PHYSICAL REVIEW VOLUME 130, NUMBER 6 15 JUNE 1963

Electron Capture by Protons Passing Through Hydrogen

T. PRADHAN AND D. N. TRIPATHY
Saha Institute of Nuclear Physics, Calcutta, India

(Received 18 January 1963)

Computational errors in a previous paper on this subject by one of us (TP) have been rectified. The recomputed capture cross sections agree fairly well with experimental data over the entire energy range from 50 to 1000 keV. In the original paper the disagreement was at energies above 150 keV, in spite of the fact that the approximation scheme adopted was expected to be better at higher than at lower energies.

ONE of us (TP) developed an approximation scheme[1] for the calculation of the cross section of the process,

$$H^{(+)}+H(1s)\rightarrow H(1s)+H^{(+)},$$

in which the three-body Møller matrix was expanded in terms of two-body Møller matrices and certain terms in this expansion were neglected in an impulse-approximation-like manner. The initial and final wave functions, as a result, turned out to be orthogonal to each other in the limit of the ratio (electron mass)/(proton mass) approaching zero, thereby making the contribution of the proton-proton interaction to the capture cross section zero in conformity with the conjecture made by Wick that in the above limit the proton-proton interaction can be removed by a suitable canonical transformation. This approximation scheme, thus, removes one of the great drawbacks of the Born approximation for rearrangement collision problems, i.e., that the initial and the final wave functions are not orthogonal to each other.[2] Although the differential cross section in this approximation method can be obtained in closed form in terms of ordinary functions, the integration over the angles to obtain the total cross section could not be performed by analytic methods and was, therefore, done by a graphical method. Unfortunately, serious computational errors had been made in the calculations of cross section at energies above 150 keV and it so happened that experimental data at the time this work was done existed only up to 150 keV and were in good agreement with the computed values. This error was noticed by us recently while trying to understand the discrepancy between the predictions of the theory and experimental results of Barnett and Reynolds.[3] We were puzzled by the fact that the computed cross section becomes very much less than the Brinkman-Kramers[4] cross section at high energies, whereas from the equation

$$\frac{d\sigma}{d\Omega}=\frac{d\sigma_{\mathrm{BK}}}{d\Omega}f(p),$$

$$f(p)=\frac{\pi s/p}{\sinh(\pi s/p)}\exp\left[\frac{4s}{p}\arctan\left(\frac{s}{p}\right)-\frac{\pi s}{p}\right],$$

for the differential cross section, in obtaining which no computation was necessary and which was, therefore, free of computational error, it is quite clear that for large p (high energy or large angle of scattering)

$$f(p)\rightarrow 1,\quad d\sigma/d\Omega\rightarrow d\sigma_{\mathrm{BK}}/d\Omega.$$

This led us to doubt the correctness of the computations made in reference 1 to obtain the total cross section. Recomputation has proved that there were errors. The revised cross sections are compared with experimental data in Fig. 1. It should be mentioned here that the incorrect cross sections given in reference 1 have been

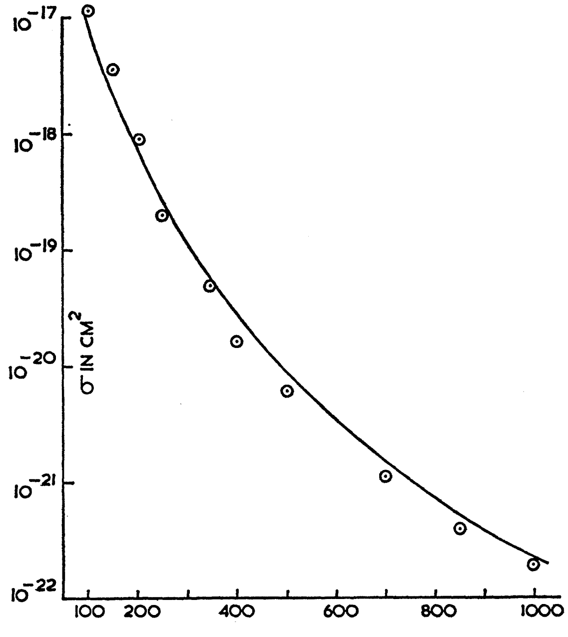

FIG. 1. Capture cross section as a function of incident proton energy. The solid line gives the theoretical prediction and the points surrounded by small circles give the experimental values of Barnett and Reynolds.

---

[1] T. Pradhan, Phys. Rev. **105**, 1250 (1957).

[2] With this drawback and the conjecture of R. Aaron, R. D. Amado, and B. N. Lee [Phys. Rev. **121**, 319 (1961)] that the Born series is not convergent for rearrangement collisions, it is difficult to understand the agreement of the Born-approximation calculations of J. D. Jackson and H. Schiff [Phys. Rev. **89**, 359 (1953)] with experiment over the entire energy range.

