Strong-Interaction Effects in Antiprotonic Atoms*

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(Received 28 August 1972)

We have measured the energies and widths of the x-ray lines from the $4f \rightarrow 3d$ transition in antiprotonic atoms of ^{14}N and ^{16}O. The results are discussed in terms of a phenomenological optical potential. We have also observed the x-ray line from the $3d \rightarrow 4p$ transition in the antiprotonic ^{4}He atom.

We report here measurements of the widths and the energies of the x-ray lines from the $4f \rightarrow 3d$ transition in antiprotonic atoms with nuclei of ^{14}N and ^{16}O. Experimental results are interpreted in terms of a $\bar{p}$-nucleus optical potential. Antiprotonic atoms have previously been observed[1] in experiments at CERN, but strong-interaction energy shifts and level widths were not reported.

In these experiments, antiprotons with momentum 800 MeV/c from the Argonne National Laboratory zero-gradient synchrotron were brought to rest in targets of oxygen (H_2O) or nitrogen (liquid) of thickness about 7 g/cm^2. A small (2-cm^2 area, 0.5 cm thick), high-resolution (600-eV full width at half-maximum at 122 keV) Ge(Li) detector, placed at the side of the target, was used to detect the x rays. Antiprotons in the beam were identified by use of a counter and logic system which included time-of-flight determination and a pion Cherenkov counter in anticoincidence. Sources of ^{203}Hg and ^{241}Am, suitably placed, provided x and γ rays for energy and instrumental width calibration. Signals from the Ge(Li) detector were routed to one 1600-channel memory if they were in coincidence (within 100 nsec) with a $\bar{p}$ in the beam, or into a second 1600-channel memory if they were not. Signals were stored only during the zero-gradient synchrotron beam-on time.

The x-ray spectra for ^{14}N and ^{16}O are shown in Fig. 1. They were obtained with, respectively, about 5×10^6 and 11×10^6 stopping $\bar{p}$. From the x-ray and calibration data, we have determined the energies and the natural widths of the lines resulting from the $4f \rightarrow 3d$ transition. The fits to the lines were made as follows. The calibration lines were fitted with Gaussian functions superimposed on three-parameter polynomial-shape backgrounds. The Gaussian shape so obtained was folded into the calculated fine-structure pattern of the $\bar{p}$ x-ray line. A Lorentzian function was then folded in, and the Lorentzian width and line position adjusted to fit the x-ray line. The results for the Lorentzian widths and the energies (centroid of the fine-structure pattern) are given in Table I. Also given in Table I are the energy centroids calculated using a relativistic wave equation in which the effects of finite charge size and vacuum polarization are included, but in which no strong-interaction potential is included. The nuclear

