the data on polarization of the observed radiation in order to obtain the predicted experimental Q_{90} cross sections, which were then divided to obtain R_{90}. It is the predicted ratios determined in this manner that are shown in Fig. 5.

It is seen in Fig. 5 that above 10.8 eV the experimental ratios appear to be slightly lower than those predicted by close coupling theory. The disagreement may not be as large as indicated however because there was an uncertainty in the electron energy of ± 0.1 eV. A shift of experimental points by this amount toward higher energies would reduce the discrepancies shown. In general, however, it appears that there is good agreement between theory and experiment for the values of R_{90} at the low energies.

The total experimental Q(2S) cross section shown in Fig. 6 was deduced from the formula

$$Q(2S) = (1-P/3)\, R_{90}\, Q_{90}(2P) \ , \qquad (9)$$

where P = -0.323[10], R_{90} is the experimentally determined ratio, and $Q_{90}(2P)$ is the 90° cross section for direct excitation of Lyman alpha by electron impact. Above 200 eV the Born approximation values were used for $Q_{90}(2P)$. In the energy range extending from 15 to 200 eV the experimental $Q_{90}(2P)$ data of Long et al.[8] was used which was normalized to the Born approximation at 200 eV. The $Q_{90}(2P)$ cross section values used at and below 15.0 eV were obtained from the total Lyman alpha excitation cross section measurements of McGowan et al.[20] who referenced their data to Long et al.[8] in the energy region 30 to 50 eV. The error bars shown in Fig. 6 represent the standard deviations accumulated for Q(2S) from equation (9). Below 15.0 eV the standard deviations are of the order of ± 10%.

At energies above 15 eV the statistical error in counting for the measured ratios and the errors in $Q_{90}(2P)$ are considered to be the major sources of error in the present determination of the Q(2S) cross section. Previous determinations of the Q_{90}(2P) cross section[4,5,8,20] are in good agreement above 15 eV and it is believed that uncertainties in Q_{90}(2P) contribute little to uncertainties in Q_{90}(2S).

In the energy range extending from threshold (10.2 eV) up to 15.0 eV there is a greater uncertainty than there is above 15 eV in determining the Q(2S) cross section by the ratio method, especially in assigning a maximum value to the Q(2S) cross section which is expected in the vicinity of 11.7 eV.[2,7] This increased uncertainty is due partly to the uncertainty of ± 0.1 eV in the calibration of the absolute electron energy which is quite significant between 11.0 and 14.0 eV because the experimental ratios have a rather strong electron energy dependence in this energy region as can be seen in Figs. 4 and 5.

Another item to be considered below 15.0 eV is that the Q_{90}(2P) cross section has not been investigated as extensively as above 15 eV. The measurement of the Q(2P) cross section by McGowan et al.[20] has been the only thorough determination in this energy region using high energy resolution. Long et al.[8] have measured the Q_{90}(2P) cross section at three energies below 15.0 eV and a relative measurement of the Q_{90}(2P) cross section was made in the present experiment; however, it was elected to use the results of McGowan et al.[20] because their experiment was specifically designed for operation in the energy range near threshold and is probably the most reliable of the available data.

The maximum value obtained for the Q(2S) cross section was $0.163 \pm 0.020\ \pi a_o^2$ at 11.6 ± 0.2 eV. The error quoted for the cross section value includes the accumulated statistical error from equation (9) plus the uncertainty in the electron energy scale. The uncertainty of ± 0.2 eV in the electron energy for the maximum cross section value arises from the uncertainty in the absolute electron energy scale plus the statistical errors in R_{90} and Q_{90}(2P).

The experimental results of Hils et al.,[7] which were normalized to the Born approximation at higher energies, and the data of Lichten and Schultz,[8] which are normalized to the present data at 25 eV, are shown in Fig. 6 for comparison with the present results. At 15 eV and lower energies the normalized Lichten and Schultz curve rises above the present determination of Q(2S) and reaches a maximum of approximately $0.204\ \pi a_o^2$ which is almost a factor of two larger than the peak value of Hils et al. and about 20% higher than the present results.

