STUDY OF EXOTIC ATOMS WITH CRYSTAL DIFFRACTION SPECTROMETERS

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Crystal diffraction techniques has been successfully developing at PNPI for many years. Crystal diffraction spectrometers (CDS), which allow one to perform the most accurate measurements of the energy of X- and γ-lines, were widely used to investigate nuclear spectra in (n,γ) reactions, as well as to study isotopic and chemical shifts of the X-lines [1-3].

From the middle of 70s a new direction for the use of the CDS has been developing, which is related to the study of the X-ray spectra of exotic atoms at the accelerators of PNPI [4,5], IHEP [6,7] and PSI [8,9].

Measurement of the π^--meson mass

The first experiment in this direction was devoted to the measurement of the mass of the negative pion [4]. High accuracy in π^--meson mass measurement is of importance both for the improvement of the experimental estimate on the mass of the muon neutrino and for investigation of the pion-nucleus interaction with the help of pionic atoms. The lower limit on the muon neutrino mass is obtained from the energy–momentum conservation in the decay of the π^+ meson at rest:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu .$$

Three measured quantities are involved here: the mass and the momentum of the positive muon and the mass of the π^+ meson, the latter, in accordance with the CPT-theorem, being taken equal to the mass of the π^- meson, which is known with a higher accuracy.

The measurement of the π^--meson mass with a CDS was carried out for the first time in Berkeley (Shafer, 1967). Du Monde version of the spectrometer was used with the target located on the external beam of negative pions. The pion mass was determined from the measured energies of transitions between high Bohr orbits of pionic atoms, for which the influence of the strong pion-nucleus interaction is small enough and one may neglect it without considerable error to be introduced. The experiment improved the accuracy of the π^--meson mass determination by a factor of four, the relative accuracy achieved amounted to 96 ppm. For the counting rate in the maximum of the diffraction X-ray line of 3 hour^{-1} data taking was lasted 800 hours, hence the further improvement of the accuracy was hoped to be done only at the meson factories.

A new type of the experiment proposed in 1974 at PNPI was based on the use of the compound target irradiated directly by the proton beam. In 1975 a diffraction spectrometer of the Cauchois type was constructed [4,10] and placed on the proton beam of the PNPI synchrocyclotron. The new scheme of the experiment allowed one to enlarge considerably the number of good events enabling to study exotic atoms on usual accelerators with the intensities of the proton beam $\sim 10^{12}$ s^{-1}. The experimental setup is shown in Fig. 1.

Proton beam of 1 GeV energy irradiated a meson-production target, comprised 25 copper disks of 2 mm thickness and 20 mm diameter, placed in the shadow of the plates of the multislit collimator located inside the shielding wall. An X-ray target made of the species to be investigated was placed in front of the collimator slits close to the meson-production target.

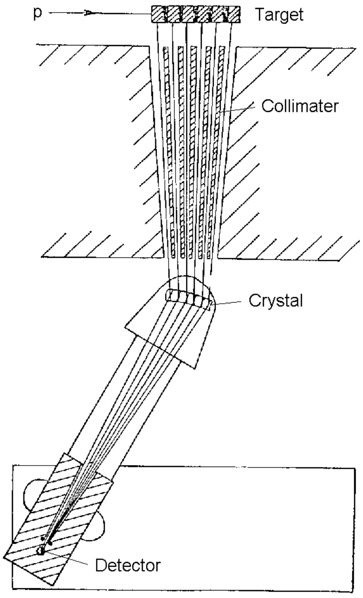

Fig. 1. Scheme of the spectrometer.

In such a geometry the density of the pion stops at the X-ray target is two orders of magnitude higher than in experiments with meson beams. In some of the experiments the X-ray target served simultaneously as a meson-production one.

