STRONG INTERACTION EFFECTS IN ANTIPROTONIC ${}^6\text{Li}/{}^7\text{Li}$ ATOMS

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ABSTRACT

The effects of strong interaction on the $3 \rightarrow 2$ X-ray transition in antiprotonic ${}^6\text{Li}/{}^7\text{Li}$ atoms have been measured at the low energy $\bar{p}$ -beam at CERN. For the shifts and widths of the levels the values $\epsilon_{2p} = (-230 \pm 72)$ eV, $\Gamma_{2p} = (443 \pm 210)$ eV, and $\Gamma_{3d} = (0.130 \pm 0.045)$ eV for ${}^6\text{Li}$, and $\epsilon_{2p} = (-336 \pm 60)$ eV, $\Gamma_{2p} = (456 \pm 190)$ eV, and $\Gamma_{3d} = (0.210 \pm 0.062)$ eV for ${}^7\text{Li}$ were found. The data are compared with optical model predictions.

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1. INTRODUCTION

The strong interaction between the antiproton and the nucleus manifests itself in broadenings and shifts of the energy levels of antiprotonic atoms, as compared to a purely electromagnetic system. With present techniques only the strong interaction effects in the last observable X-ray transitions of antiprotonic atoms are detectable. While the determination of the energy and line shape results in the strong interaction shift ϵ_{low} and the Lorentzian width Γ_{low} of the lowest observable energy level, the widths of the upper level Γ_{up} can be determined from the intensity of the last transition as compared with the intensities of transitions feeding the upper level [1]. The strong interaction effects depend on the elementary $\bar{p}$ -nucleon interaction near threshold and on the distribution of nucleons in the outer region of the nucleus. Both aspects are of great interest because of the possible existence of bound $\bar{N}N$ states near threshold and because of the scarce information available about neutron distributions far from the centre of the nucleus. The main obstacle as far as the proper interpretation of the data is concerned is the problem of disentangling both effects. A great help in this respect is the measurement of isotope pairs where the elementary $\bar{p}$ -nucleon interaction can be assumed to be nearly equal, and hence only the different nucleon distributions in the nucleus should be responsible for isotope shifts in the measured quantities. Similar experiments on pionic atoms [2] exhibiting very clear isotope effects were the main motivation for the measurements discussed here.

Because of the low intensity of previous $\bar{p}$ -beams, only data on strong interaction effects in antiprotonic atoms are available [3], where the yield of the last observable transition is not too small. As in these cases the overlap between antiproton and nucleus is rather small, the strong-interaction effects ϵ_{low} and Γ_{low} are small and difficult to establish. This is different in Li, where the $n = 3 \rightarrow n = 2$ transition has a small yield and should correspondingly show large effects in ϵ and Γ . The measurement of these effects in ${}^6\text{Li}$ and ${}^7\text{Li}$ was the aim of the experiment reported here. Great care was taken to handle both isotopes in a completely similar manner so that the isotopic differences became clearly visible.

Two previous attempts to measure the $3 \rightarrow 2$ transition were too marginal in statistics to yield significant, clear and unambiguous effects. In the first measurement only an upper limit for the yield of the $3 \rightarrow 2$ line in ${}^6\text{Li}$ was given [4], and in the second one the significances of the lines in the ${}^6\text{Li}/{}^7\text{Li}$ isotopes were only 1.6 and 2.6 standard deviations, respectively [5].

2. EXPERIMENTAL SET-UP AND DATA TAKING

The experimental set-up is shown in fig. 1. It is positioned at the focal point of the electrostatically-separated low-momentum (600 MeV/c) $\bar{p}$ -beam k_{23} at CERN. In the target (of about 1 g/cm^2 thickness in beam direction) 200 $\bar{p}$'s were stopped per machine burst. In spite of the electrostatic separation about 10^5 pions/burst also traversed the target. They were electronically vetoed using a 8 m long time-of-flight (TOF) path (T_0, T_1), a Čerenkov counter ($\check{C}$) and pulse-height discrimination in the scintillation counters T_3 and T_4 .

