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Electron Capture from Atomic Nitrogen by Protons

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The total Oppenheimer-Brinkman-Kramers (OBK) cross sections for 1*s*-, 2*s*-, and 2*p*-orbital electron capture from atomic nitrogen by protons are adjusted to correspond to capture from N_2 by deuterons, and are compared with recent measurements of Berkner *et al.* Calculated cross sections for 1*s* capture are dominant above 3 MeV, and the total OBK cross section still exceeds the measured cross section at the deuteron energy of 21.5 MeV.

RECENTLY published measurements of cross sections for electron capture from N_2 by deuterons differ markedly from the OBK (Oppenheimer-Brinkman-Kramers) cross sections for electron capture from N by protons when expressed as cross sections per gas molecule at the appropriate impact energy for deuterons.[1] One of the chief sources of the disagreement in this comparison originates from using calculated cross sections for only *p*-orbital capture at impact energies where capture from inner subshells is dominant.[2]

The importance of 1*s*- and 2*s*-orbital capture at high impact energies was emphasized in I, but only estimates of these cross sections could be given since the wave functions for the atomic ions, $N^+(^5S,^3S)$, configurations $(1s)^2 2s(2p)^3$ and $1s(2s)^2(2p)^3$, were not available during the time that the calculations were effected. Since wave functions have become available,[3] OBK cross sections for 2*s*-orbital capture have been computed and published.[4] Although wave functions for the configuration $1s(2s)^2(2p)^3$ have not been published, the atomic orbitals for the ion Ne^+, configurations $1s(2s)^2(2p)^6$ and $(1s)^2 2s(2p)^6$, are given in a recent paper.[5] A comparison of the orbital functions for these two configurations of Ne^+ shows that the two sets of 1*s* and 2*s* parameters differ very little. With this in mind, it is assumed that not much error in the OBK cross sections for 1*s* capture result from using Roothaan[3] atomic orbitals of $(1s)^2 2s(2p)^3$, $N^+(^5S,^3S)$, to represent the corresponding term values of $1s(2s)^2(2p)^3$. (This is a very special application of the wave functions, and is not supposed to imply the validity of such an approximation for other purposes.)

This approximation has been used to compute cross sections for 1*s* capture, impact energies $\geqq 1$ MeV; moreover, the energy range of the cross sections for 2*s* capture[4] has been extended to 100 MeV. The cross sections are expressed as a function of the impact energy of the proton in the frame of reference where the atomic target is initially at rest. Perhaps the most notable distinction of these OBK cross sections is the dominance of 1*s*-orbital capture for impact energies exceeding 3 MeV. These cross sections pertain to capture into the 1*s* state of atomic hydrogen only, and the n^{-3} rule is used to sum the cross sections into all *s* states of hydrogen.[6] As for the contributions of simultaneous charge transfer and excitation, previous calculations for helium suggest that these processes can be neglected with small error.[7] The sum of the OBK cross sections for 1*s*-, 2*s*-, and 2*p*-orbital capture from $N(^4S)$ into all *s* states of the hydrogen atom leaving the residual ions $N^+[^3P;(1s)^2(2s)^2(2p)^2]$, $N^+[^3S,^5S;(1s)^2 2s(2p)^3]$, and $N^+[^3S,^5S;1s(2s)^2(2p)^3]$ have been multiplied by 2, and are plotted in Fig. 1.

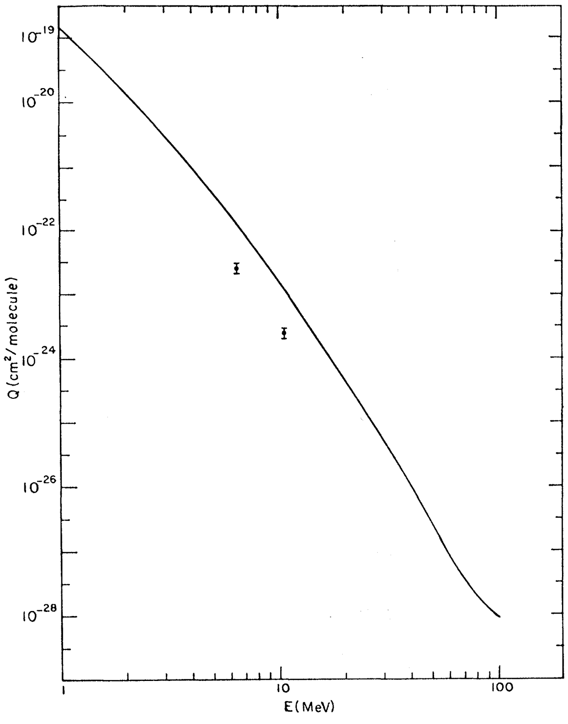

FIG. 1. Electron-capture cross sections per N_2 molecule. *E* is the impact energy of the proton in MeV. Closed circles with error bar represent experimental values taken from Table I of Berkner *et al.* Solid curve represents the sum of the OBK cross sections for atomic nitrogen multiplied by 2. (See text for the processes represented.)