The close coupling theory of Burke et al.,[17] when folded with the present experimental electron energy distribution, as shown in Fig. 6 predicts a maximum of $0.212\ \pi a_o^2$ for the Q(2S) cross section in the vicinity of 11.6 eV. Comparing this with the experimental results one finds that Q_{max}(2S) for the present data is about 20% smaller and the normalized Lichten and Schultz curve is 4% smaller than the close coupling theory.

On the basis of the present experiments, it would appear that the values reported by Stebbings et al., after corrections for the polarization of quench radiation, are quite good at low energies but that at high energies their measured values of R_{90} were greater than the true values. It is conceivable that this error resulted from the experimental effect which Stebbings et al. identified but perhaps did not fully eliminate. The effect is due to secondary electron emission at the anode of the electron gun. In particular, if a high energy electron (where the cross section for excitation of H(2S) is small) emits secondary electrons at low energies where the H(2S) excitation cross section is large, and these secondary electrons travel along a magnetic field line back through the atom beam, the total H(2S) production will be abnormally large and abnormally high values of R_{90} will be recorded. We conjecture that this effect was still operating in the experiments of Stebbings et al. despite their efforts to eliminate it.

Similarly we conjecture that the same problem occurred in the experiments of Hils et al.,[7] thus accounting for their relative cross section curve being generally flatter than that deduced from the present experiments.

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FIGURE CAPTIONS

1. Experimental set-up for measurement of the experimental ratios of the quench signal to the directly excited Lyman alpha signal. Position A corresponds to the photon counter position for observation of the quench signal and position B for observation of Lyman alpha from the interaction region.
2. Schematic of electron gun, collector, Helmholtz coils, interaction region module, and quench plates.
3. Electric field equipotential lines for guarded parallel plates in front of a grounded plate.
4. Measured experimental ratios compared with the ratios predicted by the Born approximation.
5. Measured experimental ratios below 14.0 eV compared with the ratios predicted by the best close coupling theory of Burke et al.
6. Total experimental Q(2S) cross section compared with previous experiments and theory.

