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excited levels of the 5-mm-diam beam of neutral atoms. Magnet LM2 had a maximum field strength of 18 kG, equivalent to an electric field of 800 kV/cm in the rest frame of the 10-MeV H^0; this field is sufficient[2,3] to Lorentz-ionize some of the states of $n = 5$ and all of the levels for $n > 5$. The ionization of successively smaller levels occurred sequentially in space in the nonuniform field created by the wedge-shaped poles of LM2. Consequently, the protons resulting from ionization of levels of high n had larger deflections in LM2 and required stronger fields in A to reach the counter CC. The field in magnet A was varied to obtain a Lorentz-detachment profile. The charged-particle counter was normally collimated by a slit 3 mm wide in order to get good resolution. The resolution of the system was measured by stripping the neutral beam in an Al foil placed in various positions in the field of LM2 and sweeping the resultant beam with magnet A across two 3-mm-wide collimator slits, 22 mm apart, in front of CC. The dispersion, approx 45 mm/kG, varied by 15% over the range of parameters used. From a study of these trajectories it was estimated that the levels undergoing Lorentz detachment had an average lifetime in the field of approx 2×10^{-10} sec.

To obtain the population distribution of the beam as it emerged from a particular gas cell, one must correct for radiative decay. Field-free (spherical) lifetime calculations show that for $\ell > 0$ the radiative decay lifetimes increase with increasing n and with increasing ℓ.[4,5] In this experiment the smaller ℓ values undergo considerable decay. For example, the $n = 7$, $\ell = 1$ state decays by 50% in 2 meters. If we assume that as the beam emerges from a gas cell the populations of states within a given principal quantum level are weighted as $2\ell + 1$ (field-free), then the fraction of each level surviving at the detector can be calculated for production in the first or second gas cell (Table I). Also shown are calculations using a Stark-field statistical distribution and Stark lifetimes.[4,5] Our experimental situation is somewhere intermediate between the two, but stray magnetic fields are large enough to favor the Stark approximation.

The experiment consisted of: (a) The production of neutrals in gas cell No. 2 and the analysis of excited levels with LM2, (b) the production of neutrals in gas cell No. 1 and the analysis of excited levels with LM2, and (c) the production of neutrals in GC1, the removal of some of the excited levels with LM1, a rearrangement of excited levels by nonionizing gas collisions in GC2, and analysis by LM2.

III. RESULTS

The protons produced by Lorentz ionization at various places in LM2 were swept across the 3-mm-wide collimator with the analyzing magnet, giving curves of the kind shown in Fig. 2. In this example the pressures are 24×10^{-3} and $< 0.01 \times 10^{-3}$ torr H_2 in gas cells 1 and 2 respectively, and the magnetic fields in LM1 and LM2 are 0 and 13.85 kG (equivalent to electric fields of 0 and 607 kV/cm). The sweeping magnetic field, 1.6 kG (70 kV/cm), was set to remove the levels with $n \gtrsim 10$. The excited atom populations were considerably smaller when D^- breakup was used as the source of neutrals, in agreement with the results of earlier measurements.

Figure 3 shows an example of the decrease in the number of surviving atoms in each principal quantum level as the field of the first stripping magnet, LM1, was gradually increased. Also shown are the electric fields for which electron detachment should occur in 2×10^{-10} sec, according to the calculations by Rice and Good.[2,3] (A change of 10% in the electric field typically changes the lifetime by a factor of 10.) The $n = 5$ curve is shown dashed because the field of LM2 could not be raised high enough to ionize all the states belonging to the $n = 5$ level.

A demonstration of excitation to higher n values is given in Fig. 4. Neutral atoms were produced in the first gas cell and LM1 was set to remove all atoms with $n \geqslant 7$ (Fig. 4a). LM2 was set at 13.85 kG. As H_2 was added to gas cell No. 2 the $n = 7$ level became repopulated. In Fig. 4b, LM1 removed all atoms with $n \geqslant 6$. The $n = 6$ and $n = 7$ levels were then repopulated as the pressure in GC2 was increased. Argon in the second gas cell was approximately eight times as effective as hydrogen, per atom, for excitation to higher levels.

