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Collisional coherent excitation to the $n=2$ state of hydrogen

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This paper presents measurements of the Lyman-α photons emitted when target gases He, Ar, O_2, and N_2 are bombarded by a beam of ground-state hydrogen atoms. The collisions take place in the presence of an axial electric field and the observed Lyman-α brightness depends on field direction. This observation is interpreted as evidence for excitation of hydrogen atoms to states which are linear superpositions of $2s$ and $2p$. Measurements are presented of a "mixed" cross section σ_{sp} which characterizes the degree of coherent excitation. The real part of σ_{sp} measures the electric dipole moment created by the collision, while the imaginary part measures the rate at which the moment is changing. It is found that these quantities vary substantially over the energy range 3–30 keV, with maximal values being about as large as permitted theoretically. Coherent excitation should be present to some degree in all inelastic collisions and, when measurable, provides new tests of scattering theory. Some implications are also discussed for precision frequency measurements and searches for weak-interaction effects in atomic physics.

I. INTRODUCTION

An atomic collision may be regarded as preparing an atom in a certain state. For example, in an experiment to measure optical excitation functions, the collision is usually thought of as providing an (excited) atom in an eigenstate of the atom's internal Hamiltonian. However, in general it is to be expected that after undergoing a collision, an atom will be in a linear combination of energy eigenstates. The purpose of this paper is to describe an experiment to study such "coherent excitation." (In this context, coherent excitation means excitation to a state which is a linear superposition of energy eigenstates.)

In the experiment, schematically shown in Fig. 3, a beam of ground-state hydrogen atoms with kinetic energies in the range 3–30 keV was passed through a target gas cell containing one of the gases He, Ar, N_2, O_2. Lyman-α photons emitted by collisionally excited hydrogen atoms in the $n=2$ level were observed at right angles to the primary beam direction. The entire collision region was in a constant electric field which could be directed either along the beam direction or antiparallel to it. It was observed that the Lyman-α count rate changed by a few percent when the field direction was reversed. As will be explained in the following paragraphs, and as was first pointed out by Eck,[1] this may be interpreted as evidence for coherent excitation of the various near-degenerate states with principal quantum number $n=2$: that is, just after a collision, each excited hydrogen atom is in the same linear superposition of the various fine and hyperfine states. (For incoherent excitation, the probability of Lyman-α emission depends only on the *magnitude* of the electric field.)

Further experimental details are presented in Sec. III. Briefly, the apparatus was a very conventional one, with no technological tricks being required. The counting rates, of order 10^2 sec^{-1}, were large enough that statistical errors were noticeable but not significant. The principal sources of uncertainty are in possible systematic errors. These are discussed in Sec. III B.

Coherent excitation should be generally present in all collisions (atomic, molecular, and nuclear). The magnitudes of associated effects depend on the relative phases of scattering amplitudes (among other parameters), and hence measurements of coherent excitation effects provide new tests of theory—based on "mixed" cross sections. In terms of scattering amplitudes, the measured asymmetry depends on a mixed cross section σ_{sp} defined by

$$\sigma_{sp}=\sum_{\alpha}\int_{4\pi} f_{2s;\alpha} f^{*}_{2p_0;\alpha}\, d\Omega\,, \tag{1.1}$$

where the f's are scattering amplitudes for production of the $2s$ and $2p_0$ states in hydrogen (with the target atom being left in state α). σ_{sp} is in general complex, which reflects the extra phase information available through coherent excitation.

The experiment is similar to ones in which quantum beats are observed in fluorescence excited by short light pulses. In such radiative excitation, only levels of the same parity are coherently excited; in collisional excitation, coherence can be established between levels of either the same or different parities.

Our experiment is also similar to one reported by Sellin *et al.* in Ref. 2. In their experiment,

$2s$-$2p$ coherence was observed in hydrogen atoms made by charge exchange in a proton beam traversing helium gas under single-collision conditions. Quantum beats were detected in an electric field region downstream from a thin gas cell. In our experiment, the excited hydrogen atoms were made by collisional excitation of a neutral hydrogen beam, instead of by charge transfer, and the coherence detected in light emitted by a section of the beam long enough to contain many quantum beats. The technique of Sellin *et al.* is perhaps clearer; ours is applicable to lower energies.

Coherent excitation has long been observed in beam foil experiments. (See, for example, the review by Berry in Ref. 3, Sec. 7-3.) Foil excited coherence in the $n=2$ level of hydrogen has been studied by Gaupp *et al.*,[4] and Sellin *et al.*,[4] using the reversing field technique. In such experiments the excited atoms are produced by interaction with a macroscopic system (the foil), whereas in our experiment, and in that of Sellin *et al.*,[2] the interaction is between two atoms.