X-rays to be measured went through the multi-slit collimator and after diffracting on the cylindrically bent crystal were registered by a Ge(Li)-detector. In this experiment a 4.7 mm thick quartz crystal (reflecting plane $13\bar{4}0$) with the bend radius of 5 m and the aperture of 80×90 mm^2 was used. The half-width of the diffraction profile amounted to 20 angular seconds. The calibration was performed with the 59.3 keV K_{α_1}-line of tungsten and with the 67.7 and 101.1 keV γ-lines accompanying the β-decay of ^{182}Ta. The relative accuracy of the spectrometer was $\simeq 5\cdot10^{-6}$ in the energy range from 50 to 100 keV.

In this experiment $4f$–$3d$ transitions in pionic titanium and calcium atoms were measured. Fig. 2 shows diffraction profiles of the transition in the pionic calcium atom for left and right positions of the device. The counting rate in the line maximum amounted to 1200 hour^{-1} for the proton beam intensity of 10^{12} s^{-1}, background counting rate being 1500 hour^{-1}.

The values $87\,649.2\pm1.9$ eV and $72\,347.0\pm1.1$ eV were obtained for the $4f$–$3d$ transitions in pionic titanium and calcium atoms, respectively, that allowed to obtain for the weighted mean of the π^--meson mass

$$m_{\pi^-} = 139\,565.7 \pm 1.7 \text{ keV} \quad (\pm 12 \text{ ppm}).$$

Thus, the proposed scheme of the experiment allowed us to improve the accuracy of the mass measurement by about an order of magnitude at the accelerator with the ~0.2 μA current.

The method described was widely used in the π^--meson mass measurements in the USA (Wu, 1980; relative accuracy 6.4 ppm), as well as at the Swiss meson factory (Leisi, 1986 and Jeckelmann, 1994; relative accuracy 2.6 ppm). In the latter experiment the PNPI–PSI spectrometer described in Ref. [8] was used.

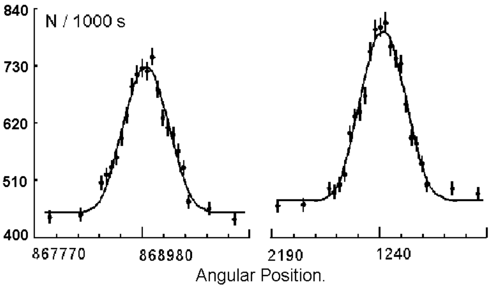

Fig. 2. Left and right diffraction profiles for the $4f$–$3d$ transition in π–Ca atom.

High accuracy obtained in the π^--meson mass determination has stimulated a series of precision measurements of the muon momentum in the pion decay $\pi^+ \rightarrow \mu^+\nu_\mu$ (Frosch, 1994). As a result, the upper limit on the muon neutrino mass was lowered

$$\text{from} \qquad m_{\nu_\mu} \leq 2.7 \text{ MeV} \quad \text{(Shafer, 1967)} \qquad \text{to} \qquad m_{\nu_\mu} \leq 0.16 \text{ MeV} \quad \text{(Frosch, 1994).}$$

Study of the strong pion-nucleus interaction in light pionic atoms

Strong interaction of the π^- meson with a nucleus leads to the shift and broadening of levels in pionic atoms. The experimental values of transition energies and level widths can be compared with the theoretical calculations based on various approaches. In order to perform a detailed check of theoretical models and to determine more precisely their parameters one needs a high experimental accuracy, a high energy resolution as well as a wide range of pionic atoms investigated.

The method developed at PNPI, which allowed to increase the counting rate by more than two orders of magnitude, has opened new opportunities for systematic investigation of the pionic atoms. In 1977 at the PNPI synchrocyclotron the $3d$–$2p$-transitions in pionic ^{23}Na, ^{24,25,26}Mg, ^{27}Al, ^{28}Si, ^{31}P, ^{32}S atoms [5,10–12] were studied. The accuracy of measurement of the shifts and widths of the $2p$ levels was considerably increased having allowed to measure directly for the first time the natural widths of the $3d$–$2p$ transitions. The results are given in Table 1 ($E_{3d\text{-}2p}$ – transition energy, ϵ_{2p}, Γ_{2p} – $2p$-level shift and width, respectively, caused by the strong pion-nucleus interaction).

