STUDY ON ANTIPROTONIC ATOMS OF LIGHT NUCLEI AND ISOTOPES^{x)}

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ABSTRACT

New data on strong interaction effects in light antiprotonic atoms (N, ¹⁶O, ¹⁸O, S) are presented. For the first time an isotope effect could be observed in $\bar{p}$ -¹⁶O/¹⁸O which is used to gain new information about the $\bar{p}$ -n interaction in nuclei. A comparison between all existing $\bar{p}$ -atomic data and an optical model calculation is performed, yielding a set of fit parameters for the potential.

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1. INTRODUCTION

The strong interaction between the antiproton and the nucleus causes shifts and a broadening of the atomic levels, which are detectable only in the last observable transition of the $\bar{p}$ cascade. From an accurate energy measurement (E_{meas}), one can deduce the strong interaction shift ϵ_{low} of the lower level of this transition, where ϵ_{low} is defined as the difference between E_{meas} and E_{em} (E_{em} = transition energy including all electromagnetic and QED effects but no strong interactions). The determination of the Lorentzian line-shape yields the strong interaction width of the lower level (Γ_{low}), while the strong interaction width of the upper level (Γ_{up}) can be deduced from the intensities of the lines in the spectra. All details about these procedures can be found elsewhere¹⁻⁵.

The strong interaction effects (ϵ_{low} , Γ_{low} , Γ_{up}) depend on the elementary $\bar{p}$ -p and $\bar{p}$ -n interactions at relative energies around the threshold and on the distribution of protons (ρ_p) and neutrons (ρ_n) in the tail of the matter distribution. The threshold behaviour of the $\bar{p}$ -N scattering amplitudes is characterized by the complex scattering lengths $A_{\bar{p}n}$ and $A_{\bar{p}p}$. Values for the scattering lengths were derived from an analysis of low-energy $\bar{p}$ -N scattering experiments⁶), but neither their signs nor their magnitude can be considered as definitely determined owing to the lack of experimental data. Nothing at all is known about the spin dependence. The knowledge of these scattering lengths, however, is of great interest since it is related to the question of the existence of bound states or resonances near the threshold of the $\bar{p}$ -N system⁷⁻¹⁰) and to cosmological problems¹¹). From measurements of $\bar{p}$ atoms with $A > 1$, only effective scattering lengths A^{eff} can be extracted. From a single nucleus only the sum of $A_{\bar{p}n}^{\text{eff}}$ and $A_{\bar{p}p}^{\text{eff}}$ can be deduced. In this paper, for the first time, both effective scattering lengths could be determined independently for the $\bar{p}$ -N interaction. This becomes possible by comparing the strong interaction effects on two isotopes ($^{16}\text{O}/^{18}\text{O}$). The interpretation of the data in terms of the $\bar{p}$ -N interaction depends on the knowledge of the proton and neutron distributions in the nuclear tail. These distributions can be determined with the necessary accuracy, taking into account elastic electron scattering data and muonic atom data¹²). The procedure of deriving neutron distributions from these data will be discussed in this paper.

Shortly after the discovery at CERN of antiprotonic X-ray transitions¹³), a first survey of strong interaction effects¹⁴) was performed. The intensity reduction of the last observable transition caused by the strong $\bar{p}$ -N absorption was clearly visible in all cases, but only marginal data were available about line-shapes and accurate energies. In a later paper¹⁵) from Brookhaven experiments, more accurate values for shifts and widths were given for $\bar{p}$ nitrogen and oxygen. The data discussed in the following come from a series of measurements performed

at the CERN Proton Synchrotron (PS). The experiments aimed at accurate measurements of energies, line-shapes, and intensities of the X-rays in light antiprotonic atoms; parts of these were performed several times under slightly modified conditions. The measurement on the $^{16}\text{O}/^{18}\text{O}$ isotopes was done in a manner which allowed a nearly complete suppression of systematic errors for the relative effects.

