PHYSICAL REVIEW C

NUCLEAR PHYSICS

THIRD SERIES, VOLUME 58, NUMBER 4 **OCTOBER 1998**

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New precision measurement of the pionic deuterium *s*-wave strong interaction parameters

P. Hauser, K. Kirch, and L. M. Simons
Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

G. Borchert, D. Gotta, and Th. Siems
Institut für Kernphysik, Forschungszentrum Jülich D-52425 Jülich, Germany

P. El-Khoury and P. Indelicato
Laboratoire Kastler-Brossel, Université Pierre et Marie Curie F-75252 Paris Cedex 05, France

M. Augsburger,* D. Chatellard,* and J.-P. Egger
Institut de Physique de l'Université, CH-2000 Neuchâtel, Switzerland

D. F. Anagnostopoulos
Department of Physics, University of Ioannina, GR-45110 Ioannina, Greece
(Received 13 July 1998)

The x rays of the pionic deuterium 2p-1s transition were measured with a high resolution crystal spectrometer including a cyclotron trap (a magnetic device to increase the pion stopping density) and a CCD (charge-coupled device) detector system. The 1s strong interaction shift ϵ_{1s} and total width Γ_{1s} were determined from the position and line shape of the x-ray peak. The (complex) pionic deuterium s-wave scattering length $a_{\pi^- d}$ was deduced. Its real part was related to the pion-nucleon scattering lengths, and the isoscalar coupling constant for π^- absorption was deduced from the imaginary part. [S0556-2813(98)50310-X]

PACS number(s): 25.80.Hp, 36.10.Gv

A program to measure the strong interaction parameters (shift and width) of both pionic hydrogen and deuterium was carried out over the last few years at the Paul Scherrer Institute (PSI) at Villigen. In the case of pionic deuterium the 3p-1s transition was measured at a gas target pressure equivalent to 15 bar (1 bar at 22 K). The final results were published in 1997 [1]. The strong interaction shift (ϵ_{1s}) was over an order of magnitude more precise and approximately a factor of two smaller than the previous experimental results. The strong interaction width (Γ_{1s}) had never before been measured before. The results were

$$\epsilon_{1s} = 2.43 \pm 0.10 \text{ eV},$$

$$\Gamma_{1s} = 1.06 \pm 0.17 \text{ eV}.$$

Γ_{1s} here is the total width including both the strong interaction width and Doppler broadening due to Coulomb deexcitation. The pionic deuterium s-wave scattering length $a_{\pi^- d}$ was deduced from these values. Experimental details and more can be found in [1].

In the pionic hydrogen case the first experimental series has been finished. Experimental details and the newest results may be found in [2,3]. An extremely precise value for ϵ_{1s} was obtained whereas the precision of Γ_{1s} was still limited by statistics and the signal/background ratio of 7. In addition the Doppler contribution is not yet well known. In parallel, many pion-nucleon scattering and charge exchange experiments at low pion laboratory energies were carried out at the different meson factories in order to also determine the

*Present address: Institut de Physique, Université de Fribourg, Pérolles, CH-1700 Fribourg, Switzerland.

TABLE I. Energies and Bragg angles of the measured transitions.

	Transition	Energy [eV]	Ref.	Bragg angle[a]
Energy calibration	Cl Kα_1	2622.44 ± 0.04	b	48°56′12.3″
	Cl Kα_2	2620.85 ± 0.04	b	
Response function	π^- ^{20}Ne (7i-6h)	2718.751	c	46°39′30.2″
Parallel transition	π^- ^{20}Ne (7h-6g)	2719.358	c	
Isotope	π^- ^{22}Ne (7i-6h)	2720.592	c	
QED energy[d]	π^- D (2p-1s)	2597.527	c	49°33′42.6″

[a]Includes refraction index correction.
[b]Reference [20].
[c]Reference [21].
[d]Radius of the deuteron $\langle r^2\rangle^{1/2}=2.138$ fm.

pion-nucleon (πN) *s*-wave scattering lengths. A list and discussion of this data base can be found in [4]. However the most precise *s*-wave πN scattering length combination was obtained directly from the above-mentioned pionic hydrogen ϵ_{1s} value. Therefore a new Γ_{1s} measurement in pionic hydrogen was felt to be the key to the best possible determination of both πN *s*-wave scattering lengths. In addition, a precision test of isospin symmetry can be carried out, provided that on the pionic deuterium side the most precise experiment is linked to pionic hydrogen by full theoretical treatment including all corrections. However the experimental equipment available was judged insufficient for this endeavor.

