SOVIET PHYSICS JETP VOLUME 25, NUMBER 2 AUGUST, 1967

EFFECT OF ELECTRIC FIELDS ON INTENSITY OF HYDROGEN $L\beta$ LINE EXCITED IN PROTON CHARGE EXCHANGE WITH INERT GASES

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Submitted to JETP editor July 22, 1966

J. Exptl. Theoret. Phys. (U.S.S.R.) 52, 357–363 (February, 1967)

It is found that the intensity of the L_β Lyman line (1026 Å) emitted by hydrogen atoms excited as a result of charge exchange between protons and inert gases will increase when the charge exchange occurs in an electric field. The excitation cross sections for this line emitted in association with charge exchange of 10–40 keV protons in He, Ne, Ar, Kr, and Xe are measured in a 600 V/cm field and in zero field.

1. INTRODUCTION

We have previously [1] investigated the emission of the L_α Lyman line by fast hydrogen atoms formed through charge exchange between protons and inert gases. When a constant uniform electric field was applied in the charge-exchange chamber the L_α intensity increased because the field disturbed the metastable 2s state. By measuring the L_α intensity both without and with a field we were enabled to determine the separate probabilities of 2s and 2p excitation.

It was noticed that the intensity of the second Lyman line L_β (1026 Å) also increases when an electric field is applied in the charge-exchange chamber. As an example, Fig. 1 shows the relation that we observed between the intensity I of the L_β line and the external field strength $\mathscr{E}$ for charge between protons and helium.

The present work has been an investigation of the observed effect; the absolute L_β excitation cross sections were determined for proton charge exchange in He, Ne, Ar, Kr, and Xe. We measured the excitation cross sections $\sigma_0(L_\beta)$ without a field inside the collision chamber, and $\sigma_{\mathscr{E}}(L_\beta)$ in the presence of an external electric field; the proton energies were in the range 10—40 keV.

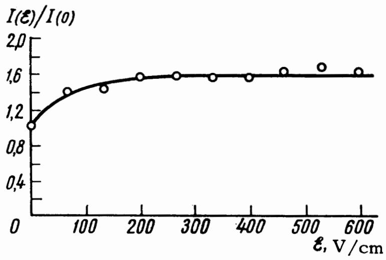

FIG. 1. L_β intensity ratio (with and without a field) vs. external electric field strength for charge exchange between 14-keV protons and He.

2. EXPERIMENT

1. A detailed description of the experimental apparatus was given in [1]. The radiation was analyzed perpendicular to a proton beam ($J_m = 2$ mA/cm^2) traversing a chamber filled with the test gas. The pressure in the collision chamber did not exceed 10^{-3} mm Hg. The L_β line was discriminated by means of a Seija-Namioka monochromator. In order to enhance the sensitivity of L_β detection we registered individual quanta with a scintillation photoelectron counter (Fig. 2). A plane-parallel capacitor (with 3.5-cm long plates) mounted inside the collision chamber was used to apply a 600-V/cm field.

2. The excitation function of the L_β line with and without a field was measured for charge exchange between protons and inert gases in the case of single collisions. Since in our experimental work the time of flight of fast excited hydrogen

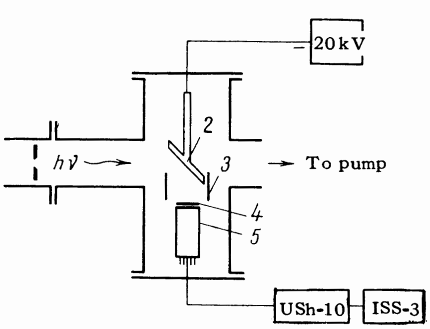

FIG. 2. Scheme of quantum detector. 1—exit slit of vacuum monochromator; 2—converter, 3—focusing electrode, 4—scintillator, 5—photomultiplier FÉU-38.

atoms moving from the entrance slit of the collision chamber to the observed region (and for measurements in a field, from the front limit of the electric field to the same observed region) is commensurate with the lifetime of n = 3 excited states, the L_β intensity measurements had to be corrected for the lifetimes of the produced excited particles. The L_β intensities measured in the absence of a field were corrected for the lifetime of the hydrogen 3p state ($\tau_{3p} = 0.54 \times 10^{-8}$ sec [2]). We shall show that in an electric field L_β is emitted due to the decay of two Stark levels with slightly different lifetimes (0.8×10^{-8} and 0.94×10^{-8} sec [2]); mean values were used in calculating the corrections. The error in the relative measurements of L_β intensity did not exceed 10%. A calculation showed that 3p excitation through cascade transitions from higher-lying levels amounted to at most one-tenth of the direct excitation of this level.