Coherent excitation in electron-helium collisions has been studied by Eminyan *et al.*[5] In this case, coherence was observed between the three magnetic substates of a helium atom excited to the 3^1P state by electron bombardment. A coincidence technique was used to isolate only those excited atoms recoiling in a selected direction. Since 1975, a number of similar experiments have been reported. (For a review, see Ref. 6.) Our experiment involves a sum over all scattering angles, and also differs in that coherence is observed between states of different angular momentum and energy.

Coherence between magnetic substates of an excited level is also commonly observed if the excited atomic state is populated by electron bombardment, with the direction of the electron beam being perpendicular to that of an ambient, constant, magnetic field. Quantum beats may be detected if the electron beam is pulsed.[7] In such experiments, the coherence between magnetic substates is induced by the transverse magnetic field, and not by the electron bombardment. Quantum beats could be observed even if only one magnetic substate were populated relative to the axis of quantization defined by the electron beam. (In general, more than one magnetic substate is populated, but a symmetry argument can be used to show that after integration over all scattering angles states of different magnetic quantum number are incoherent with each other. The symmetry argument assumes that the initial state is invariant under rotations about the electron beam direction.)

An experiment in coherent excitation has been reported by Mahan and Smith[8] and is discussed in the references.[9,10] In this experiment electrons were used to excite the Balmer-α lines of hydrogen in the presence of an electric field. A small change in light intensity was observed when the direction of the electric field was reversed, and this change was attributed to coherent excitation of the $3s$, $3p$, and $3d$ levels. Coherent excitation of the $n=3$ level in H has also been observed by Lombardi and Giroud[17] in an experiment on emission of Balmer-α light from an H_2 target bombarded by a beam of Na^+ ions. In this case, coherent excitation showed up as a dependence of light polarization on an applied electric field.

II. THEORY

A. The initial state

Our experimental data has been analyzed on the basis of the following model: A hydrogen atom leaving the collision volume in a particular direction, and leaving behind a target atom in a particular internal state, is regarded as being in a linear superposition of internal hydrogen states, with the coefficients being scattering amplitudes evaluated for the internal states and direction in question. Atoms traveling in different directions are assumed to be incoherent with one another, as are those atoms which leave behind target atoms in different states.

Such a situation is illustrated in Fig. 1, which shows a collision viewed from the center-of-mass frame. After the collision, hydrogen atoms are to be described by a density matrix whose matrix elements are

$$\rho_{ij}=N\sum_{\alpha}\int_{4\pi} f_{i;\alpha}(\Omega)f^{*}_{j;\alpha}(\Omega)\,d\Omega\,. \tag{2.1}$$

In (2.1), i and j label internal eigenstates of the hydrogen atom and α the internal states of the target atom; $f_{i;\alpha}(\Omega)$ is the scattering amplitude to produce a hydrogen atom in the internal state i and a target atom in internal state α, the pair separating in a direction specified by Ω. N is a normalization constant defined by the condition

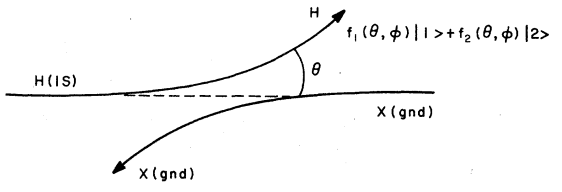

FIG. 1. Diagram to illustrate the conditions under which coherent excitation is assumed to occur. (See text, Sec. II). Only two internal states of H are considered. f_1 and f_2 are scattering amplitudes to these states.

$$\mathrm{Tr}\rho \equiv \sum_i \rho_{ii} = 1 . \tag{2.2}$$

The diagonal elements ρ_{ii} are essentially cross sections for production of state i. (They are not exactly proportional to such cross sections because the latter include kinematical factors k_f/k_i, where $\hbar k_i, \hbar k_f$, are relative linear momenta in the initial and final channels.)

The experiments described in this paper were carried out at energies high enough that the relevant scattering amplitudes were sharply peaked forward. This suggests that the magnitude of the off-diagonal element ρ_{ij} is approximately equal to the geometric mean of the diagonal elements ρ_{ii} and ρ_{jj}:

$$|\rho_{ij}| \sim (\rho_{ii}\rho_{jj})^{1/2} . \tag{2.3}$$

Hence these off-diagonal elements need not be small.

The reaction $\mathrm{H}(1s)+X(\mathrm{gnd}) \rightarrow \mathrm{H}(n=2)+X(\mathrm{gnd})$, may be described by four scattering amplitudes: f_{2s}, f_{2p_1}, f_{2p_0}, and $f_{2p_{\bar{1}}}$. There are 16 hydrogen states with $n=2$ (if electronic and nuclear spin are included), but the 16 amplitudes can all be expressed in terms of the above four if it is assumed that the collision is dominated by Coulomb forces. In this case, there is only one mixed cross section to be considered, and that is

$$\sigma_{sp} = \sum_\alpha \int_{4\pi} f_{2s;\alpha}(\Omega) f^*_{2p_0;\alpha}(\Omega)\, d\Omega . \tag{2.4}$$