For the runs on ${}^6\text{Li}/{}^7\text{Li}$ two metallic targets of dimensions $100 \times 100 \times 11 \text{ mm}^3$ were used. For the first part of the run (A) they were covered by $50 \text{ }\mu\text{m}$ polyethylene foils, for the second part (B) by $100 \text{ }\mu\text{m}$ polyethylene plus $10 \text{ }\mu\text{m}$ mylar plus an outer bag filled with argon in order to prevent the formation of Li_3N on the surface of the metallic targets. Both targets were oriented at 45° with respect to the beam direction in order to optimize the count rate and the absorption losses of low-energy X-rays simultaneously. They were mounted one above the other and exposed to the beam alternately using a pneumatic system, so that both isotopes were measured under completely equivalent conditions. The ${}^6\text{Li}/{}^7\text{Li}$ isotopes had an isotopic purity of 91.1 and 92.1%, respectively. In addition, for a high statistics measurement on ${}^7\text{Li}$ (C), a powdered ${}^7\text{LiH}$ target (92.6% isotopic purity) with the dimensions $150 \times 100 \times 34 \text{ mm}^3$, wrapped in $50 \text{ }\mu\text{m}$ polyethylene and $10 \text{ }\mu\text{m}$ mylar foils, was used.

The detection of the relevant $\bar{p}$ X-rays in the energy range from 3 to 60 keV was done mainly by four Si(Li) detectors^{*)}. Two of the diodes were housed in one cryostat so that in total two twin detectors were available. Each single diode

^{*)} From Kevex Corporation.

had an effective area of 80 mm^2 , a thickness of 3 mm, and an off-beam energy resolution of 260 eV at 6.4 keV. The window was of $12 \text{ } \mu\text{m}$ Be, which allowed the detection of X-rays as low as 3 keV. The amplification of the four spectrometer systems was adjusted in such a way that the signals of the diodes could be added hardware-wise without loss of energy resolution. The system turned out to be very stable over the whole running period (3 months) so that only minor corrections had to be applied when the gains of the diodes were checked once per day with an ^{241}Am source. In addition to these four diodes, a fifth diode [an intrinsic Ge-detector^{*)}] was used in order to detect background lines of higher energies. Its energy resolution and spectra were very similar to those of the four Si(Li) diodes, but were not explicitly used for the data analysis discussed later. The detector signals were analyzed by spectroscopy analog-to-digital converters (ADCs) after having been amplified. The data processing, the monitoring of the experiment, and the writing of the data on magnetic tape were performed with a PDP 11/20 on-line computer.

The data taking on the $^6\text{Li}/^7\text{Li}$ isotopes was performed in the above-mentioned two long runs A and B, where 7.6×10^7 and 6.1×10^7 $\bar{\text{p}}$'s were stopped in each target. For the high-statistics measurement on ^7LiH 2.4×10^8 $\bar{\text{p}}$'s were stopped. The energy resolution under beam conditions worsened by 30 eV as compared to measurements with radioactive sources. Regular runs with beam and ^{241}Am sources simultaneously showed that even under beam conditions the efficiencies of the systems did not change.

3. ANALYSIS OF SPECTRA

The sum spectra for ^6Li and ^7Li as obtained from the four Si-diodes during the runs A and B are displayed in figs. 2a and 2b. The N and M series of antiprotonic Li are clearly visible in both cases, the attenuated $3 \rightarrow 2$ transition at an energy around 27 keV has however a very small yield. The peak/background ratio appears to be very good for the lines of high yields such as the $5 \rightarrow 4$ and $4 \rightarrow 3$ antiprotonic Li transitions. In addition to the lines from antiprotonic Li atoms antiprotonic lines from materials in the environment of the target, such as carbon, nitrogen, oxygen, aluminium, and argon, appear as background in the spectra. Even a pionic

*) From Princeton-Gamma-Tech.

transition in aluminium is seen originating from annihilation pions stopping in the cap of the X-ray detectors and forming pionic atoms. The spectra around the interesting energy of 27 keV are shown separately in fig. 3. The Li $3 \rightarrow 2$ transition is partially overlapping two disturbing structures originating from high-yield background lines of $\bar{p}$ -N and $\bar{p}$ -Ar. This fact initiated a very careful investigation of all possible background lines. For this reason short runs on pionic ${}^6\text{Li}/{}^7\text{Li}$ and antiprotonic ${}^7\text{Li}_3\text{N}$ were performed. The analysis [6] of all available data led to an identification of all background lines (see figs. 2 and 3) and even the geometrical origin of the lines could be determined: the oxygen, carbon and argon lines were produced mainly by antiprotons stopping in the telescope counter T_4 and in the argon bag around the target. The aluminium lines originated from antiprotonic and pionic atoms being formed in the cap of the Si(Li) detectors. The nitrogen background was partly due to $\bar{p}$ -stops in the air around the target, partly to a thin Li_3N cover of the surface of the metallic Li targets. A great help in the disentangling of background and Li lines was the ${}^6\text{Li} - {}^7\text{Li}$ difference spectrum, as shown in fig. 2c. The single spectra were recorded under completely identical conditions (regular exchange of geometrically identical Li targets) so that all background lines disappear in the difference spectrum and only the Li lines -- different in energies because of the reduced mass effect and different strong interaction -- remain.