3. In a separate experiment at 16 keV we obtained comparative measurements of L_β intensities from proton charge exchange with all the test gases, with and without a field. All the cross sections $\sigma_0(L_\beta)$ and $\sigma_{\mathscr{E}}(L_\beta)$ were normalized to $\sigma_0(L_\beta)$ for the process $H^+ + Ne \rightarrow L_\beta$ (E = 16 keV).

3. DETERMINATION OF ABSOLUTE CROSS SECTIONS FOR L_β EXCITATION

At the present time no reliable method exists for measuring directly the absolute intensity of L_β emission. We know two channels of n = 3 hydrogen atom decay: 1) with emission of the H_α Balmer line at 6563 Å (the transition n = 3 → n = 1), and 2) with emission of the L_β line (the transition n = 3 → n = 1). In the absence of an external field the transition accompanied by H_α emission is initiated at all three fine-structure levels (3s, 3p, and 3d), whereas L_β is emitted only as a result of the 3p – 1s transition (Fig. 3a).

If the populations of the 3s, 3p, and 3d sublevels are known, then when we also know the probabilities of the respective transitions we can easily determine the number of L_β quanta by measurements that indicate the number of H_α quanta. In the present work we were not able to determine by any simple method the populations of the fine-structure levels (3s, 3p, and 3d) belonging to the newly-produced fast excited hydrogen atom. However, we previously [3] had determined the absolute cross section σ(3p) for the dissociation of the H_2 molecule acted on by the He^+ ion ($He^+ + H_2 \rightarrow L_2$). The cross section, calculated from Eq. (14) of [3], for L_β excitation [$\sigma_0(L_\beta) = (2.1 \pm 0.2) \times 10^{-18}$ cm^2 for E = 16 keV] enables us to determine the sensitivity of the recording instruments (monochromator + quantum counter) to L_β radiation. We measured in a separate experiment the intensity ratio of L_β excited by charge exchange of 16-keV protons in Ne to the same line excited through H_2 dissociation by collisions with 16-keV He^+ ions. Using the indicated value of the cross section for the second process, we then obtained $(1.2 \pm 0.2) \times 10^{-18}$ cm^2 as the cross section $\sigma_0(L_\beta)$ for L_β excitation in the first process. From the known transition probabilities we obtained the cross sections for L_β excitation in the other gases.

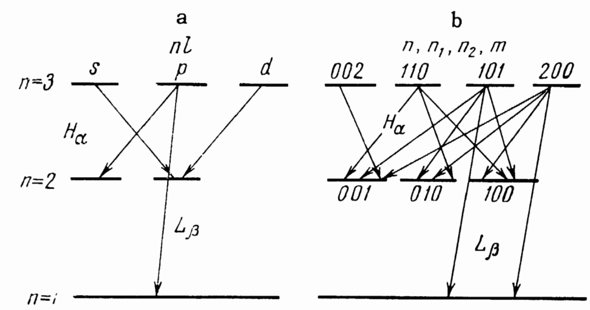

FIG. 3. Level scheme for hydrogen states with n = 1,2, and 3: a) in the absence of external fields, and b) in an electric field for which a linear approximation of Stark-effect theory is applicable.

The absolute cross sections for L_β excitation in an electric field were obtained from the measured ratios of I(L_β) with and without a field.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Figures 4–8 show the measured absolute cross sections $\sigma_0(L_\beta)$ and $\sigma_{\mathscr{E}}(L_\beta)$ for charge exchange of 10–40-keV protons in He, Ne, Ar, Kr, and Xe.

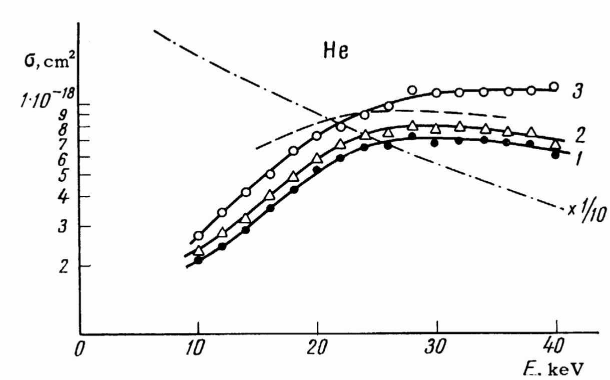

FIG. 4. Excitation cross sections resulting from proton-helium charge exchange vs. proton energy: 1–Cross section for L_β emission in zero field, 2–for excitation of the 3p state, 3–L_β emission in a field. The dashed curve pertains to 3p excitation data in [6]; the dot-dash curve pertains to 3p excitation data in [5].