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[1] K. H. Berkner, S. N. Kaplan, G. A. Paulikas, and R. V. Pyle, Phys. Rev. **140**, A729 (1965).

[2] R. A. Mapleton, Phys. Rev. **130**, 1829 (1963). This is referred to as I.

[3] C. C. J. Roothaan and P. S. Kelley, Phys. Rev. **131**, 1177 (1963).

[4] R. A. Mapleton, Proc. Phys. Soc. (London) **85**, 1109 (1965).

[5] P. S. Bagus, Phys. Rev. **139**, A619 (1965).

[6] J. R. Oppenheimer, Phys. Rev. **31**, 349 (1928); J. D. Jackson and H. Schiff, *ibid.* **89**, 359 (1953).

[7] R. A. Mapleton, Phys. Rev. **122**, 528 (1961).

It is seen that the two experimental values of Berkner, *et al.* are less than the corresponding OBK values, which fact suggests that the asymptotic energy region may not yet be reached. Of course, it is not known whether OBK cross sections are the asymptotic values of a correct theory, and at what energy the onset of the asymptotic value would occur. Little is also known how well electron capture from N_2 can be described in terms of N atoms[8] (factor of 2) or how much the present OBK values would be altered by a recalculation with improved wave functions. In the author's opinion, it is very difficult to decide theoretically what the asymptotic cross section is for a target as complicated as N_2.

An atomic system much more tractable to theoretical analysis is helium, and the energy range of the OBK calculations[9] using the 6-parameter helium wave function have also been extended to 100 MeV. The OBK cross sections for capture from He, N, and O, described in this paper, can be obtained from the author.

Gratitude is expressed to Professor A. Dalgarno for informing the author of these measurements.

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[8] T. F. Tuan and E. Gerjuoy, Phys. Rev. **117**, 756 (1960).

[9] R. A. Mapleton, Phys. Rev. **130**, 1839 (1963).

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Radiative Lifetime of the First $^2P_{3/2}$ State of Ionized Calcium and Magnesium by the Hanle Effect*

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The lifetime of the Ca$^+$ $4^2P_{3/2}$ state and that of the Mg$^+$ $3^2P_{3/2}$ state have been measured by the Hanle-effect method with optical excitation from the ground states of the ions. The lifetimes are, respectively, $(6.72\pm0.20)\times10^{-9}$ and $(3.67\pm0.18)\times10^{-9}$ sec. The ions were produced by introducing traces of calcium or magnesium into an argon discharge. "Alignment" depolarization cross sections σ were obtained for the collisional depolarization of the following states of calcium and magnesium due to collisions with argon:

$$\sigma(\text{Ca } 4^1P_1 \text{ state}) = (1.9\pm0.3)\times10^{-14}\text{ cm}^2;$$
$$\sigma(\text{Ca}^+\ 4^2P_{3/2} \text{ state}) = (1.4\pm0.2)\times10^{-14}\text{ cm}^2;$$
$$\sigma(\text{Mg } 3^1P_1 \text{ state}) = (1.9\pm0.3)10^{-14}\text{ cm}^2;$$
$$\sigma(\text{Mg}^+\ 3^2P_{3/2} \text{ state}) = (1.3\pm0.25)\times10^{-14}\text{ cm}^2.$$

The magnitudes of these cross sections are in accord with the theories of Byron and Foley and of Omont; we give a discussion of the extension of these theories to include ion-atom collisions.

I. INTRODUCTION

WE report here the application of the Hanle-effect technique to the measurement of lifetimes of excited states of ions. Ca$^+$ and Mg$^+$ were chosen, since their absolute oscillator strengths are of astrophysical importance and are useful for testing various theoretical methods of calculating oscillator strengths.[1] The Hanle effect has been known for many years as a technique for measuring lifetimes or transition probabilities for optical resonance lines in atoms.[2] The method has been used frequently in recent years, primarily by the group at Columbia.[3] This recent work has demonstrated the accuracy of the method for measuring atomic state lifetimes (a typical uncertainty is 3%), and it is an aim of the present paper to demonstrate that the method can be used to measure ionic state lifetimes with comparable accuracy. Although the results reported here are only for Group II ions, we think that the method should have wide application for precision determinations of transition probabilities of resonance lines of other ions.

Methods for measuring transition probabilities of atoms or ions may be divided into two classes: those which measure oscillator strengths directly and those which measure excited-state lifetimes. Typical of the first class are the methods of anomalous dispersion (the "hook" method),[2] emission from thermal arcs,[4] and

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[1] See, for example, A. S. Douglas and R. H. Garstang, Proc. Cambridge Phil. Soc. **58**, 377 (1962).

[2] A. C. G. Mitchell and M. W. Zemansky, *Resonance Radiation and Excited Atoms* (Cambridge University Press, New York, 1961), Chap. V.

[3] For a review of the theory and experimental techniques, see A. Lurio, R. L. deZafra, and R. J. Goshen, Phys. Rev. **134**, A1198 (1964), and references contained therein.

[4] See, for example, C. H. Corliss and W. R. Bozman, Natl. Bur. Std. (U. S.) Monograph 53 (1962).