2. X-RAYS OF ANTIPROTONIC N, ^{16}O , ^{18}O , AND S ATOMS

The experiments were done at the low-momentum electrostatically separated $\bar{p}$ beam of the CERN PS. About 100 $\bar{p}$'s were stopped per machine burst in 1 g/cm^2 material. The experimental set-up and the generation of the stop-trigger signal have already been described^{13,14)}. The nuclei under investigation were used in the following chemical compounds: N_2 (liquid), C^{16}O_2 (solid), D_2^{16}O (liquid), and D_2^{18}O (liquid). Sulfur was measured in the form of a powder, as was done in the former experiment¹⁴⁾. All targets were several g/cm^2 thick. Their thickness was optimized such that the absorption of the X-rays of interest was not greater than 50%. The X-rays were measured with Ge(Li) and intrinsic Ge detectors with volumes of about 2 cm^3 . The in-beam energy resolution at 70 keV was as good as 600 eV. More detailed information about the experiments can be found elsewhere^{16,17)}. Two typical spectra (^{16}O and ^{18}O) are shown in Fig. 1. The lines which show strong interaction effects are the $4 \rightarrow 3$ transitions. The intensity reductions of the lines can be seen easily by comparison with the intensities of the $5 \rightarrow 4$ transitions. Also the broadening of the $4 \rightarrow 3$ lines, which originates from the unresolved fine structure (FS) splitting (about 100 eV) and the strong absorption broadening of the levels, is clearly visible.

2.1 Intensities

The results of the measurements are listed in Table 1. In column 3, the intensity of the last observable transition is given, normalized to a population of 100% of the upper level. As discussed earlier^{1-5,18,19)} the population P can be deduced by adding up the intensities (Y) of all X-ray transitions feeding the upper level and correcting this number for parallel transitions and Auger effect. The experimentally observable ratio Y/P then depends only on relative corrections for X-ray absorption in the target and relative detector efficiencies. The target absorption corrections were calculated with the computer program TARGET; the relative detector efficiency was taken from an in-beam efficiency calibration with radioactive sources. The corrections for parallel transitions and Auger transitions were obtained from the computer program CASCADE, with an initial ℓ -distribution at $n = 29$, chosen such that all intensity ratios seen in the spectra are reproduced. The results given in column 3 are averaged over the different targets and detectors used. The error contains the statistical contributions and the uncertainties arising from the correction procedures.

In the case of oxygen cascade, strong chemical effects were observed. The results of the relative intensities of the lines, normalized to the intensity of the 5→4 transition, are given in Table 2 for C¹⁶O₂ and D₂¹⁶O (cols. 2 and 3). The intensities of, for example, Δn = 3 transitions differ by as much as a factor of 2. In the case of D₂¹⁶O the inner levels of the energy level scheme (ℓ < n-1) apparently are much more strongly populated than in CO₂. One straightforward explanation would be a transfer of the antiproton between the deuteron and the oxygen atom, which populates preferentially the inner levels. In spite of the large differences in the cascades, the Y/P value for ¹⁶O is the same for the measurements in CO₂ and D₂O. This behaviour is, of course, expected and gives additional confidence in the method of deriving this ratio from the measured data. In column 4 of Table 2, the relative intensities of the D₂¹⁸O X-ray cascade are given. Within the experimental errors these numbers coincide with the relative intensities of ¹⁶O, given in column 3; this shows that the de-excitation process in D₂¹⁶O and D₂¹⁸O is identical,

2.2 Line widths

The results for the directly measured broadenings of the lower levels are given in Table 1, column 4. In the analysis of the line-shapes the FS pattern of the transitions, due to the energy splitting, was taken into account²⁰⁾:

$$\Delta E = \left\{ g_0 + 2 \frac{\mu}{m_{\bar{p}}} g_1 \right\} \frac{(Z\alpha)^4}{2n^3} \frac{\mu c^2}{\ell(\ell + 1)}.$$

Here μ denotes the reduced $\bar{p}$ nucleus mass, $m_{\bar{p}}$ is the antiproton mass, g_0 and g_1 the Dirac and anomalous part of the g-factor of the antiproton. A Lorentzian line-shape folded with the experimental Gaussian shape was fitted to each component of the transitions. The Gaussian width was obtained from other lines of the spectra near the broadened transition. In the case of ¹⁶O and ¹⁸O as well as for sulfur, two detectors placed at 90° to the beam direction on both sides of the targets were used.