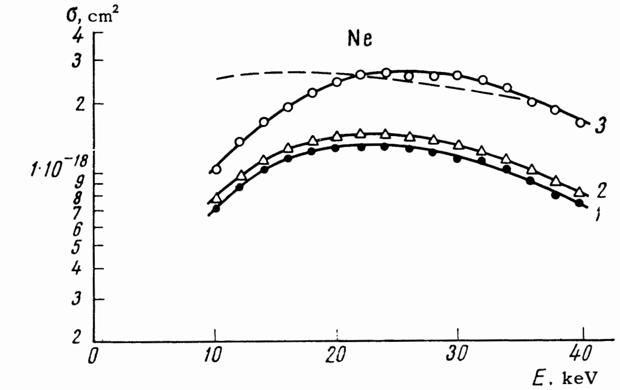

FIG. 5. The same as Fig. 4, for protons in neon.

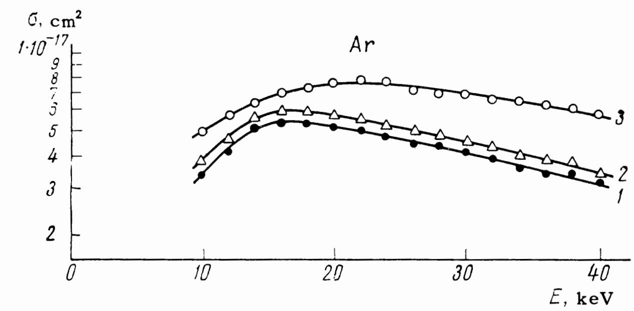

FIG. 6. The same as Fig. 4, for protons in argon.

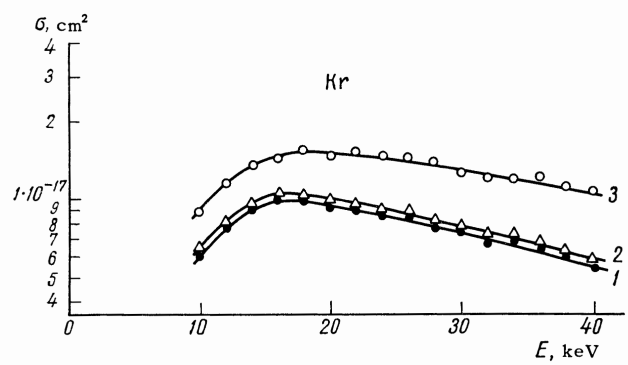

FIG. 7. The same as Fig. 4, for protons in krypton.

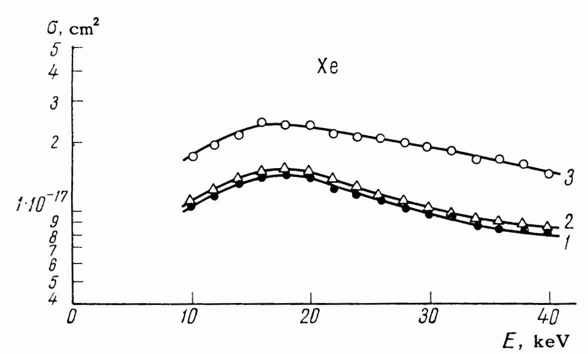

FIG. 8. The same as Fig. 4, for protons in xenon.

We observe that $\sigma_{\mathscr{E}}(L_\beta)$ is 1.5 to 2 times greater than $\sigma_0(L_\beta)$ for all these gases in the entire given proton energy range. Both $\sigma_0(L_\beta)$ and $\sigma_{\mathscr{E}}(L_\beta)$ increase as we go from lighter to heavier target atoms. Each curve exhibits a maximum [except $\sigma_{\mathscr{E}}(L_\beta)$ for He]; with increasing atomic number of the target gas the proton energy at the curve peak is reduced.

In the absence of an electric field $\sigma_0(L_\beta)$ can be used to determine the cross section $\sigma(3p)$ for excitation of the 3p level, using the obvious relation

$$\sigma(3p) = \sigma_0(L_\beta)\gamma_{3p} / \gamma_{3p-1s}. \quad (1)$$

The transition probabilities $\gamma_{3p-1s} = 1.64 \times 10^8 \text{ sec}^{-1}$ and $\gamma_{3p} = \gamma_{3p-1s} + \gamma_{3p-2s} = 1.86 \times 10^8 \text{ sec}^{-1}$ were taken from [2]. Figures 4–8 also show curves for $\sigma(3p)$.