Table 1

	$E_{3d\text{-}2p}$, eV	ϵ_{2p}, eV	Γ_{2p}, eV
^{23}Na	62447±2.0	86±2.0	60±14
^{24}Mg	74405±1.2	133±1.2	87±6.3
^{25}Mg	74427±2.5	137±2.5	76±19
^{26}Mg	74437±2.0	130±2.0	76±7.1
^{27}Al	87480±3.4	210±3.4	102±19
^{28}Si	101571±3.4	288±3.4	181±15.3
^{31}P	116797±13	410±13	246± 60
^{32}S	133126±21	619±21	635±145

The experiment was continued at the Swiss meson factory (PSI) where in the early 80s a crystal diffraction spectrometer of the Du-Monde type was constructed according to the joint PNPI–PSI project [8,13]. The scheme of the setup is shown in Fig. 3. The meson-production target consisted of two beryllium plates. The ring made of the substance to be studied, placed between the beryllium plates, was used as an X-ray target in which π mesons stopped and formed pionic atoms. Mesonic X-rays diffracted on the bent cylindrical quartz crystal of 5 m radius were registered by a scintillation detector. The Du-Monde scheme allowed to work with rather small X-ray targets (up to 5 g weight) that made it possible to use samples of various isotopic content.

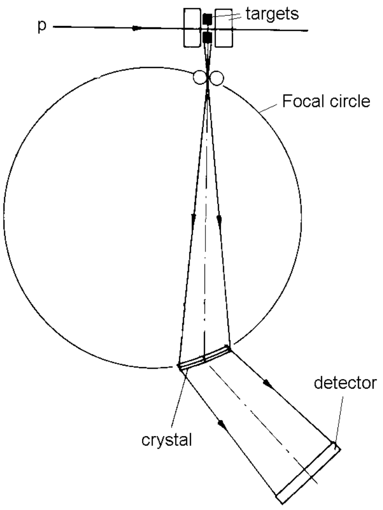

Fig. 3. Scheme of the setup at PSI.

The laser interferometer which was used for measuring diffraction angles provided the accuracy of ± 0.02 angular seconds in the angular range between $+20°$ and $-20°$. The counting rate in the line maximum ranged from 0.1 s^{-1} to 5 s^{-1} (depending on the isotopic content) for the proton current of 20μA, signal-to-background ratio being ~ 1 (Fig. 4).

The spectrometer was used at the PSI to study the $3d$–$2p$ transitions in pionic atoms ^{12}C, ^{16,18}O, ^{24,26}Mg and ^{28,30}Si. These atoms are of interest from various points of view. The properties of the ground states of light nuclei are well known that makes the determination of the pion-nucleus interaction parameters easier. Charge distributions are well investigated for this range of nuclei allowing to determine reliably the proton distribution; the neutron distribution can be considered to be similar to the proton one, at least for $N = Z$. As for the pionic atoms in question, the radius of the $2p$ orbit is much larger than that of the nucleus, so the shift of $2p$ level is determined mainly by the p-wave (non-local) part of the pion-nucleus interaction. At the same time, one can use the known data on the shifts and widths of the s-state to obtain the s-wave part of the interaction.

In Table 2 the results of the measurements at PSI [9] are given (notations are the same as in Table 1). One can see that the accuracy of the energy measurement of pionic atom transitions amounts to 4–18 ppm, for width measurement it is 2–14%, which is 3–5 times higher than the accuracy achieved in Ref. [5] (Table 1).