The data on C¹⁶O₂ were not used for the extraction of the 3d strong interaction width. The reason is that for these experiments Pb shielding was used where electronic K_α and K_β Pb-lines were produced which bracket the $\bar{p}$ 4→3 transition. In spite of their smallness they can broaden the Lorentzian line-shape considerably. Neglecting their influence, the Lorentzian width in C¹⁶O₂ was nearly doubled compared to the D₂¹⁶O measurement, where no Pb shielding at all was present.

The errors given in column 4 of Table 1 result from an averaging procedure over all available spectra. They contain statistical errors, as well as the errors due to uncertainties of the evaluation procedure. As an example, the two measurements (different detectors) on $\bar{p}$ D₂¹⁶O are discussed in more detail. The values for the width of the 4→3 transition (Γ) and the contributions to the total error ΔΓ_{tot} are

given in Table 3. The statistical error $\Delta\Gamma_{\text{stat}}$ is always rather small. Larger contributions to the total error come from the uncertainty in the definition of the background under the broadened transition ($\Delta\Gamma_{\text{background}}$), from the choice of the extension of the fit-region ($\Delta\Gamma_{\text{region}}$), and from the uncertainty with which the experimental (Gaussian) in beam energy resolution is known ($\Delta\Gamma_{\text{resol.}}$). The sum of all these errors is called $\Delta\Gamma_{\text{tot}}$, and is quoted in the last column of Table 3. The weighted average over the data of the two detectors is given in Table 1, column 4. This example shows that in cases where the Lorentzian and the Gaussian line-widths have the same magnitude, the error in the Lorentzian width is mainly determined by systematic uncertainties in the evaluation procedure.

The values quoted in brackets in Table 1 come from the BNL work¹⁵⁾. A large discrepancy exists between our 3d width for ^{16}O and their value. A possible explanation might be a different treatment of the errors involved in the evaluation, or the presence of weak background lines in the tail of the Lorentzian line, as was the case in our CO_2 measurement.

2.3 Energies

The energies of the last observable transitions are given in Table 1, column 5. For the in-beam energy calibration of the detection system, the lines of radioactive calibration sources and antiprotonic lines of other nuclei occurring in the spectra were used. The energy calibration during the ^{16}O and ^{18}O measurements was done in a particular way: the samples of heavy and superheavy water were contained in Ti boxes with thin walls. The antiprotons stopping in the Ti material produced prompt $\bar{p}$ Ti X-rays appearing in the same spectrum as the oxygen lines (Fig. 1). The container material (Ti) was chosen such that lines of high yield and easily calculable energy (strong interaction effects were negligible) appear near the broadened oxygen lines and serve as excellent calibration standards. This method avoids any systematic shifts of the calibration lines with respect to the interesting lines. It provides also an accurate line-shape standard. The uncertainties in the evaluation procedure, as discussed above for the widths, also enlarge the errors in the determination of the line energies, but play a minor role. They are included in the errors given in Table 1, column 5.