It should be possible to obtain some information about radiative lifetimes by analyzing neutral beams that were produced in the first and second gas cells. However, the beam does not decay in a simple exponential way because of the different lifetimes associated with the various states belonging to a particular level n. We observed that $n = 6$ decays more rapidly than $n = 7$, as expected, but are not yet able to draw quantitative conclusions.

IV. DISCUSSION

Figure 3 shows that the threshold fields for Lorentz ionization of the $n = 5$ through $n = 9$ states are in agreement with the calculations by Rice and Good. The rapid attenuation of each level as the magnetic field of LM1 was raised slightly above the threshold field is consistent with a statistical distribution among the states of each principal quantum level.

The populations of the excited levels can be obtained by integrating curves of the kind shown in Fig. 2. The results obtained from the data of Fig. 2 are given in the first column of Table II. For lack of experimental information we assume a statistical distribution of states, and obtain column 2 of Table II. The neutral beam produced in the H_2^+ breakup process is expected[6] to have excited populations produced in proportion to a/n^3, where a can range from 2 to 8, depending on the vibrational population. However, the experimental evidence of Fig. 4 suggests that the population distribution of atomic levels could be strongly modified by the nonionizing gas collisions within the gas cell.

Excitation and ionization cross sections have been determined from the experiment in the following way: The atomic beam is stripped of all states above a given level, n, and the repopulation of the $(n + 1)$st level is measured as a function of the gas pressure. The excitation cross section, $\sigma_{n,n+1}$, is inferred from the slope of the repopulation curve in the linear region. For example, the data of Fig. 4 give $\sigma_{6,7} \approx 1 \times 10^{-18}$ cm^2. The ionization cross sections are derived from the measured equilibrium population distribution of the beam emerging from the first gas cell, and from the excitation cross sections derived above. The equilibrium population distribution is determined by the competition between production, excitation, de-excitation, and ionization processes. If N_k denotes the number of atoms in the kth level, $\sigma_{k,k+1}$, the excitation cross section linking the kth and $(k + 1)$st levels, $\sigma_{k,i}$ the ionization cross section for the kth level, σ_{pk} the partial cross section for production into the kth level, and N^+ the number of ions in the beam, then the equilibrium population distribution is determined by the equations

$$-\sigma_{k-1,\,k} N_{k-1} + A_k N_k - \sigma_{k+1,\,k} N_{k+1} = N^+ \sigma_{pk} \quad \text{for} \quad k = 1, 2, \cdots \lambda, \qquad (1)$$

where $A_k = \sigma_{k,k-1} + \sigma_{k,k+1} + \sigma_{k,i}$, and λ is the number of bound states of the atom. In the approximation $\sigma_{k,k+1} \gg \sigma_{k,i}$, the equilibrium distribution is dominated by the excitation cross sections and the sum of the partial captures over the lower excited states. If the capture cross sections, σ_{pk}, up to the 6th level are included, Eqs. (1) can be solved to give

$$\frac{N_7}{N_6} = \frac{\sigma_{6,7}}{A_7 - \dfrac{\sigma_{8,7}\sigma_{7,8}(A_9A_{10} - \sigma_{9,10}\sigma_{10,9})}{A_8(A_9A_{10} - \sigma_{9,10}\sigma_{10,9}) - \sigma_{8,9}\sigma_{9,8}A_{10}}}, \tag{2}$$

where we have included the dependence on the excitation and ionization cross sections up to $n = 10$. Since this expression involves the excitation and ionization cross sections covering a range of levels, it is necessary to assume a functional dependence of the cross sections with principal quantum number. In a later paragraph we present evidence to suggest that the excitation cross section is proportional to n. The value for the ionization cross section derived from Eq. (2) is not critically dependent on this functional dependence. The de-excitation cross sections for a statistical distribution of states for a level n can be shown to be $\sigma_{k,k-1} = [(k-1)^2/k^2]\ \sigma_{k-1,k}$. In terms of the experimental equilibrium ratio $N_7/N_6 = 0.63$, we conclude the ionization cross section $\sigma_{6i} \approx (1/5)\ \sigma_{6,7}$.