[If $f_{2p_0;\alpha}$ in (2.4) is replaced by $f_{2p_{-1};\alpha}$ or $f_{2p_{+1};\alpha}$, the integral is zero by a symmetry argument.] Hence the hydrogenic density matrix prepared by the collision may be written in terms of the matrix

$$\begin{pmatrix} \sigma_{2s} & 0 & \sigma_{sp} & 0 \\ 0 & \sigma_{2p_{-1}} & 0 & 0 \\ \sigma^*_{sp} & 0 & \sigma_{2p_0} & 0 \\ 0 & 0 & 0 & \sigma_{2p_1} \end{pmatrix} . \tag{2.5}$$

In (2.5) the basis states have been chosen to be products of functions of space, electron spin, and nuclear spin. Except for a constant overall normalization factor, in this basis the density matrix consists of four blocks down the main diagonal, each block being identical to (2.5). In some other basis (for example, one defined by the hyperfine states) the density matrix may be obtained by a unitary transformation.

B. Time evolution and emission of light

In our experiment, we measure Lyman-α light emitted by atoms prepared in the density matrix constructed from (2.5). The theory of light emission from such a coherently excited state has been discussed by Macek and coworkers,[11] Blum and Kleinpoppen,[12] and by Band.[13] In terms of the density matrix $\rho(t)$ describing the atom at time t, the intensity $I(\Omega, \vec{\epsilon}, t)\, d\Omega$ emitted with polarization $\vec{\epsilon}$ into solid angle $d\Omega$ is given by

$$I(\Omega, \vec{\epsilon}, t)\, d\Omega = \mathrm{tr}[M(\Omega, \vec{\epsilon})\rho(t)] , \tag{2.6}$$

where M is a 16×16 matrix which may be constructed from products of dipole matrix elements.

It is shown by the authors quoted that Eq. (2.6) may be further simplified if ρ and M are written in terms of irreducible tensor operators. However, we choose instead to parameterize ρ by the cross sections in the matrix (2.5). Thus, to calculate the light emitted in the presence of an electric field, the initial density matrix $\rho(0)$, constructed from (2.5), was first propagated forward in time according to the equation

$$\rho(t) = e^{-iHt}\rho(0)e^{iH^\dagger t} , \tag{2.7}$$

where H is the internal Hamiltonian given by

$$H = H_0 + eFz , \tag{2.8}$$

and the intensity emitted at 90° to the initial relative velocity then calculated from Eq. (2.6) by explicitly writing the appropriate matrix M and carrying out the necessary manipulations on a computer. In (2.8), H_0 is the internal field-free Hamiltonian, including hyperfine splittings, and with decay processes taken into account by considering energies to be complex; F is the Z component of the applied electric field. H is not Hermitian, and $H^\dagger$ in (2.7) is the Hermitian adjoint of H. For given cross sections, the calculations required are lengthy but straightforward. For further details the reader is referred to Ref. 14.

To gain a qualitative feel for the nature of the light emission, consider first a special case in which the density matrix (2.5) is diagonal ($\sigma_{sp}=0$). Then each excited atom may be considered to be initially in an eigenstate of the field-free Hamiltonian. In the absence of a field, an s state will be metastable while a p state will essentially decay exponentially with the p lifetime (1.6×10^{-9} sec at zero electric field). (Strictly speaking, the exponential decay will be modulated at a frequency corresponding to the fine-structure splitting, or about 10^{10} Hz, because the $2p_{1/2}$ and $2p_{3/2}$ states are excited coherently, but this effect is not important in our experiment.) In the presence of an electric field, the light emission is substantial-

ly modified. The intensity is a sum of exponential terms, each associated with a Stark shifted state, together with cross terms between them. The intensity of the emitted light will not depend on the direction of the applied field.

If coherent excitation is present ($\sigma_{sp} \neq 0$), the emitted light will be affected by the coherence only if an electric field is also present. The effect of an electric field can best be understood by neglecting hyperfine structure and considering only two levels: $2s_{1/2}$ and $2p_{1/2}$, each with the same magnetic quantum number M_j. If the initial atomic state was $a(0)|2s_{1/2}\rangle + b(0)|2p_{1/2}\rangle$, with $a(0)$ and $b(0)$ being definite complex numbers determined by the collision, then with the passage of time the p amplitude $b(t)$ would become an easily computable linear combination of $a(0)$ and $b(0)$. The intensity of Lyman-α emission would be essentially $|b(t)|^2$, and this would contain a cross term $a(0)b^*(0)$. The intensity of the emitted light would then contain a term which is essentially the product of a field-dependent amplitude for an s-p transition and an amplitude for decay from $2p_{1/2}$ to the ground state. This cross term depends on odd powers of the electric field F and leads to a change in Lyman-α intensity when the field is reversed.