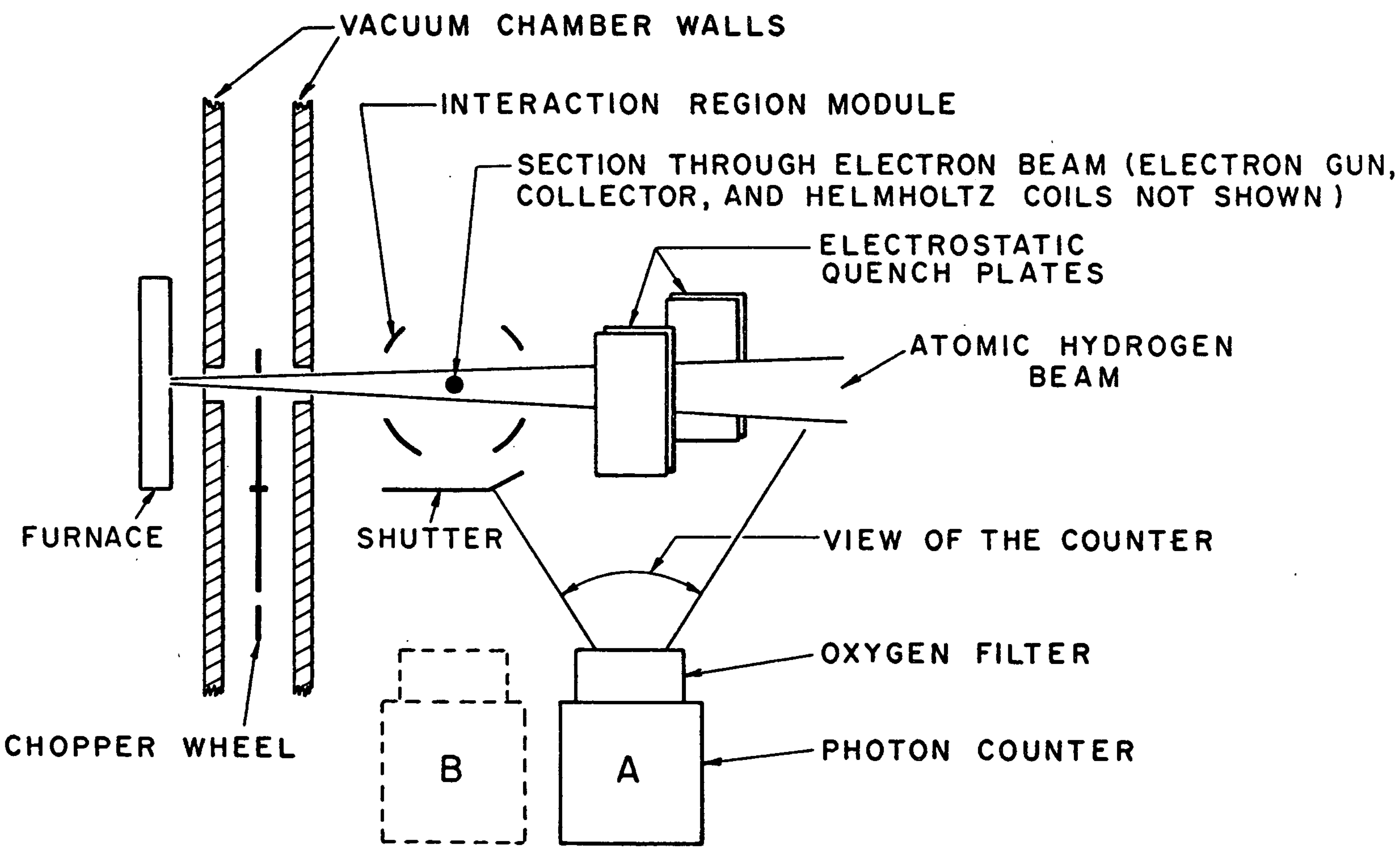

Figure 1. Experimental set-up for measurement of the experimental ratios of the quench signal to the directly excited Lyman alpha signal. Position A corresponds to the photon counter position for observation of the quench signal and position B for observation of Lyman alpha from the interaction region.