It was decided to keep the basic layout (cyclotron trap for maximizing the pion stopping density, high resolution crystal spectrometer and CCD x-ray detectors) but to redesign and rebuild the different components. A new cyclotron trap [5] was built with a pion stopping density increase of an order of magnitude. This, together with a primary proton current increase from 600 μA to 1.5 mA, solved the count-rate problem. A new crystal spectrometer [6] working in vacuum and a dedicated concrete shielding allowed for a signal/background ratio of 30, also almost an order of magnitude increase. New CCDs were also planned [7], but for the moment the existing CCDs [8] are still in use.

As a first experiment with this new setup, the pionic deuterium strong interaction parameters ϵ_{1s} and Γ_{1s} were remeasured. However this time the 2p-1s transition was used. The new results are compatible with [1] but significantly more precise. This paper presents a brief description of the experimental technique, the new results, a discussion, and conclusions.

The experiment was carried out on the πE5 beam line with a proton current of 1.5 mA. Approximately 2.5×10^8 π^- s^{-1} of 110 MeV/c momentum were injected into the cyclotron trap. A gaseous target at room temperature with a pressure of 2.5 bar was used. On their orbit around the target the pions were decelerated by degraders and reached the target center where they were stopped in the gas. The pion stop rate was about 8×10^6 s^{-1}.

A spherically bent Si(111) crystal of 95 mm diameter was used for x-ray reflection. The diameter of the Rowland circle was 2984.5 mm. The Bragg angle difference between the pionic deuterium line and the electronic chlorine Kα line was measured in order to obtain the absolute energy calibration. Since this difference is very small (see Table I), the chlorine x rays were measured at the pionic deuterium focal position, see Fig. 1. The instrumental line profile was obtained from the pionic neon (7-6) transition which has a negligible natural width. The resolution of the spectrometer was 0.48 ± 0.03 eV FWHM. Further details can be found in Table I.

The reflected x rays were recorded with charge-coupled devices (CCDs). Two deep depleted CCDs of the type CCD-05-20 [9] were used. CCDs are ideal x-ray detectors in this energy range. In addition to the excellent intrinsic position resolution (22.5 μm), a practically complete background suppression was achieved by carefully shielding the detectors and using their pixel structure and energy resolution as further background cuts. The final signal/background ratio was 30 (see Figs. 2 and 3). A detailed description of how CCDs work, including CCD pictures, can be found in [2].

Figure 3 presents the measured 2p-1s position spectrum. The difference between the measured energy and the calculated electromagnetic energy including radiative corrections and finite size effects is the strong interaction shift ϵ_{1s}:

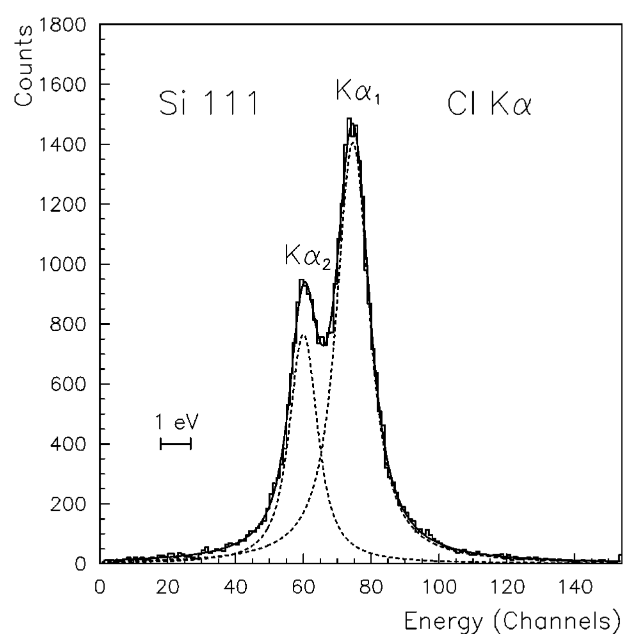

FIG. 1. Chlorine x-ray position spectrum used for energy calibration. The Kα lines are separated by 1.59 eV and have a natural width of about 0.8 eV. One channel corresponds to 5 pixels or 112.5 μm.