Another way to see the effect of field reversal is based on the fact that, if the atom is in a linear superposition of s and p states, it has an electric dipole moment—just as if there were a permanent, built in, microscopic, "bias" field. From this point of view, reversing the applied field does not "really" reverse the field the atom "sees," so naturally the Lyman-α intensity depends on field direction.

Figure 2 shows the result of a calculation in which the atom is prepared in a state with $\sigma_{sp} = (\sigma_s \sigma_{p_0})^{1/2}$, and the subsequent decay followed in an applied field of 175 V/cm. The oscillations represent interference between the amplitudes of light emitted by two decaying states. Reversal of the electric field changes both the relative phase of the two amplitudes and also their relative magnitudes. In a beam-foil experiment, such as those described in Ref. 3, the oscillations themselves are observed. In our experiment, which takes place in a gas cell, the observed light is an integral over the oscillations, which are consequently washed out, but the interference effect can still be observed through the dependence of the integrated light on field direction.

Detailed calculations show that although our observed light asymmetry depend on both real and imaginary parts of the mixed cross section σ_{sp}, the dependence on the imaginary part is weak, so we primarily measure the real part.[15]

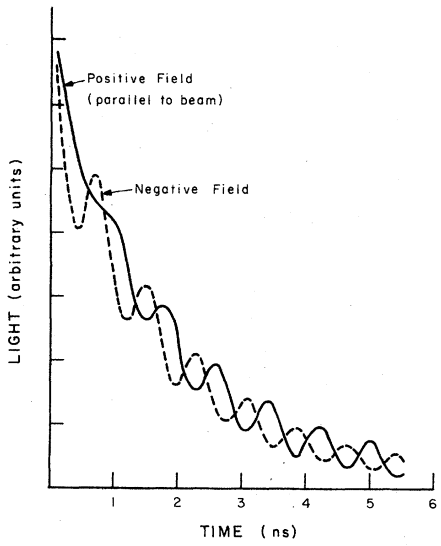

FIG. 2. Calculated light emitted by a coherently excited atom as a function of time. The degree of coherence was assumed to be maximal [$\sigma_{sp} = (\sigma_s \sigma_{p_0})^{1/2}$]. The dashed curve is for an axial electric field of −175 V/cm, the solid one for +175 V/cm. The point of the figure is to show that the direction of the field affects the emitted light. (Fast oscillations due to interference between $2p_{1/2}$ and $2p_{3/2}$ amplitudes are not shown).

III. APPARATUS

A. Description of apparatus

Figure 3 shows a schematic drawing of the interaction region. A beam of hydrogen atoms in the ground state passes from left to right through a gas cell containing the target gas. Plates P_1, and P_2, are used to provide an electric field directed parallel or antiparallel to the beam direc-

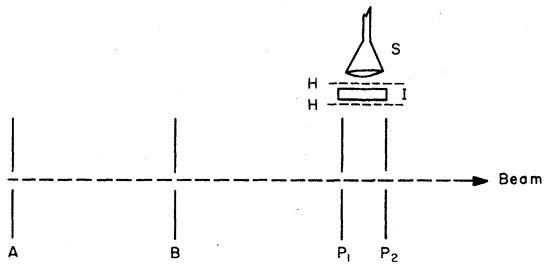

FIG. 3. Schematic drawing of the interaction region. Plates A and B were used to establish a prequench field to control the current of metastable atoms from the charge-exchange cell. The main, quench, field was between plates P_1 and P_2; H–shielding screen; I–MgF_2 window; S–Lyman-α counter. An oxygen filter (not shown) could be inserted between I and S.

tion. Lyman-α photons emitted in a direction perpendicular to the beam are counted in a Channeltron detector.

The neutral hydrogen beam was prepared in a conventional way by charge exchange of protons extracted from an rf ion source. Metastable atoms emerging from the charge exchange cell were prequenched by an appropriate field before the beam entered the interaction region. Typical neutral currents were 10^{10} sec^{-1}; the base pressure in the interaction region was 10^{-5} torr. Data were taken under conditions such that the observed Lyman-α asymmetry was independent of pressure. For further experimental details, the reader is referred to Ref. 14.

The length of the interaction region was 1 cm. This was a compromise between a number of competing effects. A curve such as the one shown in Fig. 2 represents light emitted from one atom as a function of time (or distance downstream). However, the observed Lyman-α count rate is a double integral over such a curve—one integration being over the time spent by an excited atom in the interaction region, while the other is over all the various positions at which the atom could be excited.