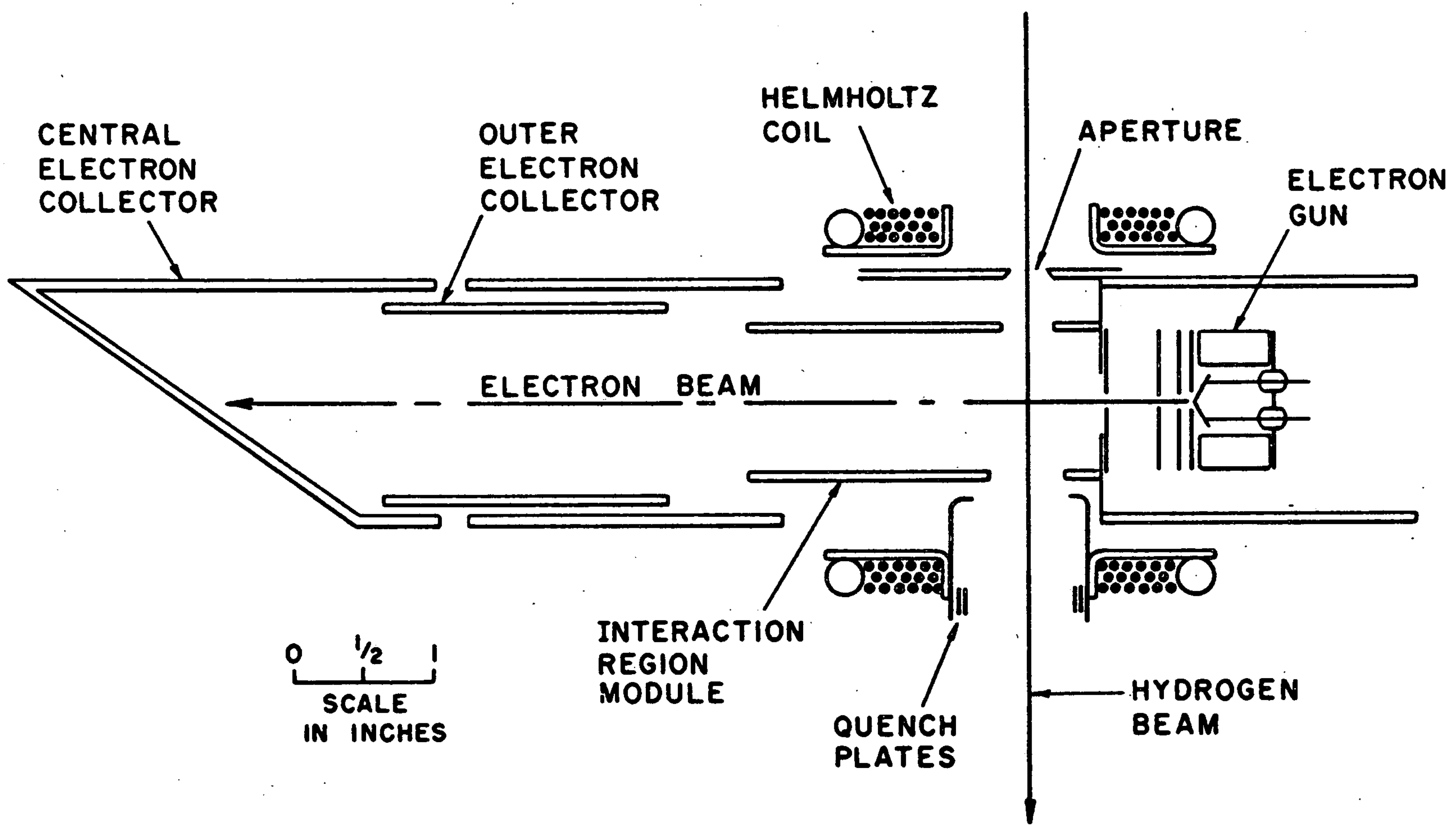

Figure 2. Schematic of electron gun, collector, Helmholtz coils, interaction region module, and quench plates.