A number of computer solutions for the excited level populations emerging from both the production and excitation cells have been obtained, on the basis of nonequilibrium rate equations and various assumptions about the various cross sections. The results substantiate the conclusions reached in the foregoing paragraphs, but no firm conclusions can be drawn until the functional dependences on n are better established.

The excitation cross sections for inelastic collisions of hydrogen atoms have been calculated in first Born approximation by Bouthilette, Healey, and Milford (BHM).[7] The partial cross sections for processes of the type

$$H(n,\ell) + H(1,s) \rightarrow H(n',\ell') + H(2s,\ 2p) \tag{3}$$

have been calculated for $n = 2, 3, 4$ for those excitations in which $n' = n+1$. The dominant partial cross sections are those involving the highest angular momentum states, i.e., $\ell = n-1 \rightarrow \ell' = n'-1$; these partial cross sections vary approximately in proportion to n. Assuming that this dependence on n can be extrapolated to the $n = 6$ level, the experimental value for $\sigma_{6,7}$ reported here is larger than the sum of all partial cross sections, (3), given by BHM. The partial cross sections, including excitations into the continuum, of the form

$$H(n, \ell) + H(1, s) \rightarrow H(n', \ell') + H^+ + e^- \tag{4}$$

contribute a significant amount in the case of excitation of the ground state.[8] Our experimental results, when compared with the theoretical results of BHM, suggest that the major part of the total cross section is due to process (4).

It is interesting to note the cross sections that would be inferred by a $1/E$ extrapolation to our energy of Milford et al.'s calculations[9] for the different case of hydrogen atomic collisions with electrons. In this case the excitation cross sections vary as n^4, and, for example, $\sigma_{6,7} \approx 600 \times 10^{-18} \text{cm}^2$, vs our experimental value of $\approx 1 \times 10^{-18} \text{cm}^2$.

Milford has shown that in neutral-charged collisions the excitation cross sections with $|\Delta n| \geq 2$ are smaller by at least an order of magnitude than in the case of $|\Delta n| = 1$. Data of the kind shown in Fig. 4, where the $n = 6$ and $n = 7$ states appear to be filling at almost the same rate, suggest that $|\Delta n| > 1$ transitions may be important in these neutral-neutral collisions.

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Table I. Fraction of atoms (in %) in quantum levels, n, that survive radiative decay over the indicated paths.

	GC1 to GC2 (225 cm)		GC2 to LM2 (200 cm)		GC1 to LM2 (450 cm)	
n	Spherical	Stark	Spherical	Stark	Spherical	Stark
2	25	0	25	0	25	0
3	12	3	13	3	6	0
4	35	25	38	28	16	8
5	63	57	65	60	43	34
6	80	77	82	79	66	60
7	89	88	89	89	80	77
8	93	93	94	94	88	86
9	96	96	96	96	92	92
10	97	97	98	97	95	97

FIGURE CAPTIONS

Fig. 1. The experimental arrangement.

Fig. 2. A typical Lorentz-detachment curve. The parameters are given in the text. The peak labeled "Background" is caused by breakup on collimators and residual gas.

Fig. 3. The excited-state populations as a function of the equivalent electric field of the first stripping magnet. Also shown for each level are the ranges of electric field corresponding to a mean life of 2×10^{-10} sec, as calculated by Rice and Good.

Fig. 4. The repopulations of depleted quantum levels by nonionizing collisions in H_2 at several pressures in GC2: •, $p < 10^{-5}$ torr; o, 19×10^{-3} torr; Δ, 63×10^{-3} torr; □, 2×10^{-3} torr. The counts were adjusted to constant neutral beam incident on GC2 by correcting the transmitted beam with a total ionization cross section, $\sigma_i = 1.1 \times 10^{-18}$ cm^2 (experimental). (a) LM1 = 7.45 kG, (b) LM1 = 15.2 kG.