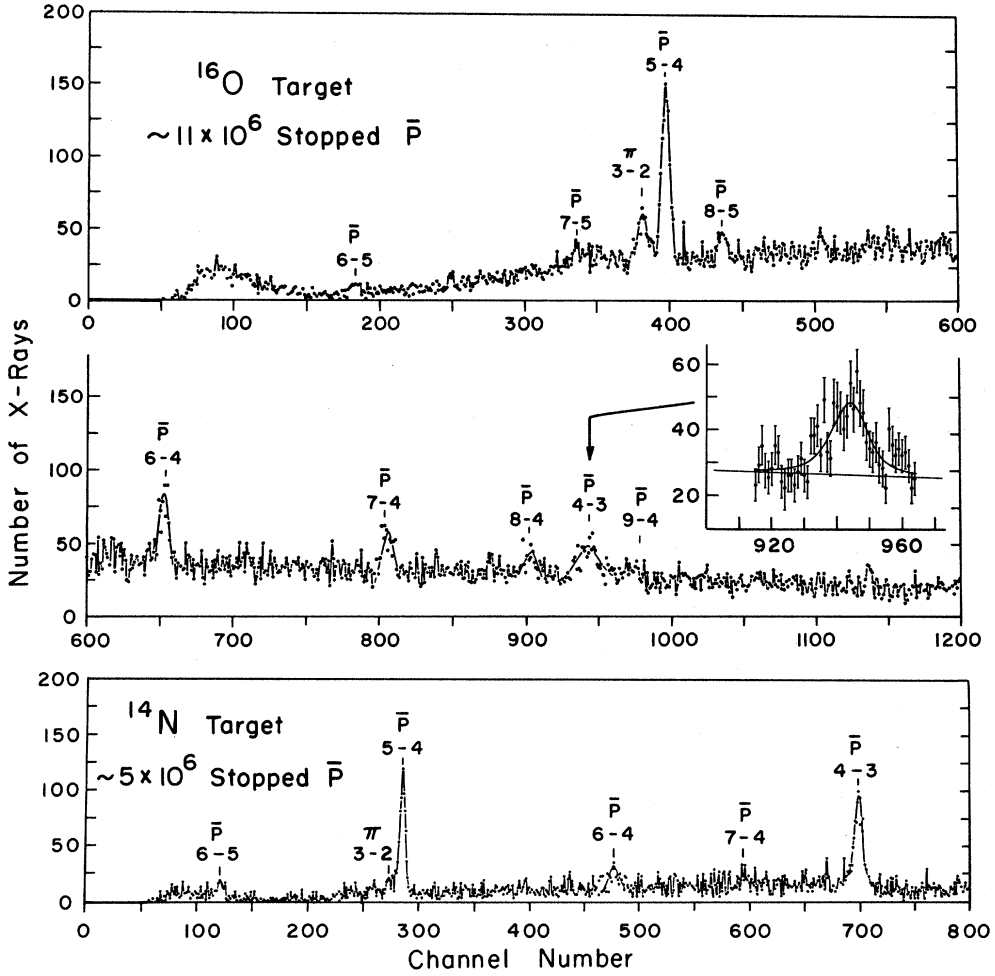

FIG. 1. X-ray spectra from antiprotonic atoms of ^{16}O and ^{14}N. The dispersion was 72.42 eV per channel. The energy E in terms of channel number n is given by $E = (0.07242n + 5.107)$ keV.

shapes used were of the Fermi form

$$\rho(r) = \rho_0\{1 + \exp[(r-c)/z]\}^{-1},$$

with c and z of, respectively, 2.434 and 0.425 F for nitrogen and 2.600 and 0.500 F for oxygen.

In order to extract information from these data concerning the nucleon-antinucleon strong interaction and nuclear shape, we have solved the wave equation as above but including a strong-interaction potential of the form[2]

$$V(r) = -(2\pi/\mu)(1 + M_{\bar{p}}/M_N)\bar{a}\rho(r),$$

where μ is the $\bar{p}$-nucleus reduced mass, ρ is the nuclear density normalized to nucleon number A, $M_{\bar{p}}$ and M_N are the $\bar{p}$ and nucleon masses, respectively, and $\bar{a}$ is a complex scattering length. ρ was taken to have the Fermi form given above with the same values of c and z. The real and imaginary parts of $\bar{a}$ were varied to obtain the best fits to the measured energies and widths of the x-ray lines. In this manner we find from the ^{16}O line energy and width $\bar{a} = [+(2.8 \pm 1.5) + i(1.2^{+1.5}_{-0.5})]$

TABLE I. Measured transition energies and widths for the $4f \rightarrow 3d$ transitions in ^{14}N and ^{16}O. The theoretical energy value is the centroid of the calculated fine-structure pattern obtained from a relativistic wave equation with finite nuclear size and vacuum polarization included, but with no strong-interaction potential. The nuclear distribution used had a Fermi shape, with parameters as given in the text. The widths given below are the observed linewidths after removing the broadening due to fine-structure splitting and instrumental resolution (see text).