2.4 Results

The values for Γ_{up} , Γ_{low} , and ϵ_{low} , derived from the experimental results of Table 1, are given in Table 4, columns 3-5; Γ_{up} is calculated from the measured ratio Y/P, using the expression^{1,4,5,18)}

$$\Gamma_{\text{up}} = \left(\frac{P}{Y} - 1 \right) \Gamma^x - \Gamma^{\text{Aug}},$$

where Γ^X and Γ^{Aug} are the partial widths of the upper level corresponding to a $\bar{p}$ transition to the lower level with the emission of an X-ray (E1 transition) or an Auger electron, respectively. The calculation of Γ^X and Γ^{Aug} is straightforward, but attention has to be paid to the fact that the movement of the $\bar{p}$ -N system around its common centre of mass gives a non-negligible contribution²¹⁾. This centre-of-mass correction enhances the radiation and Auger widths by the factor

$$C = \left(\frac{M + m_{\bar{p}} Z_{eff}}{M + m_{\bar{p}}} \right)^2,$$

where M is the nuclear mass and $m_{\bar{p}}$ the antiproton mass. In the nuclei discussed here, Z_{eff} can be put equal to Z in a good approximation²¹⁾. In Table 4, column 3, also the Γ_{up} values for P, Cl, K, Sn, I, and Pr are listed. They are calculated from the Y/P results given in Ref. 14, including the Fried-Martin factor C . The Γ_{low} of Table 3 is identical to the Lorentzian line-shape width of Table 1, column 4. For the determination of ϵ_{low} , the transition energies E_{em} are needed. They were calculated with the program PIATOM, taking into account all electromagnetic effects which give contributions larger than 1 eV.

3. ISOTOPIC EFFECTS IN $^{16}O/^{18}O$

A special technique was used to eliminate systematic errors in the comparison of the strong interaction effects of the two isotopically pure samples (impurity less than 0.1%) of $D_2^{16}O$ and $D_2^{18}O$. Both liquids were contained in Ti boxes of identical thickness and geometry; these were mounted one above the other on a remotely controlled support which moved the targets alternately into the beam. Depending on which target was in the beam, the pulses from the two diodes were routed accordingly. The targets were interchanged after a preselected number of $\bar{p}$ -stops were registered (about every five minutes). The spectra obtained in this manner are shown in Fig. 1. The background in both spectra is identical. With the exception of the $4 \rightarrow 3$ $\bar{p}$ oxygen transition, all corresponding lines have the same intensity, which shows that the capture and cascade process of the antiproton is completely independent of the oxygen isotope. The small relative shift of the $^{16}O/^{18}O$ lines with respect to each other comes from the different reduced masses. For the evaluation of the isotope effects in the shifts and intensities, a special analysis has been applied¹⁶⁾. To extract the isotope effect in the shift, we made use of the energy-independent ratio (ratio of the reduced masses of $^{16}O/^{18}O$) of the position of the unperturbed lines. The deviation of the ratio for the shifted lines from this constant yields the isotope effect in the shift obtained. An energy calibration with all inherent uncertainties could thus be avoided. For the isotope effect in the intensities, both spectra were subtracted from each other, channel by channel (Fig. 2). Owing to the reduced mass shift, only the oxygen lines survive as dipole-like oscillations, while all other calibration lines vanish. The difference

in the intensities was obtained by integrating the dipole structure of the $4 \rightarrow 3$ line to the left and to the right from the zero crossover. This provides good control of convergence and of discontinuities (as, for example, satellites) around the $4 \rightarrow 3$ transition. In order to add up the information from both detectors used and to be free of uncertainties in the efficiencies of the detectors, this difference has been normalized to the intensity of the $4 \rightarrow 3$ transition in ^{18}O . The isotope effect in the Lorentzian width was obtained from the differences of the single values. Since for both spectra the conditions are the same, only the statistical error contributes. Thus the errors for all three quantities are determined purely by the statistics. The results for the differences ($\delta = ^{18}\text{O} - ^{16}\text{O}$) derived in this way are

$$\begin{aligned} \frac{\delta \varepsilon}{^{16}\text{E}} &= (-1.06 \pm 0.65) \times 10^{-3}, \\ \delta \Gamma_{\text{low}} &= (245 \pm 100) \text{ eV}, \\ \frac{\delta I}{^{18}\text{I}} &= -0.34 \pm 0.10. \end{aligned} \quad (1)$$

If $\Gamma_{\text{up}} \gg \Gamma^x + \Gamma^{\text{Aug}}$, as is the case here, the $\delta I / ^{18}\text{I}$ can be related to the relative difference in the upper width by $\delta I / ^{18}\text{I} = -\delta \Gamma_{\text{up}} / ^{16}\Gamma_{\text{up}}$.