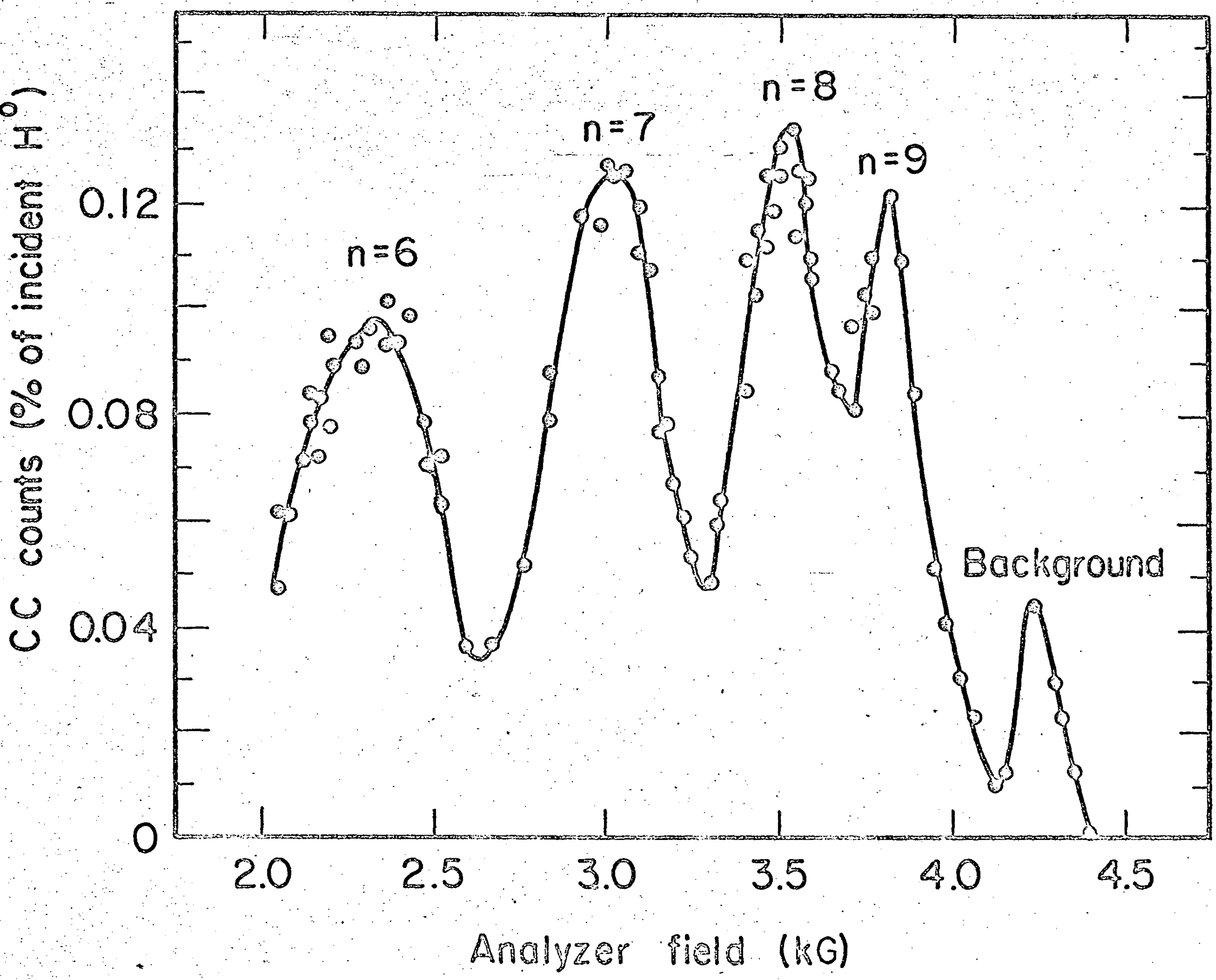

Fig. 2.