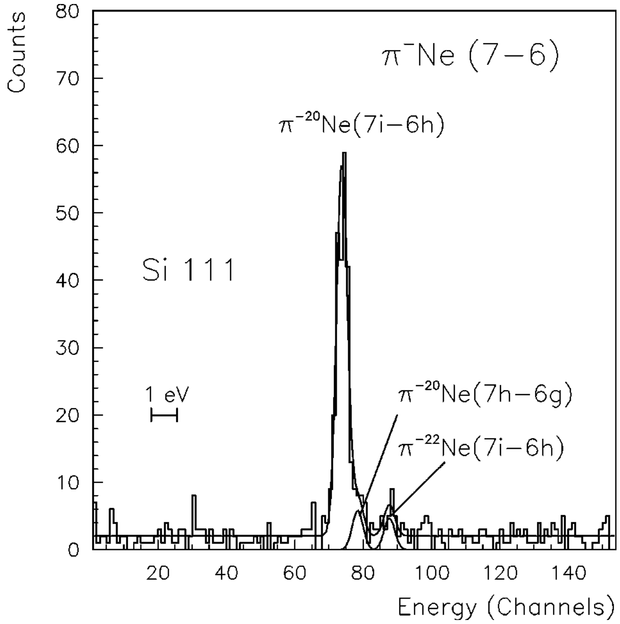

FIG. 2. Pionic neon (7-6) x-ray position spectrum used for the determination of the experimental line profile. The main line ^{20}Ne (7i-6h), and the ^{20}Ne (7h-6g) and ^{22}Ne (7i-6h) transitions are visible.

$$\epsilon_{1s} = 2.469 \pm 0.055 \ \text{eV (repulsive)}.$$

See Table II for a detailed account of the different errors. This value is statistically compatible with the result of Ref. [1]. The two measurements can therefore be averaged:

$$\epsilon_{1s} = 2.460 \pm 0.048 \ \text{eV}.$$

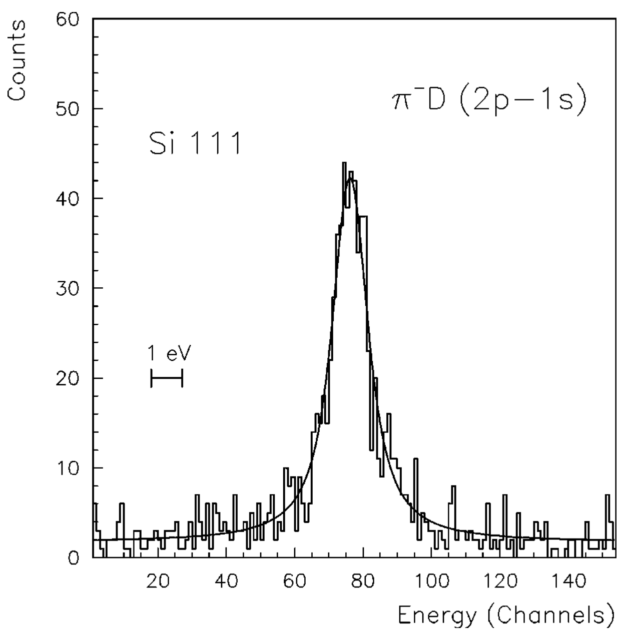

FIG. 3. Pionic deuterium x-ray 2p-1s position spectrum. One channel corresponds to 5 pixels or 112.5 μm. The comparison of the peak position with the chlorine Kα_1 peak position of Fig. 1, yields the transition energy. The total width is obtained after deconvolution of this spectrum with the main peak of Fig. 2.

Figure 2 shows the instrumental line profile obtained from the pionic neon (7-6) transition which has a negligible natural width. After deconvolution, the remaining Voigt profile yields the total width

$$\Gamma_{1s} = 1.194 \pm 0.105 \ \text{eV}.$$

Table II shows the errors obtained. The value of Γ_{1s} includes an unknown contribution from Doppler broadening caused by Coulomb deexcitation during the cascade [3,10]. This contribution changes with pressure and depends in its characteristics on the measured x-ray transition. It is therefore not possible to average the results of the present measurement ($P=2.5$ bar, 2p-1s transition) with the previous one ($P=15$ bar, 3p-1s transition). Nevertheless both values agree within the quoted errors.

The Coulomb deexcitation is presently subject of different investigations in the πp system [11,12] which will lead to a precise determination of the contribution of Doppler broadening to the total width necessary for future progress.