The data show that the isotope effects seen for the first time in strong interaction in antiprotonic atoms are statistically significant and remarkably large.

4. COMPARISON BETWEEN DATA AND CALCULATIONS

A possible ansatz for the strong $\bar{p}$ -N interaction is an optical potential of the form

$$V_{\bar{p}\text{-N}} = -\frac{2\pi}{\mu} \left(1 + \frac{m_{\bar{p}}}{M} \right) \left[A_{\bar{p}p}^{\text{eff}} \rho_p(r) + A_{\bar{p}n}^{\text{eff}} \rho_n(r) \right], \quad (2)$$

where μ is the reduced $\bar{p}$ nucleus mass, M is the nucleon mass, $m_{\bar{p}}$ is the antiproton mass, $\rho_p(r)$ and $\rho_n(r)$ are the distributions of protons and neutrons in the nucleus, and $A_{\bar{p}p}^{\text{eff}}$ and $A_{\bar{p}n}^{\text{eff}}$ are complex numbers which describe the effective interaction between the low-energy antiproton, and the protons and neutrons of the nucleus. Similar ansätze were tried for pionic and kaonic atoms and were able to reproduce the gross features of the data satisfactorily. In both cases a relation between A^{eff} and the free scattering amplitude A could be found²²⁻²⁷.

To derive shifts and widths of the levels from the optical potential, the expression for $V_{\bar{p}\text{-N}}$ is introduced into the Dirac equation and integrated numerically. QED and other corrections were computed in perturbation theory. The numerical integration of the equation yields the complex energy value $E - i(\Gamma/2)$ of the levels as a function of the parameters $A_{\bar{p}p}^{\text{eff}}$, $A_{\bar{p}n}^{\text{eff}}$, and the distributions ρ_p , ρ_n . As for kaonic atoms, it turns out that only the tails of the nuclear distributions give important contributions.

The idea behind the analysis of the data presented here is to gain information on the $\bar{p}$ -N interactions taking place in nuclei. The analysis is split into two parts: a) the ansatz, as introduced above, is shown to be useful for the nuclei under investigation. By adjusting the parameters of the ansatz so that the data are reproduced, a least squares fit value for the sum $(A_{pp}^{eff} + A_{pn}^{eff})$ is deduced from nuclei with $\rho_n(r) \approx \rho_p(r)$. b) The strong interaction effects in $^{16}\text{O}/^{18}\text{O}$ are significantly different. This difference is almost completely due to the two additional neutrons of ^{18}O . Thus the $^{16}\text{O}/^{18}\text{O}$ data are used to get an independent value for A_{pn}^{eff} and, together with the result from (a), also for A_{pp}^{eff} . For both parts of the analysis a reliable input for the proton and neutron radial density distributions is needed. For ^{16}O , ^{18}O , and S these distributions were determined as described below.

4.1 Proton and neutron distributions of light nuclei

For the protons, the density is well known from elastic electron scattering and muonic atom data. For the neutrons, however, very little is known experimentally. Probably the best assumption that can be made is that protons and neutrons move in the same average nuclear potential. For $N = Z$ nuclei, this assumption is verified quite well by Hartree-Fock calculations^{28,29)}. For $N \approx Z$ nuclei, the usual additional term for the isospin dependence³⁰⁾ of the average nuclear potential has to be applied in addition.