	Transition energy (keV)		Width (eV)
Nucleus	Measured	Theoretical	Measured
^{14}N	55.785 ± 0.051	55.824 ± 0.003	173 ± 34
^{16}O	73.502 ± 0.073	73.562 ± 0.003	648 ± 150

F and from the ^{14}N line $\bar{a} = [+(3.4^{+2.0}_{-2.9}) + i(3.3^{+6.7}_{-2.6})]$ F. The very large uncertainties in the scattering lengths for ^{14}N compared to ^{16}O reflect the fact that the $3d$ atomic state is less sensitive to the strong $\bar{p}$-nucleus interaction in nitrogen than in oxygen. A more precise measurement of the shifts and widths would be useful in constraining $\bar{a}$ for oxygen, but less useful for nitrogen because of the lower sensitivity. Statistically the value of $\bar{a}$ which best fits all four pieces of data is $\bar{a} = [(2.9^{+1.4}_{-1.0}) + i(1.5^{+1.2}_{-0.6})]$ F. Even though these parameters have large errors, the real part seems considerably different from the value obtained by properly averaging the zero-energy S-wave $\bar{p}$-nucleon scattering lengths given by Bryan and Phillips,[3] namely, $\bar{a} = (-0.88 + i0.81)$ F. Similar behavior has been noted in kaonic-atom data.[4] However, one might not expect agreement since our treatment is rather a simple one and also, with the $\bar{p}$-nucleus system, we are concerned with energies below threshold.

It is of interest to investigate the sensitivity of the calculations to the nuclear-shape parameters. If we assume a strong-interaction potential of the (Fermi) form given above with our central value for $\bar{a} = (2.9 + i1.5)$ F and with the values of $\bar{c}$ given earlier, we find that the linewidth measurement restricts the value of z to the range 0.43 to 0.55 F for ^{16}O and to the range 0.40 to 0.47 F for ^{14}N.

We also wish to report here the observation of the x ray from the $3d \rightarrow 2p$ transition in the $\bar{p}$-He atom. Although the data obtained so far are not sufficiently precise to enable us to obtain a significant value for the width or energy of the line, nevertheless, the observation shows that Stark-effect mixing is not strong enough to cause the nuclear absorption of the antiprotons before they reach the $2p$ state.

Further analysis of all these data is proceeding and will be fully reported later.

We wish to thank many of our colleagues for help and valuable discussions of this work, in particular Dr. M. Sternheim, Dr. J. Koch, Dr. D. Anderson, Dr. L. Wolfenstein, Dr. R. Seki, and Dr. A. Kerman. We also wish to acknowledge the invaluable aid and support given by the staff at Argonne National Laboratory. We are greatly indebted to Mr. H. F. Ludwig for his unstinting help in providing the liquid-helium target.

*Work performed under the auspices of the U. S. Atomic Energy Commission and the National Science Foundation.

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Multiphoton Ionization and Dissociation of Molecular Hydrogen at 1.06 μm

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(Received 25 August 1972)

This paper reports the experimental investigation of the multiphoton dissociation and ionization of the hydrogen molecule under the influence of Nd-glass laser radiation at 1.06 μm. The higher electronic states of the potential-energy curves of H_2 are found to play the dominant role. An eleven-photon process is the initial step in the formation of H^+ and a twelve-photon process is the initial step in the formation of H_2^+.

Very little work has been carried out on multiphoton ionization and dissociation of molecules under the influence of laser radiation.[1,2] This Letter presents the results of an experimental investigation of multiphoton ionization and dissociation of hydrogen molecules with Nd-glass laser radiation at 10 590 Å.

The experimental method is the same as that employed in multiphoton ionization of atoms.[3] The radiation generated by a Q-switched neodymium glass laser is focused with an aspheric lens of 50 mm focal length into a vacuum chamber in order to obtain a laser intensity of up to 10^{13} W/cm^2. Molecular hydrogen is admitted into the