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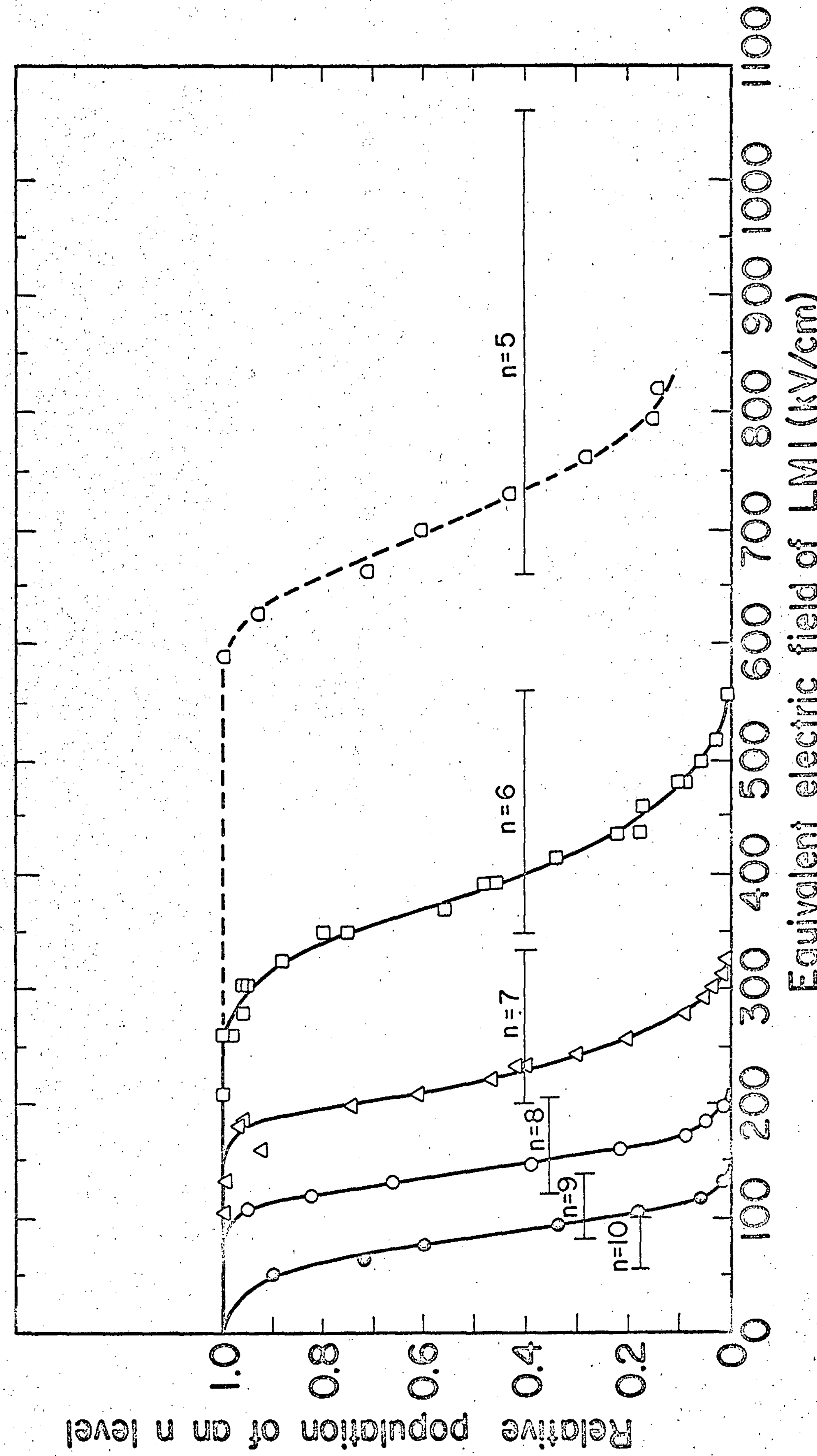

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Fig. 3.