The energies and the line shapes of all background lines could be fixed unambiguously and were used as input for the analysis of the antiprotonic ${}^6\text{Li}/{}^7\text{Li}$ spectra. Particularly the $5 \rightarrow 4$ $\bar{p}$ -N and $9 \rightarrow 8$ $\bar{p}$ -Ar transitions lying near the antiprotonic Li $3 \rightarrow 2$ transition were treated in this manner and were accounted for in the fit of the line pattern around 27 keV as shown in fig. 3. Additional support for the correct identification of the pattern comes from the high-statistics measurements on antiprotonic ${}^7\text{LiH}$, where the $3 \rightarrow 2$ transition in ${}^7\text{Li}$ stands out quite clearly above the background (fig. 4).

For the determination of $\Gamma_{\text{up}} = \Gamma_{3d}$ the intensities of the lines feeding the $n = 3$, $l = 2$ level are needed. The width of the upper level is then given by [1]

$$\Gamma_{up} = \Gamma_{3 \rightarrow 2}^x \left[P_{3d} / I_{3d \rightarrow 2p} - 1 \right], \quad (1)$$

where $\Gamma_{3 \rightarrow 2}^x$ is the radiative width and P_{3d} the population of the 3d level, which can be expressed as the sum of all transitions feeding the level:

$$P_{3d} = \sum_{n=4}^{\infty} [I_{nf \rightarrow 3d} + I_{np \rightarrow 3d}]. \quad (2)$$

The advantage of this method is that only intensity ratios occur and hence no absolute normalization is necessary. The intensities $I_{nf \rightarrow 3d}$ and $I_{np \rightarrow 3d}$ occurring in eq. (2) refer not only to X-ray intensities but also contain Auger transitions, which amount in the most extreme case ($4f \rightarrow 3d$) to about 10% and are easily calculable. In addition, small corrections for parallel transitions which coincide in energy had to be applied to the measured X-ray intensities. Their intensity was taken from a cascade calculation, the initial parameters of which were adapted to the measured intensities of all N- and M-series lines and fitted very well. Finally, all measured X-ray intensities were corrected for the efficiencies of the Si detectors which were carefully measured in- and off-beam and for absorption in the target.

4. RESULTS AND COMPARISON WITH THEORY

The results for the strong interaction effects in the $3 \rightarrow 2$ transition obtained as the weighted average over the runs A-C are given in table 1. Within the errors the results of the single runs are consistent with each other. The energy shift ϵ is determined as the difference between the measured $3d \rightarrow 2p$ energies and the electromagnetic values including all corrections. The largest correction to the point nucleus value comes from the vacuum polarization term (133 eV in ${}^6\text{Li}$, 138 eV in ${}^7\text{Li}$), while the other corrections such as the finite-size effect and the anomalous magnetic moment of $\bar{p}$ are less than 10 eV. The final electromagnetic values for the $3 \rightarrow 2$ transition energies (averaged over fine-structure components) are for ${}^6\text{Li}$ 26.882 keV, and for ${}^7\text{Li}$ 27.446 keV. From the Lorentzian width of the $3d \rightarrow 2p$ transition Γ_{low} was deduced and Γ_{up} was determined using the expres-

sions (1) and (2). The relative yield of the $3d \rightarrow 2p$ transition is defined as $I_{3d \rightarrow 2p}/P_{3d}$. The absolute yields per $\bar{p}$ -stop are affected by large systematic errors due to the badly known normalization factors and should be considered as estimates only. The errors in ε_{2p} and Γ_{3d} are small enough to exhibit a clear isotopic effect. Because of the limited statistics, the determination of the line shape is difficult, which is reflected in the large errors for Γ_{2p} .