[3] C. F. Barnett and H. K. Reynolds, Phys. Rev. **109**, 355 (1958).

[4] H. C. Brinkman and H. A. Kramers, Proc. Acad. Sci. Amsterdam **33**, 1973 (1930).

used in a number of papers published later by various authors.[2,5]

We would like to take this opportunity to point out that the comment of Bassel and Gerjuoy[5] that the wrong matrix element is used in reference 1 to evaluate the capture amplitude ignores the fact that in reference 1 the matrix element evaluated has been proved to be approximately equal to the correct matrix element and that at very high energy, where the Born approximation can be taken to be exact, the equality of these two matrix elements is exact. It is, therefore, difficult to see how Drisko's estimates referred to by Bassel and Gerjuoy can indicate that the error caused by the use of the "wrong" matrix element is serious in the high-energy limit. Our belief, which is based on the proof given in reference 1, is that the matrix element evaluated by Pradhan and used by us in the present work for the computation of the total cross section is so close to the correct one that the error is negligible.

---

[5] R. H. Bassel and E. Gerjuoy, Phys. Rev. **117**, 749 (1960); M. R. C. McDowell, Proc. Roy. Soc. (London) **A264**, 277 (1961).

PHYSICAL REVIEW VOLUME 130, NUMBER 6 15 JUNE 1963

Balmer Emissions Induced by Proton Impact on Molecular Hydrogen*

R. H. HUGHES, SABRINA LIN,† AND L. L. HATFIELD
Physics Department, University of Arkansas, Fayetteville, Arkansas

(Received 15 February 1963)

Absolute cross sections for the production of H_α, H_β, and H_γ emissions by proton impact on molecular hydrogen have been measured. Emissions produced through the process of electron capture into excited states by fast protons are Doppler shifted from emissions produced through dissociative excitation of the target gas, which allows separate measurements of these processes. Comparisons are made with theoretical calculations of proton impact on atomic hydrogen.

I. APPARATUS

A POSITIVE-ION accelerator has been built at the University of Arkansas to accelerate ions through a maximum potential of about 140 kV for the purpose of studying the spectra induced by ion impact on gases. The ion beam is magnetically analyzed as it is bent through 30° into the collision chamber. Figure 1 shows the details of the differentially pumped collision chamber. Not shown is a liquid-air trap at the end of the collision chamber. This trap was installed to remove condensable vapors from the collision chamber.

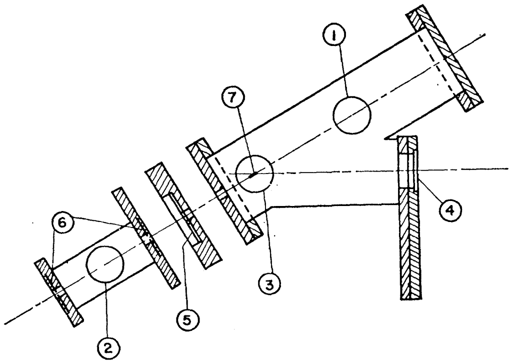

FIG. 1. Collision chamber—(1) gas inlet, (2) differential pumping outlet, (3) McLeod gauge, (4) view port, (5) electron repeller, imbedded in Lucite which insulates the collision chamber, (6) collimating apertures ($\frac{1}{16}$-in. holes), (7) Pirani gauge.

Spectroscopic observation of the collision region is made at an angle of 30° to the beam. This allows measurements on Doppler-shifted emissions produced through the process of electron capture into excited states by fast protons to be separated from the unshifted radiation produced by direct excitation processes in the target gas. A JaCo 500 mm Ebert spectrometer was calibrated for use in the $\lambda 3800$ to $\lambda 6600$ Å spectral range. The calibration procedure has been previously described.[1] The spectrometer now uses an EMI 6095B photomultiplier as a detector.

Pressure measurements are made with a trapped McLeod gauge while a Pirani gauge is used to monitor the pressure. The hydrogen was introduced into the collision chamber via a heated palladium leak. Pressure ranged from 1.5μ Hg for the low-energy work to 9μ for the higher energies.

II. RESULTS AND DISCUSSION

Balmer radiations, H_α, H_β, and H_γ were measured for proton impact on H_2. These emissions were linear with current and above 10 keV they were measured in a pressure range where the emissions were linear with pressure. Below 20 keV, we suffer a loss in beam current

---

* Supported by the Air Force Cambridge Research Laboratories and the National Science Foundation.

† Present address: Physics Department, Cornell University, Ithaca, New York.

[1] R. H. Hughes, R. C. Waring, and C. Y. Fan, Phys. Rev. **122**, 525 (1961).