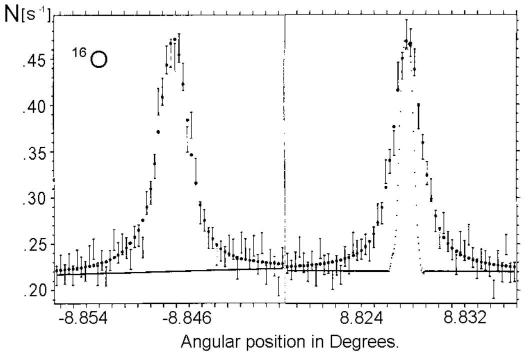

Fig. 4. Diffraction profile for $3d$–$2p$ transition in π–^{16}O atom for right and left spectrometer positions. Instrument line is shown inside the experimental profile (on the right). The broadening of the experimental line is caused by the inelastic part of the pion-nucleus interaction.

Table 2

	$E_{3d\text{-}2p}$, eV	ϵ_{2p}, eV	Γ_{2p}, eV
^{12}C	18401.88±0.10	3.16±0.16	1.36±0.22
^{16}O	32858.28±0.16	15.05±0.26	6.76±0.36
^{18}O	32892.79±0.17	15.50±0.27	7.47±0.44
^{24}Mg	74403.18±0.41	128.45±0.62	72.5±1.8
^{26}Mg	74436.45±0.43	126.08±0.63	81.1±1.9
^{28}Si	101573.7±1.2	284.7±1.4	196.2±5.3
^{30}Si	101605.2±1.9	281.6±2.1	195.5±7.9

For all pionic atoms investigated the shifts and widths of the $2p$ levels were calculated both in the frame of the optical model and in the approach taking into account the nuclear relativism [14,15]. The quality of description is about the same in both approaches. The comparison of the experimental and the theoretical values for the shifts and widths is given in Fig. 5 (for the approach taking into account nuclear relativism).

K^--meson mass measurement

The proposal [16] for studying kaonic and hyperonic atoms at the IHEP proton synchrotron was a natural development of this investigation. The proposal was approved in 1979. As a result of the joint efforts of the PNPI and IHEP, the CDS "Quartz" was built for measurements on the external 70 GeV proton beam [17,18]. At the first stage, in 1980–83 the spectrometer described in Ref. [10] was used. The intensities of a number of pionic lines have been measured, some estimates have been obtained for intensities of kaonic and hyperonic lines, the background radiation spectra for various targets in the X-ray region have been studied [19].

Based on these data, a new spectrometer of the same type was constructed in 1987–89

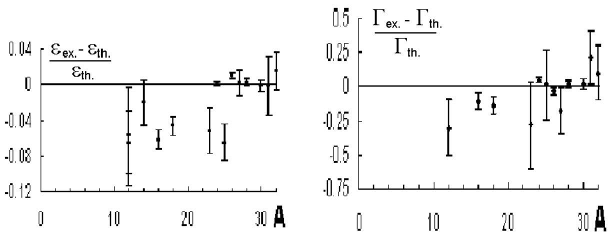

Fig. 5. Relative difference between experimental (ex) and theoretical (th) values of the energy shifts (ϵ) and the widths (Γ) of $2p$ levels caused by strong interaction, for pionic atoms, as a function of the mass number.

at PNPI (Fig. 1); it had a working range extended to the low-energy region of 20 keV, higher luminosity and better shielding against the background of secondaries. A new detector and the angle measuring device based on the interferometer of an original design were used. At the same time, a new booster was put into operation at the IHEP, it increased considerably the beam intensity. All this has given an opportunity to perform the first successful investigation of the X-ray radiation from the kaonic and hyperonic atoms with the crystal diffraction method [6,7,20–22].

The first important result obtained with the new device was the K^--meson mass [6] which changed considerably the world average of that value [23]. In this experiment the $4f$–$3d$ transition energy of 22.1 keV of the K–C atom was measured. $K_{\alpha1}$ and $K_{\alpha2}$ lines of silver with the energies of 22.16 and 21.99 keV were used for calibration. A check was made by measuring the non-circular $4d$–$2p$ transition in the π–C atom with the energy of 24.8 keV (a circular $3d$–$2p$ transition is 5 times more intensive but its energy 18.4 keV is beyond the range of the spectrometer).