In the absence of a microscopic description of the interaction of antiprotons with light nuclei the data on the strong interaction effects were compared with the results of a simple optical potential calculation. The $\bar{p}$ -nucleus strong interaction is described by

$$V_{SI} = -4\pi \frac{\hbar^2}{\mu} \frac{m}{\mu^*} a \rho(r) . \quad (3)$$

Here $\rho(r) = \rho_p(r) + \rho_n(r)$ is the sum of the proton and neutron distributions in the nucleus, μ is the reduced $\bar{p}$ -nucleus mass, μ^* the reduced $\bar{p}$ -N mass, and m the antiproton mass. The quantity $a = \frac{1}{2} (a_{pp}^{eff} + a_{pn}^{eff})$ is the sum of the complex $\bar{p}p$ and $\bar{p}n$ scattering lengths for protons and neutrons bound in a nucleus, which differ from the "free" scattering lengths and must hence be considered as parameters to be fitted to the experimental data.

Adding this complex potential to the finite-size Coulomb potential and inserting it into the Klein-Gordon equation yields the energies and widths of the antiprotonic levels (spin effects neglected) which can be compared with the measured values. The analysis of previous data resulted in effective scattering lengths a , with real parts between 1 and 2 fm and imaginary parts between 2 and 3 fm.

The data on ${}^6\text{Li}/{}^7\text{Li}$ as presented here cannot be reproduced by the parameters of these optical potentials. Whereas the imaginary part is similar, considerably smaller real parts are required and they are different for the two isotopes: ${}^6\text{Li}$: $(0.2 \pm 0.03) + i(1.4 \pm 0.5)$; ${}^7\text{Li}$: $(0.4 \pm 1.6) + i(3.0 \pm 2.0)$. The small error in ${}^6\text{Li}$ is connected with the fact that all three measured quantities converge to the same value for a , while in ${}^7\text{Li}$ that is not the case. In this fit for $\rho(r)$ a harmonic oscillator distribution with the r.m.s. radii 2.56 fm for ${}^6\text{Li}$ [8] and

2.39 fm for ${}^7\text{Li}$ [9] was used. In order to explain the small real parts and the discrepancy between the optimal parameter sets for the two isotopes we tried to vary the shape of the proton and/or neutron distributions within reasonable limits. None of these variations was able to explain the discrepancies [6]. This shows again that the simple optical potential (3) is not sufficient to describe all the data on heavier nuclei consistently with a unique set of parameters. The present measurement seems to establish the fact that an optical potential of the type (3) is not adequate to reproduce even small sets of data of limited accuracy.

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Table 1

Strong interaction effects in antiprotonic ${}^6\text{Li}$ and ${}^7\text{Li}$

Measured quantity	${}^6\text{Li}$	${}^7\text{Li}$
E_{exp} [keV]	26.652 ± 0.072	27.110 ± 0.060
ϵ_{2p} [eV]	-230 ± 72	-336 ± 60
Γ_{2p} [eV]	443 ± 210	456 ± 190
Γ_{3d} [eV]	0.13 ± 0.045	0.21 ± 0.062
Y_{rel}	0.048 ± 0.017	0.030 ± 0.009
Y_{abs} per $\bar{p}$ stop	~ 0.011	~ 0.007

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Figure captions

- Fig. 1 : Experimental set-up. $T_0, \dots, T_5$ = scintillation counters.
 $\check{C}$ = Čerenkov counter to veto pions in the beam, M_1, M_2, M_3 = moderators
(Cu, C) of fixed and variable thicknesses, $D_1, \dots, D_4$ = Si(Li) detectors.
- Fig. 2 : a) X-ray spectrum of antiprotonic ${}^7\text{Li}$, sum of four Si(Li) detectors,
Run periods A + B, 1.37×10^8 $\bar{p}$ -stops.
b) X-ray spectrum of antiprotonic ${}^6\text{Li}$, sum of four Si(Li) detectors,
Run periods A + B, 1.37×10^8 $\bar{p}$ -stops.
c) Difference spectrum: b-a. The isotopic mass effect on the ${}^6\text{Li}/{}^7\text{Li}$
lines is clearly visible. All background lines disappear because of
identical set-ups (alternating exposure) of both targets.
- Fig. 3 : Spectra (a) and (b) of Fig. 2 in the energy region between 21 and 32 keV.
The fit is the result of a careful analysis of all background lines as
explained in the text.
- Fig. 4 : X-ray spectrum of the transitions in antiprotonic ${}^7\text{LiH}$. 2.36×10^8
 $\bar{p}$ -stops.

Fig. 1

Fig. 2

Fig. 3

Fig. 4