The observed enhancement of L_β intensity when an external electric field is present in the collision chamber can be attributed qualitatively to the stimulation of deexcitation processes in hydrogen. Accompanying charge exchange between protons and inert gases hydrogen atoms require an excitation time $\sim 10^{-16}$ sec, which is the collision time. In an external field the excitation levels that had existed in the absence of the field are converted into the so-called Stark levels within a time that is inversely proportional to the Stark splitting. For the n = 3 level and $\mathscr{E} \sim 500$ V/cm[1)] this time is about 10^{-10} sec, which is considerably shorter than the n = 3 lifetime (10^{-8} sec) with respect to radiative decay. Thus an electric field of 600 V/cm does not affect charge exchange, and the excitation cross section of a level having the principal quantum number n = 3 does not depend on whether or not an external electric field exists in the collision chamber.[2)] However, the external electric field can exert considerable influence on the decay of an excited state and on the corresponding radiation.

In a region that is free of external fields the decay of the n = 3 level proceeds according to the scheme shown in Fig. 3a. In an external electric field the lifetime of an excited hydrogen state and therefore the intensity of the corresponding emission are functions of the field strength. However, the relation $I(L_\beta) = f(\mathscr{E})$ in Fig. 1 shows that in

1)In this field the Stark splitting of the hydrogen n = 3 level is of the same order as the fine structure.

2)The situation changes in high electric fields (~ 10^8 V/cm), where levels having different quantum numbers n begin to mix. In this case the field can have considerable effect on the population of a level with a given quantum number n.

fields beginning with 200 V/cm the L_β line intensity is almost independent of the field. On this basis we can postulate that a linear approximation would be adequate in the Stark-effect theory for a field of 500 V/cm. We are therefore justified in using calculations for the n = 3 level that were based on parabolic wave functions in strong fields.[2]

It follows from quantum mechanics that the n = 3 level of hydrogen in the aforementioned fields consists of four Stark levels characterized by the quantum numbers n, n_1, n_2, m: 002, 110, 101, 200 (Fig. 3b). In this case the observed L_β intensity represents the decay of only two levels, 101 and 200, whereas the H_α line represents transitions from all four levels. It can be shown that each Stark level in Fig. 3b represents a superposition of the 3s, 3p, and 3d states that exist in the absence of a field.[3] The L_β intensity in a field can differ from the zero-field intensity as a function of the populations of these states. Therefore the observed influence of an external electric field on the L_β emission excited through charge exchange between protons and inert gases can be attributed to an alteration in the type of hydrogen emission process under the influence of an electric field.

In one experimental investigation[4] the measured zero-field L_β intensity was used to determine the 3p excitation cross section for charge exchange between 5—35-keV protons and He or Ne. The cross sections given in[4] exceed those in Figs. 4 and 5 by a factor of 1.5—2. Mapleton[5] has published calculations of 3p excitation cross sections in connection with proton-He charge exchange. These calculations represent a Born approximation using a crude wave function for the He atom. The derived cross sections diminish as the proton energy grows in the range 10—40 keV, and are an order greater than our results in the present work (Fig. 4).

We note in conclusion that besides the higher L_β intensity when an external field exists in the collision chamber one also observes 1) different behavior, as a function of the proton energy, exhibited by the H_α and L_β excitation functions measured for one and the same process (Fig. 9 gives as an example the H_α and L_β excitation functions for proton-Ar charge exchange in a field $\mathcal{E}$ = 600 V/cm), and 2) the appreciable polarization of H_α emission in zero field (Fig. 10). It follows from the quantum-mechanical calculations that for a statistical population of the hydrogen fine structure the emitted radiation should be unpolarized, and the H_α and L_β intensities should not vary in the field; the excitation functions of these lines should exhibit identical behavior. The effects observed by us therefore indicate that when charge exchange occurs between fast protons and inert gases the 3s, 3p, and 3d states do not have statistical populations.[3)]

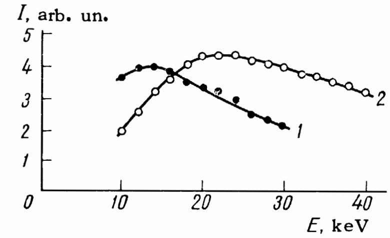

FIG. 9. Excitation functions of the lines (1) H_α and (2) L_β for proton-argon charge exchange ($\mathcal{E}$ = 600 V/cm).

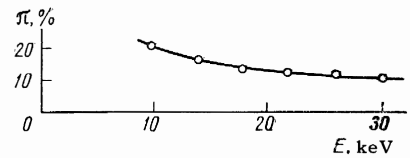

FIG. 10. Polarization of H_α emission induced by proton-argon charge exchange vs. proton energy; $\pi = (I_\parallel - I_\perp) / (I_\parallel + I_\perp)$.

The authors are indebted to Professor V. M. Dukel'skiĭ for daily assistance with the present work.

3)For proton charge exchange in a strong magnetic field (as shown in our work on the measurement of lifetimes and relative intensities of Balmer lines emitted by excited hydrogen atoms [6,7]) these atoms have a nearly statistical distribution among the fine-structure sublevels.

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Translated by I. Emin
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