A thick compound meson-production target comprised the layers of the super-dense graphite was placed against the collimator slits, and copper layers wrapped in the molybdenum foil were placed against the collimator walls. Copper plates were used to increase the number of the stops in graphite, while molybdenum ones – to suppress the bremsstrahlung background of electrons. Intensity, location and transverse dimensions of the beam on the target were measured with the secondary emission chambers and were taken into account in data processing. A helium filled $\sim$ 10 m length tube was used to avoid the radiation loss in air.

A natural quartz plate with reflecting planes (130) orthogonal to large sides was used. The 1.1 mm thick plate with a bend radius of 5 m had the elastic quasi-mosaic of 12 angular seconds. The bending was performed by fixing the plate between the steel cylindrical mirrors with an opening 8×8 cm^2 for radiation. The range of the diffraction angles amounted to about $\pm 15^\circ$, the angular position was determined with the optical interferometer with the accuracy of 0.04 angular seconds.

Diffracted X-rays were detected by a Ge(Li)-detector of $4 \times 5 \times 160$ mm^3 volume, which had an energy resolution 1.8 keV. For the inlet slit of 0.35 mm width and 160 mm height the angular resolution of the CDS was equal to 14 angular seconds, which corresponded to the energy resolution of 6.3 eV for X-rays with the energy of 22.1 keV. Such a resolution excluded the contribution of the non-circular $4d$–$3p$ transition to the experimental line eliminating thus a systematic error connected with this transition. The efficiency of the device for the radiation in question amounted to $2 \cdot 10^{-9}$.

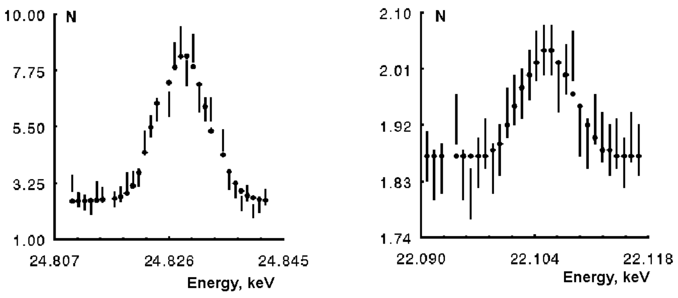

Fig. 6. Diffraction profiles for the $4d$–$2p$ transition in the π–C atom and $4f$–$3d$ transition in the K–C atom. N – the number of counts per 10^{12} protons. Points show the result of the fit.

In Fig. 6 the measured diffraction profiles for the $4d$–$2p$ transition in the π–C atom and $4f$–$3d$ transition in the K–C atom are shown. For average intensity of the 70 GeV proton beam of $4 \cdot 10^{11}$ s^{-1} the counting rate in the maximum of the K-line amounted to 300 hour^{-1}, background level being 3000 hour^{-1}. For non-circular $4d$–$2p$ π-atomic line the counting rate was equal to 9800 hour^{-1} with the background about 4000 hour^{-1}. Recalculating this to the counting rate of the circular $3d$–$2p$ transition gives the value of 50 000 hours^{-1} for the same background level. Measured intensities are in agreement with calculated ones. Comparing the data with other experiments one may conclude that the use of the proton beam not only allows to investigate the kaonic atoms but also provides excellent conditions for studying the pionic atoms.

The energies of the kaonic $4f$–$3d$ and pionic $4d$–$2p$ transitions were found to be equal to $22\,105.61 \pm 0.26 \pm 0.14$ eV and $24\,828.36 \pm 0.15 \pm 0.15$ eV, respectively. The first error is statistical, the second is systematic.