Given the fact that $\bar{p}$ atoms test essentially the large- r region of the density, wave functions having the correct asymptotic behaviour are required. In this region the proton and neutron densities become very different, the near-exponential fall-off being determined by the (different) separation energies. Together with the assumption of an equal nuclear potential (besides isotopic effects) for protons and neutrons, this leads us to the following procedure for the calculation of the proton and neutron radial wave functions. The average nuclear potential is parametrized in the form of a Saxon-Woods (SW) potential, the depth of which is essentially determined by the experimentally known proton separation energies. The shape of the SW-well is determined by requiring that the charge distribution calculated from the single-particle wave functions in this potential reproduces elastic electron-scattering data. The same potential, with small adjustments of the depth in order to reproduce exactly the neutron separation energies, is then used to calculate the neutron radial wave functions.

A three-parameter SW potential, with variable depth, radius, and surface thickness, is employed. It is complemented by a symmetry and a (surface) spin-orbit term and the Coulomb potential. For the different shells, small adjustments of the potential depth are allowed for, in order to reproduce exactly the experimental separation energies³⁰⁾ with the same geometry. The single-particle wave functions

calculated by solving the Schrödinger equation numerically are folded with the finite proton size and approximately corrected for centre-of-mass movement³¹⁾. In the case of ^{32}S , where considerable configuration mixing occurs, the occupation of the different shells according to experimental spectroscopic factors³²⁾ is taken into account. For the resulting charge density the elastic electron scattering cross-sections are calculated using a phase-shift code; they are compared to the available experimental data^{31,33)} between 100-800 MeV/c momentum transfer. When available, μ -atom data³⁴⁾ are also included in the fit.

From the proton nuclear potential, we obtain the neutron average potential by applying the isospin-dependent correction to the depth. Again, the neutron radial wave functions are calculated by solving the Schrödinger equation numerically. As an example for the densities found, Fig. 3 shows the proton and neutron densities in ^{16}O and ^{18}O .

4.2 Determination of $(A_{pp}^{\text{eff}} + A_{pn}^{\text{eff}})$

To check whether an ansatz of the form (2) is at all possible, a further reduction in the number of the free parameters seems meaningful. For the nuclei N, ^{16}O , and S, a rather small difference between $\rho_p(r)$ and $\rho_n(r)$ is found, even in the nuclear tail which matters here. With $\rho_n(r) = \rho_p(r)$ the ansatz (2) can be written as

$$V_{p-N} = - \frac{2\pi}{\mu} \left[1 + \frac{m_p}{M} \right] 2A_S^{\text{eff}} \rho_p(r), \quad \text{with } A_S^{\text{eff}} = \frac{1}{2}(A_{pp}^{\text{eff}} + A_{pn}^{\text{eff}}). \quad (3)$$

For ^{16}O and S, $\rho_p(r)$ was determined as described above. For nitrogen, a harmonic well distribution with $\langle R^2 \rangle_p^{1/2} = 2.54$ fm was used. The result of the least squares fit to the data of Table 4 is displayed in a scattering plot for χ^2 distribution (Fig. 4). The minimum is found at

$$A_S^{\text{eff}} = (2.0 + i 2.0) \text{ fm}. \quad (4)$$

This result can be compared with the result of a least squares fit to the BNL data¹⁵⁾ on N and O, where the assumption $A_{pp}^{\text{eff}} = A_{pn}^{\text{eff}}$ was made. Within the errors, both analyses yield consistent results. How well the data are fitted using Eq. (3) can be seen from Table 4, where the values calculated with Eq. (3) are given in brackets.

To see the influence of the shape of the ρ distributions, another least squares fit was performed with ρ distributions given by conventional two-parameter Fermi distributions¹⁶⁾. The χ^2 was considerably larger than the one using the more realistic distributions, as discussed before, A similar effect was observed in the analysis of the data on K^- atoms²⁵⁾.