The outcome of the integrations is a fractional light asymmetry A for given cell length, beam energy, field strength, and assumed cross sections σ_s, σ_{p_m}, and σ_{sp}. A is defined to be

$$A = \frac{(I_+ - I_-)}{\frac{1}{2}(I_+ + I_-)} , \tag{3.1}$$

where I_+ and I_- are Lyman-α count rates with the electric field directed parallel and antiparallel to the beam velocity. The solid curve in Fig. 4 is

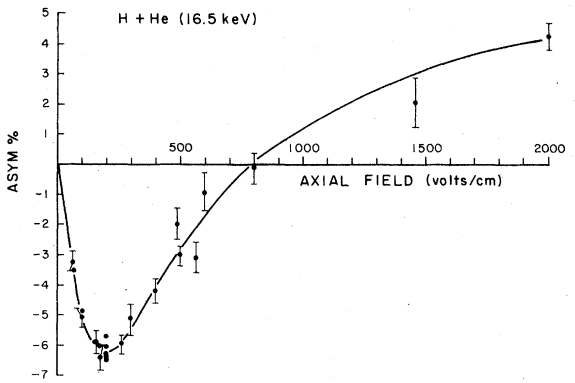

FIG. 4. Measured values of fractional light asymmetry, as defined by Eq. (3.1), plotted against electric field magnitude. Not all error bars are shown. The solid curve is a theoretical one calculated using cross sections from Table I.

the result of such a calculation for a cell length of 1 cm, beam energy 16.5 keV (in the laboratory frame), and for cross sections as listed in Table I. When similar calculations are carried out for other cell lengths and beam energies, it is found that the magnitude of the maximum asymmetry (and the field at which it occurs) depends on the length of the interaction region and the velocity of the excited atom. For very long regions, the asymmetry is small because practically all the atoms decay within the field of view of the counter, no matter what is the direction of the field. For very short regions, the target is poorly defined (end effects become important).

TABLE I. Experimental results for H + He → Lyman-α.

Energy [a] (keV)	σ_{2s} (10^{-17} cm^2)	σ_{2p} (10^{-17} cm^2)	$\sigma_{p_0}/\sigma_{p_1}$ [b]	Reσ_{sp} (10^{-17} cm^3)	$\frac{\text{Re}\sigma_{sp}}{(\sigma_s\sigma_{p_0})^{1/2}}$	Maximum asymmetry (%)
2.1	1.0 [c]	4.4 [c]	4.6	−0.46 ± 0.24	−0.24	−2.3 ± 0.3
4.0	0.95 [c]	3.7 [c]	1.7	−0.22 ± 0.06	−0.15	−2.6 ± 0.3
9.3	0.57 [c]	2.0 [c]	1.5	−0.25 ± 0.04	−0.30	−4.9 ± 0.5
11.3	0.54 [c]	1.8 [c]	1.5	−0.24 ± 0.05	−0.32	−5.9 ± 0.4
16.5	0.46 [c]	1.2 [c]	1.5	−0.18 ± 0.04	−0.31	−6.2 ± 0.6
21.7	0.41 [c]	0.87 [c]	1.7	−0.093 ± 0.03	−0.20	−5.3 ± 0.5
28.4	0.26 [d]	0.50 [d]	0.8	−0.038 ± 0.02	−0.16	−3.2 ± 0.8

[a] Laboratory frame.
[b] V. Dose, R. Gunz, and V. Meyer, Helv. Phys. Acta 41, 264 (1968).
[c] J. H. Birely and R. J. McNeal, Phys. Rev. A 5, 257 (1972).
[d] A. L. Orbeli, E. P. Andreev, V. A. Ankudinov, and V. M. Dukelski, Zh. Eksp. Teor. Fiz. 57, 108 (1969) [Sov. Phys.—JETP 30, 63 (1970)].

B. Instrumental asymmetries

To test for unwanted, instrumental asymmetries, the Lyman-α count rate was measured with no gas in the cell (apart from the residue associated with base pressure), and with the upstream, prequench, field turned off. Under these conditions, the count rate was very low (~5 sec^{-1}) with no applied field in the interaction region, but increased rapidly with increasing field. This light was attributed to quenching of metastable hydrogen atoms which were produced in the charge exchange cell. The observed count rate depended in the expected way on the magnitudes of the prequench field and of the field applied in the interaction region. (For details, see Ref. 14.)

The light due to these metastable atoms should exhibit no asymmetry since it arises from atoms prepared in a pure metastable state (as if $\sigma_p = \sigma_{sp} = 0$). However, an asymmetry of about 1% was actually observed for a field strength of 175 V/cm. The exact amount varied from day to day and also depended on the magnitude of the applied field. This unwanted asymmetry was ascribed to a difference in work function between the two plates P_1 and P_2 (Fig. 3) producing the electric field. Such a difference in work function would lead to the presence of an electric field even if the plates were externally shorted together; with such a bias field, reversal of an external voltage source would not lead to a true reversal of the field felt by an atom and hence lead to a spurious asymmetry.

To check on this interpretation, an external bucking battery was placed in series with the cell plates and it was usually found that for suitable choice of battery voltage, the unwanted asymmetry disappeared, i.e., for one fixed value of bucking voltage, there was negligible asymmetry for any value of applied field. The magnitude of the required bucking voltage was about 1 V, but drifted slowly from day to day, and even over one afternoon, as might be expected for room temperature aluminum surfaces in a vacuum of ~10^{-5} torr. The required bucking voltage also depended somewhat on beam energy. This effect is thought to be due to surface charges resulting from ion and electron bombardment.