The strong interaction shift ϵ_{1s} and the total width Γ_{1s} may be related to the s-wave scattering length $a_{\pi^- d}$ through the Deser formula [13]:

$$-\epsilon_{1s} + i\frac{\Gamma_{1s}}{2} = \frac{4E_{1s}}{r_B} a_{\pi^- d}. \tag{1}$$

E_{1s} is the electromagnetic binding energy of the π^- in the 1s orbit and r_B the corresponding Bohr radius. With $E_{1s} = 3463$ eV and $r_B = 147.2\ m_\pi^{-1}$ we obtain

$$a_{\pi^- d} = -0.0261(\pm 0.0005) + i0.0063(\pm 0.0007) m_\pi^{-1}. \tag{2}$$

Higher order corrections to Deser's formula are negligible [14]. $a_{\pi^- d}$ is the scattering length defined in the presence of the Coulomb field. Electromagnetic corrections have to be applied in order to obtain the purely hadronic scattering length. For the πd system, these electromagnetic effects have not yet been fully calculated. Estimations [15] show that they are small but exceed the experimental error by a factor 2 to 3. A careful calculation of these effects, as done for example in the pionic hydrogen case [16], is necessary. However here they have been omitted.

A more modern and rigorous approach would be to obtain a relationship between the 1s shift and width and the scattering length in the framework of chiral perturbation theory describing the low-energy properties of quantum chromodynamics (QCD). See [17] and references therein for further details.

Many theoretical investigations have related the real part of the pion deuterium scattering length Re $a_{\pi^- d}$ to the πN scattering length combination $b_0 = 1/3(a_1 + 2a_3)$. A discussion of these calculations can be found in [1]. Re $a_{\pi^- d}$ may be expressed as

$$\text{Re } a_{\pi^- d} = 4\frac{m_p + m_\pi}{m_d + m_\pi} b_0 + C = -0.0261(\pm 0.0005) m_\pi^{-1} + \textit{electromag. corrections}. \tag{3}$$

TABLE II. Errors (in meV) of this experiment. For ϵ_{1s} the errors added up in square give ± 55 meV. The total error for Γ_{1s} is ± 105 meV.

ϵ_{1s}	Statistical	Systematic		Energy	Calibration	Total
π^-D	± 35	width of response function	± 1	Cl Kα	± 40	
Cl Kα	± 6	Cl Kα satellites	± 11			
		fit region	± 6			
		crystal axis display	± 2			
		angular encoder	± 4			
	total ± 35		total ± 13		total ± 40	± 55
Γ_{1s}						
π^-D	± 100	response function	± 13			
π^-Ne	± 11					
	total ± 103		total ± 13			± 105

The mass ratio is simply the πp to πd c.m. transformation. Since b_0 is small (it vanishes in the current algebra limit [18] and the most recent experimental determination [3] is compatible with zero) the correction term C is important.

Thanks to our 2% measurement of Re $a_{\pi^- d}$, two avenues open up:

(1) Since b_0 and the electromagnetic corrections are small, this experiment induces strong constraints on the correction term C. A precise calculation of C is not just important in our case but even more useful for the determination of the kaon-nucleon s-wave scattering lengths since, contrary to pionic hydrogen, these cannot both be deduced independently from the kaonic hydrogen 1s shift and width measurements alone. An experiment to measure the kaonic hydrogen and deuterium 1s parameters is in the start-up phase at DAΦNE (Frascati) [19].

(2) With the precision reached in this experiment, a detailed calculation of the correction term C together with a new experimental determination of b_1 (planned at PSI) will allow for a precision test of isospin conservation.

The imaginary part of the pion-deuterium scattering length can be used to determine model independently g_0, the effective coupling constant for π^- absorption on a nucleon pair with isospin zero. Following the treatment given in [1] we obtain

$$|g_0| = (2.78 \pm 0.12) \quad 10^{-2} \quad m_\pi^{-2}.$$

In conclusion, this new precision measurement of the pionic deuterium 1s shift and total width opens up the possibility of interesting new insights in the low energy pion-nucleon and kaon-nucleon interactions.

We would like to thank B. Leoni and P. Wieder for their competent technical assistance during the experiment. The Bragg crystal was manufactured in collaboration with the Carl Zeiss company, Oberkochen, Germany. We are also happy to acknowledge the ''savoir faire'' of the PSI accelerator staff, delivering a high intensity stable beam. This research was partially supported by the Swiss National Science Foundation. A NATO and a Human Capital and Mobility EC grant are also acknowledged.

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