4.3 Determination of A_{pn}^{eff} from the $^{18}\text{O}/^{16}\text{O}$ results

For ^{18}O the optical potential (2) can be written as

$$^{18}V_{p-N} = - \frac{2\pi}{\mu} \left[1 + \frac{m_p}{M} \right] \left\{ 2A_S^{\text{eff}} {}^{18}\rho_p(r) + A_{pn}^{\text{eff}} [{}^{18}\rho_n(r) - {}^{18}\rho_p(r)] \right\}. \quad (5)$$

In view of the nearly equal proton distributions in ^{16}O and ^{18}O (see Fig. 3), the difference in the potentials is given by the term proportional to $A_{\text{pn}}^{\text{eff}}$. From a least squares fit of Eq. (5) to the data of ^{16}O and ^{18}O , we obtain the real and imaginary parts of $A_{\text{pn}}^{\text{eff}}$,

$$A_{\text{pn}}^{\text{eff}} = -(0.3 \pm 1.4) + i(1.0 \pm 1.7) \text{ fm}, \quad (6)$$

where the errors mean the maximal ranges of the values. These values were obtained from fits to the oxygen data only. Regarding these results, it should be kept in mind that they depend critically on the correctness of the proton and neutron distributions, which were obtained as discussed above.

An interpretation of the isotope effect independent of density models is given elsewhere³⁵⁾.

5. CONCLUSIONS

The $\bar{p}$ -N interaction can be described by a phenomenological optical potential of the form (3) with the parameters (4). For nuclei with neutron distributions different from the proton distributions, the potential (2) with the parameters (6) has to be used. The agreement between the data and the calculations with the best fit parameters is quite good, at least as far as the general behaviour for different Z is concerned. It should be pointed out that within the experimental errors the parameters (4) are independent of the atomic weight and the atomic levels involved.

Several authors³⁶⁻³⁸⁾ have presented calculations on the strong interaction effects, and have compared their results with the BNL¹⁵⁾ or the preliminary CERN data^{1,2)}. All approaches fit the data more or less satisfactorily. One of the papers³⁶⁾ treats the $\bar{p}$ -N interaction in the WKB approximation and obtains reasonable values for the widths of the levels with only one free parameter. The others^{37,38)} try to relate the $\bar{p}$ -N interaction to the $\bar{p}$ free nucleon interaction at threshold, described by the t-matrix or a $\bar{p}$ -N potential. They construct their potentials by a proper folding of the $\bar{p}$ -N interaction and the nuclear density distribution, allowing for a finite range of the interaction, and again achieve agreement between the data and their calculations. Their results, however, depend critically on the correctness of the $\bar{p}$ -N scattering lengths which came from an analysis of the medium- and low-energy $\bar{N}$ -N scattering data⁶⁾. This analysis, however, does not take into account the possible complexity of the low-energy $\bar{N}$ -N interaction⁷⁻¹⁰⁾.

With the help of the individual numbers $A_{\text{pp}}^{\text{eff}}$ and $A_{\text{pn}}^{\text{eff}}$, respectively, one would be able to determine the amount of neutrons present in the tail of the nuclear matter distribution. At present, the error in $A_{\text{pn}}^{\text{eff}}$ is still too large to make valuable statements. Further measurements are needed to test the ansatz (2) also for heavier nuclei, and to reduce the error for A^{eff} .

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Table 1

New data on strong interaction effects in $\bar{p}$ atoms.
Values in brackets from BNL (Ref. 15).

El.	Transit.	Y/P [%]	Γ_{low} [eV]	$E_{\text{meas.}}$ [keV]
1	2	3	4	5
N	4 $\rightarrow$ 3	54 $\pm$ 6	205 $\pm$ 70 (173 $\pm$ 34)	55.827 $\pm$ 0.050 (55.785 $\pm$ 0.051)
^{16}O	4 $\rightarrow$ 3	15.1 $\pm$ 2.3	320 $\pm$ 150 (648 $\pm$ 150)	73.438 $\pm$ 0.036 (73.502 $\pm$ 0.073)
^{18}O	4 $\rightarrow$ 3	11.7 $\pm$ 1.8	550 $\pm$ 240	73.861 $\pm$ 0.042
S	5 $\rightarrow$ 4	19.0 $\pm$ 3.0 a)	650 $\pm$ 100 a)	140.440 $\pm$ 0.040

a) Mean value of Ref. 13 and the present measurement.