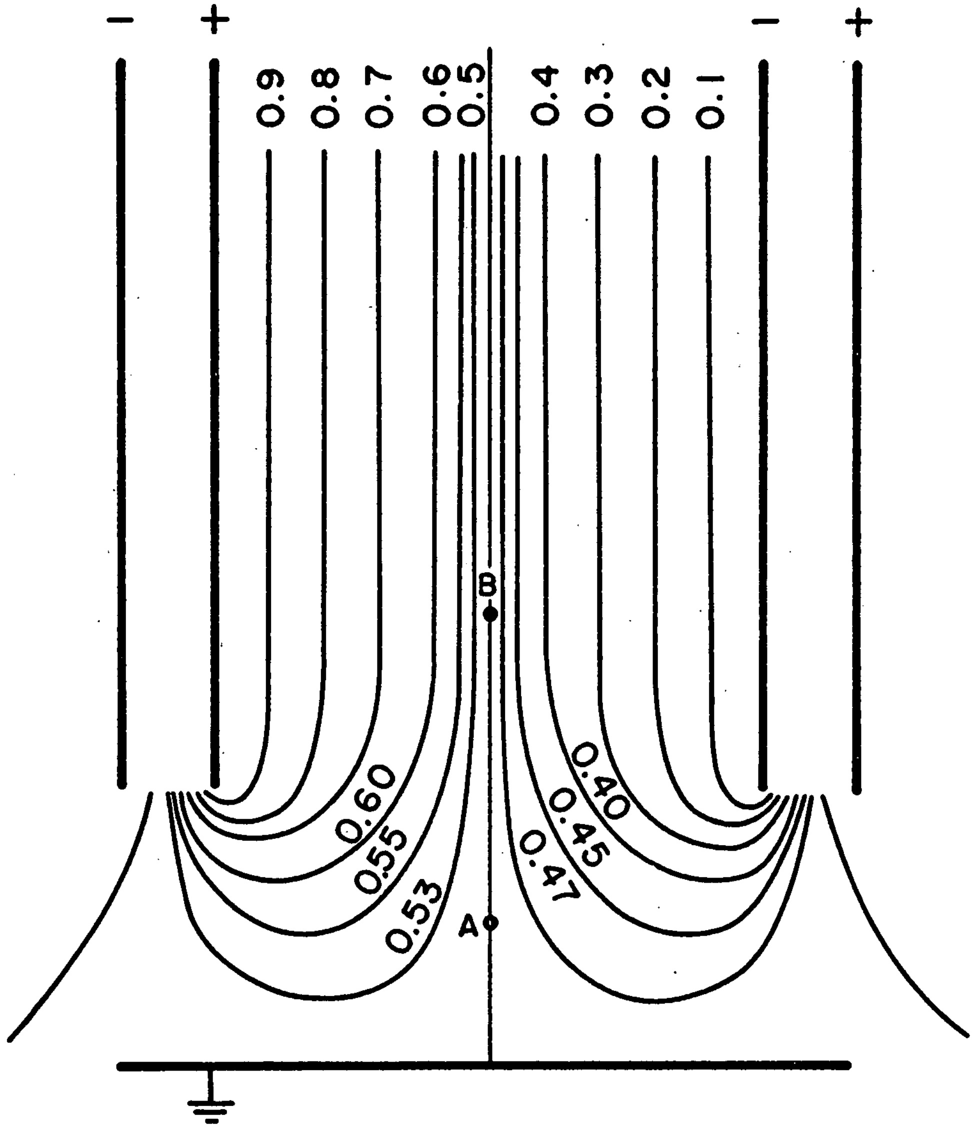

Figure 3. Electric field equipotential lines for guarded parallel plates in front of a grounded plate.

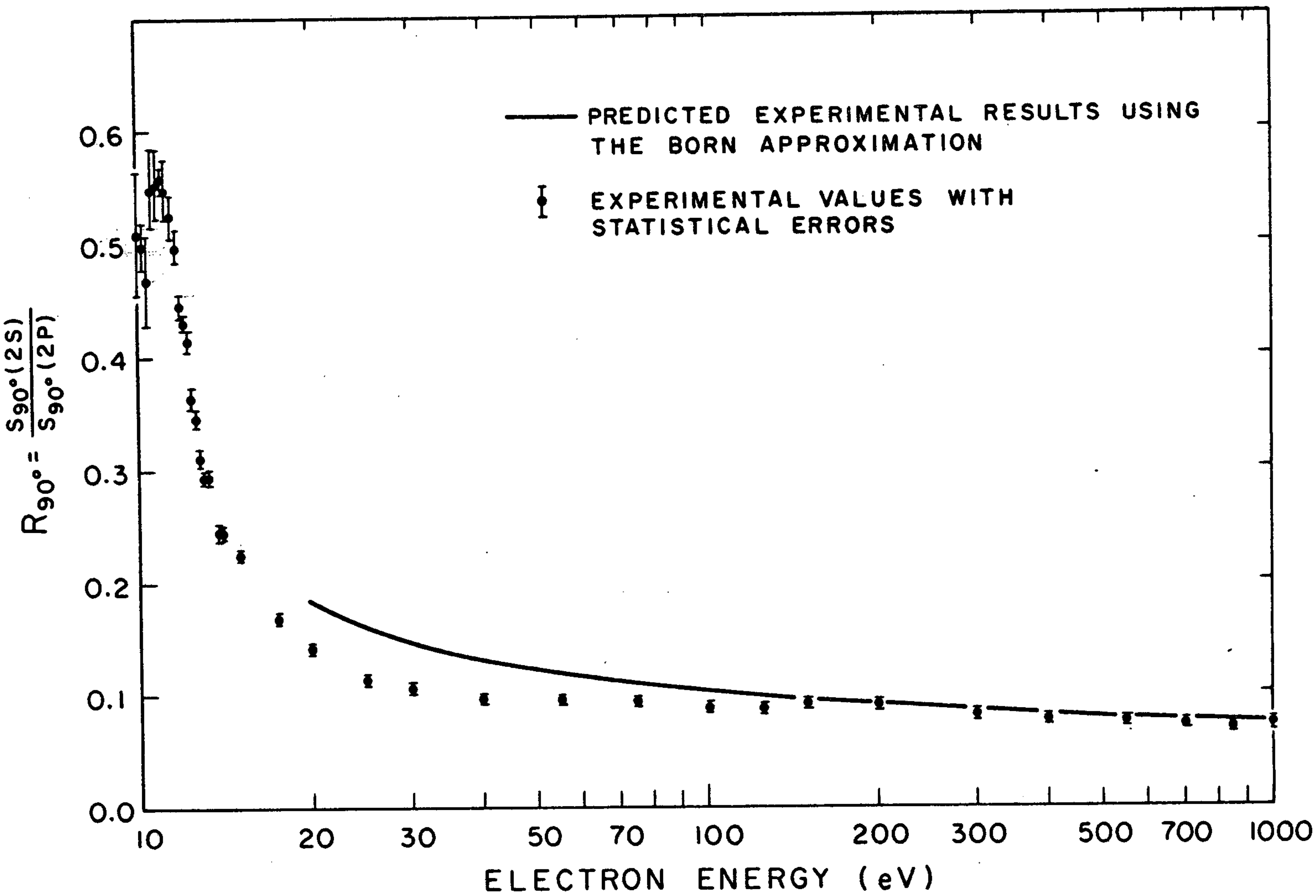

Figure 4. Measured experimental ratios compared with the ratios predicted by the Born approximation.