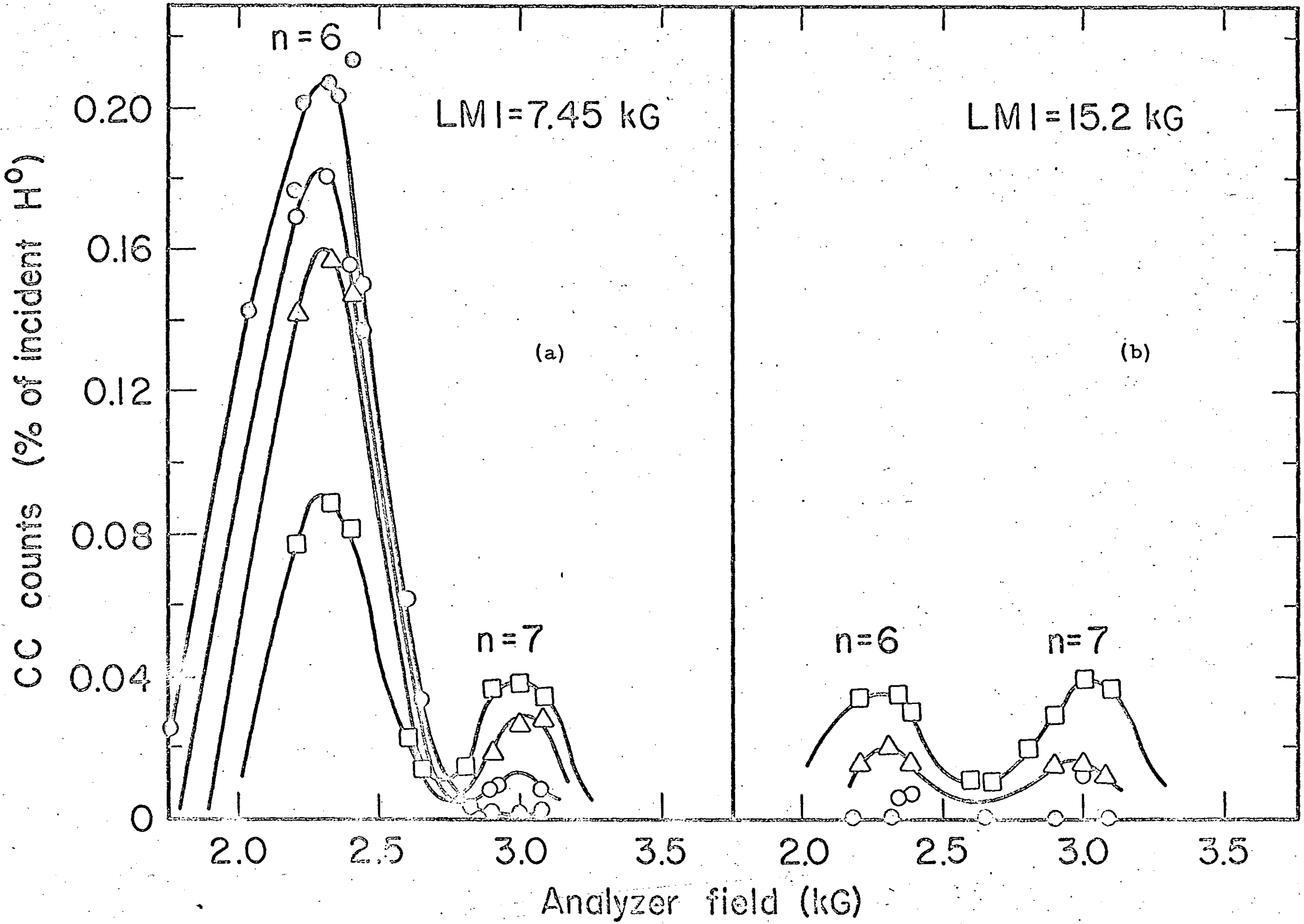

Fig. 4.

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