Table 2

Chemical effects in $\bar{p}$ oxygen

Transit.	C^{16}O_2	D_2^{16}O	D_2^{18}O
1	2	3	4
5 $\rightarrow$ 4	100 $\pm$ 4	100 $\pm$ 1	100 $\pm$ 1
6 $\rightarrow$ 4	14 $\pm$ 25	20.1 $\pm$ 2.5	20.2 $\pm$ 1.8
7 $\rightarrow$ 4	6 $\pm$ 1	11.2 $\pm$ 1.0	9.4 $\pm$ 0.9
8 $\rightarrow$ 4	2 $\pm$ 2	5.9 $\pm$ 0.7	5.4 $\pm$ 0.6
9 $\rightarrow$ 4	-	3.3 $\pm$ 0.6	3.4 $\pm$ 0.6
10 $\rightarrow$ 4	-	1.4 $\pm$ 0.6	1.3 $\pm$ 0.6
11 $\rightarrow$ 4	-	0.4 $\pm$ 0.4	0.7 $\pm$ 0.6
12 $\rightarrow$ 4	-	0.7 $\pm$ 0.6	0.8 $\pm$ 0.6

Table 3

Contributions to the total error for the
4→3 transition width in $\bar{p}^{16}\text{O}$ in eV

4→3 $\bar{p} \text{ D}_2^{16}\text{O}$	Γ	$\Delta\Gamma_{\text{stat}}$	$\Delta\Gamma_{\text{backg.}}$	$\Delta\Gamma_{\text{region}}$	$\Delta\Gamma_{\text{resol.}}$	$\Delta\Gamma_{\text{tot}}$
Detector 1 (Ortec)	300	83	150	30	100	200
Detector 2	348	66	150	140	100	238

Table 4

Comparison between measured and calculated
(in brackets) strong interaction effects

Nucleus	Last observable transition	Γ_{up} (eV)	Γ_{low} (eV)	ϵ_{low} (eV)
1	2	3	4	5
N	4→3	0.13 ± 0.03 (0.10)	205 ± 70 (144)	3 ± 50 (-31)
^{16}O	4→3	0.64 ± 0.11 (0.62) ^a	320 ± 150 (480) ^a	-124 ± 36 (-111) ^a
^{18}O	4→3	0.80 ± 0.12 (1.05) ^a	550 ± 240 (659) ^a	-189 ± 42 (-167) ^a
P	5→4	1.14 ± 0.25 (1.42)	-	-
S	5→4	3.04 ± 0.70 (2.20)	650 ± 100 (673)	-60 ± 40 (-79)
Cl	5→4	8.0 ± 2.2 (6.77)	-	-
K	5→4	26.8 ± 7.0 (24.3)	-	-
Sn	8→7	3.1 ± 1.8 (41.53)	-	-
I	8→7	9.9 ± 7.7 (22.6)	-	-
Pr	8→7	24.7 ± 56.9 (118)	-	-

a) Fitted only to the data of $^{16}\text{O}/^{18}\text{O}$.

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Figure captions

- Fig. 1 : $\bar{p}$ - $^{18}\text{O}/^{16}\text{O}$ X-ray spectrum.
- Fig. 2 : Difference spectrum, $\bar{p}$ - ^{18}O spectrum subtracted from $\bar{p}$ - ^{16}O channel by channel.
- Fig. 3 : Nucleon distributions for ^{16}O and ^{18}O and their ratios.
- Fig. 4 : χ^2 -plot of $\text{Re } A_S^{\text{eff}}$, $\text{Im } A_S^{\text{eff}}$; the minimum is at $\chi^2 = 0.75$, the circles correspond to $\chi^2 + 1$, $\chi^2 + 2$, and $\chi^2 + 3$.

Fig. 1

Difference Spectrum
Detector Princeton

56035

Fig. 2

Fig. 3

Fig. 4