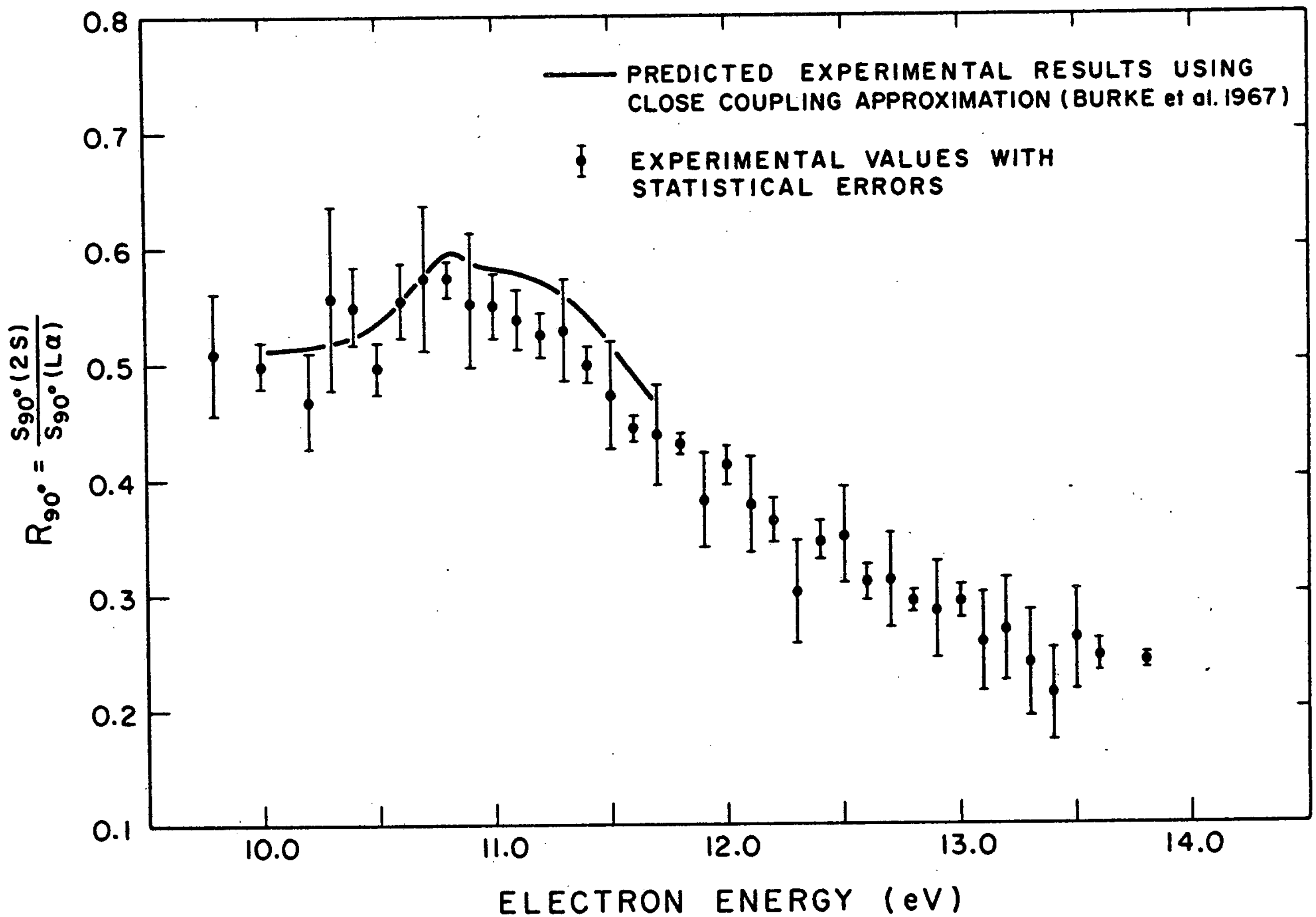

Figure 5. Measured experimental ratios below 14.0 eV compared with the ratios predicted by the best close coupling theory of Burke et al.