The experimentally measured energy of the pionic $4d$–$2p$ transition coincided with the calculated value within the error that confirmed the correctness of the method of measurement and data processing (the error of calculation was equal to 0.37 eV and was defined by the error of the screening correction; the large error excluded the opportunity to use that measurement for obtaining the new π^--mass value).

The K^--meson mass was determined by comparison of the calculated and experimental transition energies. The calculated energy was obtained by numerical integration of the Klein-Gordon equation for finite size nucleus taking into account the Coulomb interaction, vacuum polarization potential up to the third order, and optical potential of the strong interaction. Relativistic reduced mass correction, nuclear polarization, electron screening and atom recoil were also taken into account. The calculation error did not exceed 0.02 eV. After fitting a new value for the K^--meson mass was obtained

$$m_{K^-} = 493.696 \pm 0.007 \ \text{MeV} \quad (\pm 14 \ \text{ppm}),$$

which has higher accuracy than all previous measurements [23].

Σ^--hyperon mass measurement

The next step in the development of experimental studies at the "Quartz" device at the IHEP was the investigation of the Σ-atomic X-rays that lead as a result to a new determination of the Σ^--hyperon mass [7].

One should note that the study of the hyperonic atoms is a rather difficult problem because of the short hyperon lifetime preventing to obtain low-energy hyperon beams of sufficient intensity. Prior to our experiments, the only way to obtain hyperon atoms was based on the nuclear absorption of the K^- mesons stopped in the matter that leads, with the probability of about 10%, to the production of low-energy Σ^- hyperons. The latter have enough time to slow down and be captured to the atomic state before the decay.

It was clear that the same mechanism should provide in our case the intensity of Σ^- atom radiation on a level not less than 10% with respect to that of K-atomic radiation. Besides, a considerable (if not main) contribution should be expected from the production of Σ^- hyperons in the inelastic collisions of 70 GeV protons with target nuclei. Theoretical estimates for such a contribution were rather uncertain, so the final estimate could be obtained only in the experiment.

The $5g$–$4f$ transition in the Σ–C atom with the energy of 23.4 keV was chosen for measurements. The $K_{\alpha1}$ line of silver and $K_{\alpha2}$ line of tin with the energy of 25.0 keV were used as fiducial ones, check measurement was made with the $4d$–$2p$ transition in the π–C atom. Because of the search character of the experiment, the data taking was performed only in one position of the device though this increased the systematic error in the line energy. The target and the device parameters were the same as in the experiment on the K^--meson mass determination.

The result is shown in Fig. 7. The transition energy was found to be equal to $23\,420.47 \pm 0.49 \pm 0.62$ eV in a good agreement with the value calculated using table values of the mass and of the magnetic moment of the Σ^- hyperon. The calculation was performed using the code described in [24] by integrating the Dirac equation with the finite-size nuclear potential which includes Coulomb and strong interaction and takes into account all significant corrections. The coincidence of energies allowed us to identify reliably the measured line as a $5g$–$4f$ transition in the Σ–C atom.

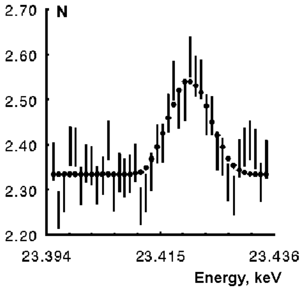

Fig. 7. Diffraction profile of the $5g$–$4f$ transition in the Σ^-–C atom. N – the number of counts per 10^{12} protons.

The measured energy allowed us to obtain a new value of the Σ^--hyperon mass

$$m_{\Sigma^-} = 1\,197.417 \pm 0.040 \text{ MeV} \quad (\pm 34 \text{ ppm}).$$

The error value here is 1.5 times lower than the error of the weighted average mass obtained in other experiments [23].