The required bucking voltage was determined by measurements on a metastable beam incident on a target cell with no gas input; when data were being taken with a ground-state beam incident on a target cell with gas, the correction introduced by the bucking battery was smaller than (but comparable to) the errors shown in Fig. 4.

Another possible source of instrumental asymmetry lies in the light produced by electrons which arise from ionization of target gas by the fast neutral beam. Such electrons will be accelerated by the applied field and upon hitting plates P_1 or P_2 could lead to ultraviolet photons whose intensity would depend on the direction of the applied field. Small currents could indeed be measured to both P_1 or P_2, and the magnitudes of the currents did depend on the direction of the applied field, but showed no correlation with observed light asymmetries. We concluded that though such ionization effects must be present they contributed negligibly to the observed asymmetry.

Reference 14 describes tests carried out to check that the observed uv signal was really due to Lyman-α, and was not significantly contaminated by uv of other frequencies. This was done by inserting an oxygen filter in front of the channeltron. No significant effect was observed (apart from the expected attenuation) and it was concluded that such unwanted uv light was not a source of error.

IV. RESULTS AND DISCUSSION

For each target gas and at each energy, light asymmetry was measured as a function of applied electric field strength. If necessary, the measured asymmetry was corrected for work function differences as described in the previous section. A typical result is plotted in Fig. 4 for helium at 16.5 keV. The experimental curve was fitted by a theoretical one in which the cross section parameters σ_s, σ_p, and $\sigma_{p_0}/\sigma_{p_1}$ were taken from the literature, while the real and imaginary parts of the mixed cross section σ_{sp} were varied to obtain a best fit. The solid curve in Fig. 4 is such a best fit. The resulting values of σ_{sp} are collected in Tables I, II, and III for a number of different target gases and beam energies. These tables summarize our experimental results, some of which are also presented graphically in Figs. 5 and 6. These tables and figures do not include estimates of the imaginary part of σ_{sp}. As mentioned above, the measured asymmetry is not sensitive to this parameter. Estimates of Im σ_{sp} (with large error bars) are presented in Ref. 14.

To extract values of σ_{sp} from the measured light asymmetries, it was necessary to adopt values for the partial cross sections σ_{p_0}, σ_{p_1} for excitation of the $|m| = 0$ and 1 magnetic substates of the $2p$ level. These were calculated from the polarization data of Dose (Ref. b in Table I) for helium and argon targets. For the molecular gases (Table III), no polarization data are available, and it was assumed that the three magnetic substates were equally populated. However, the error bars in Table III reflect the fact that the polarization is unknown.

TABLE II. Experimental results for H + Ar → Lyman-α.

Energy[a] (keV)	σ_{2s} (10^{-17} cm^2)	σ_{2p} (10^{-17} cm^2)	$\sigma_{p_0}/\sigma_{p_1}$[b]	$\mathrm{Re}\sigma_{sp}$ (10^{-17} cm^3)	$\frac{\mathrm{Re}\sigma_{sp}}{(\sigma_s\sigma_{p_0})^{1/2}}$	Maximum asymmetry (%)
1.6	4.0[c]	7.3[c]	∞	3.4 ± 0.8	0.63	9.5 ± 0.5
2.1	3.3[c]	7.0[c]	48	2.3 ± 0.5	0.49	8.1 ± 0.5
4.0	1.7[c]	6.2[c]	∞	0.74 ± 0.5	0.23	3.4 ± 0.7
9.3	1.6[c]	5.1[c]	6.9	−0.3 ± 0.3	−0.12	−0.8 ± 0.3
16.5	1.9[c]	4.3[c]	0.9	−0.1 ± 0.4	−0.04	−0.5 ± 0.5
21.7	1.9[c]	4.2[c]	0.9	0.0 ± 0.5	0.00	0.25 ± 0.6
28.4	2.5[d]	4.3[d]	0.9	0.1 ± 0.4	0.06	+1.0 ± 0.8

[a] Laboratory frame.
[b] V. Dose, R. Gunz, and V. Meyer, Helv. Phys. Acta 41, 264 (1968).
[c] J. H. Birely and R. J. McNeal, Phys. Rev. A 5, 257 (1972).
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We also measured nonzero light asymmetries for H_2 targets. However, these data are not included in this paper because at least two processes contribute: direct excitation of the H projectile, and dissociative excitation of the H_2 target. It is difficult to disentangle these two contributions; the measured asymmetries are presented in Ref. 14.

The calculations to compute the best fit curves included hyperfine splittings, though as a matter of fact the results were much the same whether or not hyperfine structure was included. It may be interesting to note that the positive assymetries apparent in Fig. 4 for high field strengths are associated with the $2p_{3/2}$ component of the fine-structure doublet. If this component is neglected in the calculation, the asymmetry does not change in sign, in disagreement with experiment.