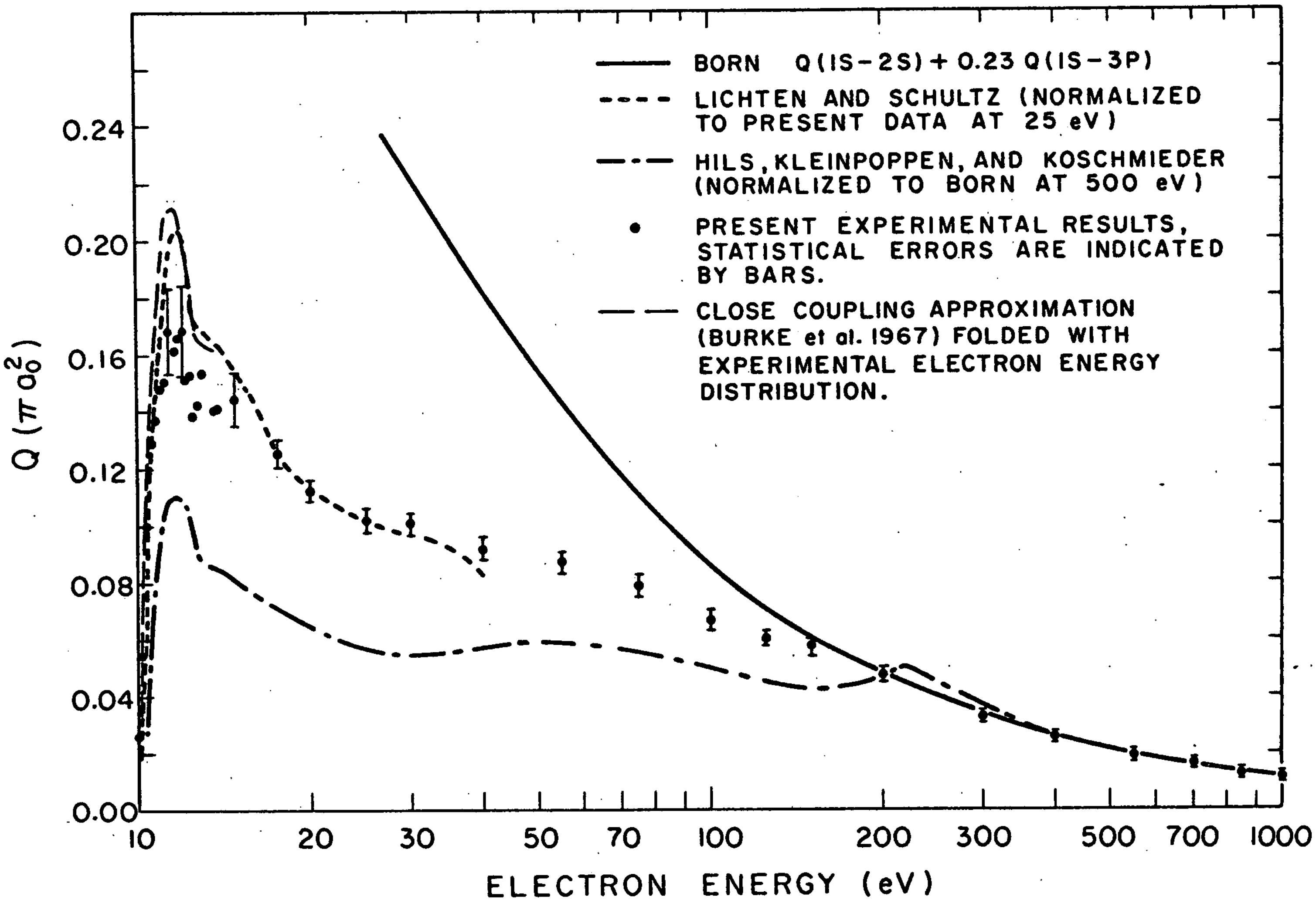

Figure 6. Total experimental Q(2S) cross section compared with previous experiments and theory.