The counting rate in the line maximum amounted to 320 hour^{-1}, it is even a little higher than the intensity of the K-atomic line. This means that the hyperonic atoms are formed mainly in the inelastic collisions of protons with nuclei. This mechanism provides the radiation intensity high enough to perform systematic investigations of Σ atoms and makes it reasonable to search for the radiation of the Ξ atoms and, possibly, Ω atoms.

Study of the pionic atom formation in the decay of hadron resonances

The considerable intensity of the pionic atom X-rays in the experiment at the IHEP accelerator has stimulated further work aimed at the search of the production of pions in the bound states [25]. Such a process was considered theoretically for reactions (γ, π^-), $(e, e'\pi^-)$ and $(n, p\pi^-)$ but was not observed yet in experiment. It was predicted that pions should be produced mainly in s-states and the investigation of these states was possible by registration of secondaries.

At high energies a considerable part of pions is produced via the production and successive decay of the hadronic resonances. The existence of a considerable decay range in this case makes possible the production of slow π^- mesons with high orbital momenta (e.g. in the three-particle η-decay) with respect to the residual nucleus, that can lead to the formation of the pionic atom states with $l \neq 0$. Deexcitation of such states should be accompanied by characteristic X-radiation which could be registered.

We have made an attempt to observe with CDS the X-line (calculated energy is 51 519 eV) of the $3d$–$2p$ transition in the pionic neon atom in the spectrum from a magnesium target (the choice of neon is good because the target does not contain neon atoms). The result is shown in Fig. 8. A possible peak is located at the energy 51 521 ± 14 eV and has the amplitude of 0.36±0.15 counts per 10^{12} protons, its width does not exceed 100 eV. This measurement yielded an upper limit for the cross section for the formation of the excited π–Ne atom in collisions of 70 GeV protons with magnesium nucleus equal to 0.5 mb.

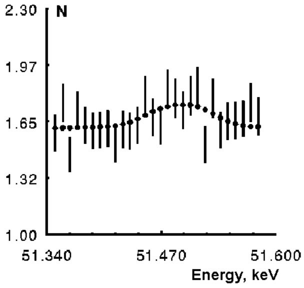

Fig. 8. Search for the $3d$–$2p$ transition in the π–Ne atom. N – the number of counts per 10^{12} protons.

Future perspectives

1. Study of mesic atoms at the Moscow meson factory with a two-crystal diffraction spectrometer

Determination of the pion-nucleon scattering amplitude at zero energy

The πN scattering lengths are usually determined from a phase shift analysis of the low energy πN scattering data using dispersion relations and extrapolation to zero energy. Such an indirect method leads to ambiguous results due to the experimental data dispersion as well as because of the difference in the phase shift analyses results. There exists, however, another way to obtain the πN scattering lengths, namely the study of the np–$1s$ transitions in the pionic hydrogen atom. The shift of the $1s$ level, ϵ_{1s}, is determined by the elastic part of the pion-nucleon interaction, while the width, Γ_{1s}, – by the inelastic one. The accuracy of obtained isoscalar b_0 and isovector b_1 scattering lengths which determine the amplitude of the s-wave πN scattering $f_{\pi N} = b_0 + b_1(\vec{\tau} \cdot \vec{t})$ does not contain theoretical uncertainties and depends only on the experimental errors. For the first time the CDS was proposed as an instrument for investigation of the pionic hydrogen atom in 1977 at PNPI [26]. Recently at PSI (Leisi, 1994) the shift $\epsilon_{1s} = 7.106 \pm 0.062$ eV and the width $\Gamma_{1s} = 0.97 \pm 0.15$ eV of the $1s$ level of the pionic hydrogen atom were measured. This allowed to obtain the scattering lengths b_0 and b_1:

$$b_0 = -0.11 \pm 0.10 \text{ fm}, \qquad b_1 = -0.136 \pm 0.010 \text{ fm}.$$

The relative accuracy for b_1 is equal to 7%, while it is ~90% for b_0, so the isoscalar pion-nucleon scattering length is practically uncertain.