The uncertainties quoted in Tables I, II and III are a measure of how well the experimental data could be fit by a theoretical curve with two variable parameters. Uncertainties in the experimental curves were partly due to counting statistics and partly due to imperfect reproducibility from run to run, with the two sources of uncertainty being comparable.

To our knowledge, there are no published calculations with which our results can be compared. Probably, this is partly due to the fact that such measurements have not been reported in the past, so there was no impetus for theorists to make predictions. Another reason may be that our measurements were made over an intermediate energy range which was experimentally convenient, but theoretically awkward. It should be noted that our measured mixed cross sections are a sum over processes where the residual target atom is in its ground state, first excited state, etc.

Our results for σ_{sp} may be interpreted in terms of a dipole moment. A short calculation shows that the real part, $\mathrm{Re}\sigma_{sp}$, is proportional to the electric dipole moment given to the hydrogen atom by the collision, the proportionality constant being positive; the imaginary part, $\mathrm{Im}\sigma_{sp}$, measures the rate of change of this dipole moment.

TABLE III. Experimental results for H + N_2, O_2 → Lyman-α.

Gas	Energy[a] (keV)	σ_{2s} (10^{-17} cm^2)	σ_{2p} (10^{-17} cm^2)	$\mathrm{Re}\sigma_{sp}$ (10^{-17} cm^2)	$\frac{\mathrm{Re}\sigma_{sp_0}}{(\sigma_s\sigma_{p_0})^{1/2}}$	Maximum asymmetry (%)
N_2	2.1	3.0[b]	6.2[b]	−0.39 ± 0.48	−0.15	−1.2 ± 0.6
	4.0	2.2[b]	5.9[b]	−0.15 ± 0.25	−0.09	−1.0 ± 0.3
	16.5	1.7[b]	4.9[b]	−0.15 ± 0.44	−0.09	−0.9 ± 0.6
O_2	2.1	3.6[b]	5.4[b]	−0.14 ± 0.43	−0.053	−0.6 ± 0.3
	4.0	3.0[b]	5.5[b]	−0.069 ± 0.42	−0.030	−0.3 ± 0.3
	16.5	1.7[b]	4.6[b]	−0.23 ± 0.40	−0.14	−1.5 ± 0.4

[a] Laboratory frame.
[b] J. H. Birely and R. J. McNeal, J. Geophys. Res. 76, 3700 (1971).

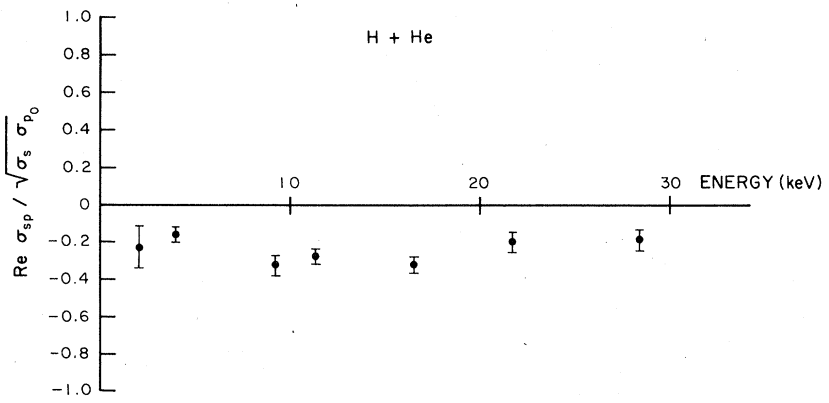

FIG. 5. The energy dependence of the real part of the mixed cross section σ_{sp} for coherent excitation of H($n=2$) by He, as a fraction of its maximum possible value $(\sigma_s\sigma_{p_0})^{1/2}$. Data taken from Table I. Energies are in the laboratory frame.

In Table I, the sign of $\mathrm{Re}\sigma_{sp}$ for helium is such that the hydrogen atom leaves the collision with its electron in front of the proton. For argon, on the other hand (Table II), the sign of $\mathrm{Re}\sigma_{sp}$ depends on energy.

We have found that the magnitude of σ_{sp} is the same order of magnitude as the ordinary cross sections σ_s, σ_{p_0} (more precisely the geometric mean of the two). The same qualitative result has been found in beam-foil experiments (Ref. 4), in charge-transfer collisions (Refs. 2 and 16), and in electron-photon coincidence measurements (Ref. 5). All these results support the general conclusion that coherence effects are large.

The existence of collision-induced dipole moments could have a bearing on experiments to measure fundamental frequencies with high precision, and to look for weak-interaction effects in atoms. For example, in an experiment to measure the Lamb shift, it is usually assumed that the hydrogen atom is prepared in a pure metastable state. If the atom were initially in a coherent mixture of s and p, subtle shifts in line shapes and positions could arise. Actually, in the precision experiments we are aware of, the atoms were excited so far from the interaction region that any p component initially present would have decayed away, and atoms entered the interaction region in the s state. (Even in this case, however, collisions in the interaction region could regenerate the p state and again lead to trouble.)

Similarly, in an experiment to look for a small

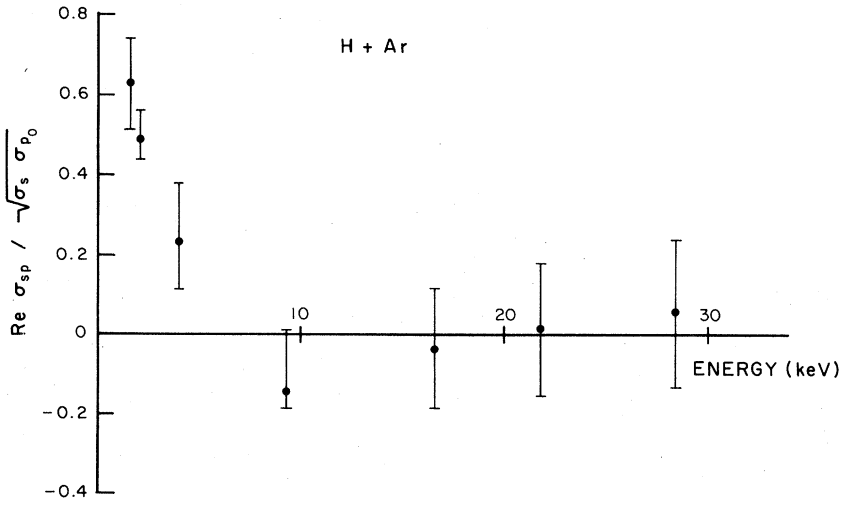

FIG. 6. Same as Fig. 5, except that the collision partner is Ar. Data from Table II.

term, perhaps due to the weak interactions, which admixes states of parity opposite to that of the primary state, coherent scattering effects could mix in just such states—in effect "dressing" the primary state—and so produce a spurious effect. One might attempt a crude estimate of the magnitude of such effects by taking them to be of order $nv|\sigma_{sp}|$, where n is the number density of the background gas, and v is the speed of the beam atoms. If n were taken to be 3×10^{8} cm^{-3}, corresponding to a pressure of 10^{-8} torr, $v=3\times10^{7}$ cm/sec, and $|\sigma_{sp}|=10^{-18}$ cm^2 (from Table I), then $nv|\sigma_{sp}|\sim10^{-2}$ sec^{-1}. The s-p matrix element of the parity nonconserving weak interaction is also about 10^{-2} sec^{-1}.

However, such an estimate is not at all reliable, even apart from the fact that Table I refers to helium, which is not the dominant background gas. Experiments under way measure an interference effect between the parity-nonconserving part of the Hamiltonian and a parity-conserving part. A much more detailed analysis of collisional effects is required before one can assess their importance. Such an analysis might start by adding phenomenological terms to the equation of motion for the atomic density matrix—terms involving both ordinary cross sections and also mixed ones such as those measured in this paper—and has not been carried out to our knowledge. However, there is also a different kind of scattering effect which would be interesting to consider. It is analogous to the well-known regeneration of K_s mesons by matter.

If a plane wave of $2s$ atoms, described by the amplitude $a(x)$, traverses gas, then forward scattering in a slab of thickness dx and number density n would contribute a scattered wave downstream which would interfere with the incident wave. This is just the effect which gives rise to an index of refraction in optics. By the same argument as used in optics,[18] the slab emits a plane wave

$$da=i\alpha\lambda n f_{aa}(0)\,dx\,, \tag{4.1}$$

where λ is the de Broglie wavelength of the incident wave, and $f_{aa}(0)$ is the forward scattering amplitude.

If the slab were considered to also emit a plane wave of atoms in the $2p$ state, one is led to a picture in which two waves [amplitudes $a(x)$ and $b(x)$] travel down the beam, with each slab of gas being a source emitting amplitudes da and db given by

$$\begin{aligned} da&=i\lambda n dx[f_{aa}(0)a+f_{ab}(0)b]\,,\\ db&=i\lambda n dx[f_{ba}(0)a+f_{bb}(0)b]\,. \end{aligned} \tag{4.2}$$

Replacing dx by vdt, and λ by h/mv, where m is an atomic mass, these equations take on the form of Schrödinger's equation, with Hamiltonian

$$H_{\text{gas}}=-2\pi n\frac{\hbar^2}{m}\begin{bmatrix} f_{aa}(0) & f_{ab}(0)\\ f_{ba}(0) & f_{bb}(0)\end{bmatrix}\,. \tag{4.3}$$

This Hamiltonian mixes s and p states and could interfere with the weak-interaction term. However, more detailed analysis is required, especially with regard to its symmetry properties. It should be emphasized that the measurements reported in this paper are of mixed cross sections σ_{sp}, not of forward scattering amplitudes $f_{ab}(0)$.

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