The accurate value of b_0 is necessary for obtaining an adequate description of the pion-nucleus interaction. Besides, the b_0 value has a close relation to such a fundamental problem of hadron physics as a chiral symmetry breaking. In particular, the value and the accuracy of the determination of the pion-nucleon σ-term depend considerably just on the b_0 value. At present, the preparation of the experiment on the study of the π–H atoms at the Moscow meson factory is in progress [27–29].

It is well known that b_0 is zero for zero pion mass (chiral limit) or under the condition of the validity of the soft pion theorem. The knowledge of the value b_0 would yield the important information on the mechanism of the chiral symmetry breaking. So measuring the isoscalar pion-nucleon scattering length b_0 and refining the isovector one b_1 remains an important experimental problem.

Measurement of the π^--meson mass

The most accurate value of the π^--meson mass was obtained at PSI (Leisi, 1986). The new analysis of these data (Jeckelmann, 1994) yielded two possible values for m_{π^-}, the difference between them being six times larger than the experimental error. The ambiguity is due to the uncertainty in the electron screening correction. We plan to perform a new accurate measurement of the pion mass to eliminate this uncertainty.

Study of the spin-dependent strong pion-nucleon interaction

This interaction leads to the additional hyperfine splitting of the π-atomic levels with $l \neq 0$. Calculations show [27–29] that the value of the effect is comparable with the electromagnetic splitting of the $2p$ levels of π atoms with $Z \leq 5$. Till now the effect was not observed in experiments. We plan to measure the hyperfine splitting of the $3d$–$2p$ transitions in the lightest pionic atoms: ^{6,7}Li, ^{9}Be, ^{10,11}B.

In order to solve these problems, in 1995 a two flat crystal diffraction spectrometer was built which allows to measure X-rays in the energy range from 2.5 to 100 keV. The device will be installed on the proton beam of the Moscow meson factory. The target geometry is like that used in the pionic mass measurement at PNPI [4].

Energy resolution of the device near the energy of the $3p$–$1s$ transition of pionic hydrogen (~ 3 keV) amounts to ~ 0.6 eV that allows one to measure the width of the $1s$-level $\Gamma_{1s} \sim 0.9$ eV with the accuracy not worse than 5%. Using for calibration the X-lines K_{α_1} and K_{α_2} of argon with energies 2957.790 ± 0.009 eV and 2955.661 ± 0.012 eV one can measure the shift of the $1s$ level of the pionic hydrogen ϵ_{1s} with the accuracy not worse than 1%.

High resolution of the spectrometer (the instrumental width ~ 1 angular second) allows to measure the hyperfine splitting of the $2p$ levels of the lightest pionic atoms and to extract the contribution of the spin-dependent interaction.

This also gives the opportunity (by a proper choice of the mesic atom transitions) to separate components responsible for the different numbers of electrons in the K-orbit. This would eliminate the main uncertainty in the π^--mass determination connected with account of the electron screening.

2. Study of exotic atoms at high energy accelerators

Successful experiments at IHEP showed that the use of the crystal diffraction methods in experiments on high energy proton beams opened new perspectives for studying kaonic and hyperonic atoms and provided excellent conditions to study pionic atoms.

At IHEP a new experiment E-177 is approved, in which we plan to measure the Σ^--hyperon mass with an accuracy of 10 ppm using the "Quartz" spectrometer. A new experiment aimed at the measurement of the π^--meson mass with the accuracy 3 ppm is considered.

A proposal is in preparation to study exotic atoms at FNAL (USA) where 120 GeV proton beam is planned to work in 2000 with the intensity of 10^{13} s^{-1}. Such intensity, an order of magnitude higher than at IHEP, will allow to study Ξ atoms and, probably, Ω atoms. High resolution of the device designed will allow to investigate the fine structure of the transitions in hyperonic atoms and to determine the parameters of the central and spin-orbital potential of hyperon-nucleus interaction. Numerous experiments aimed to solve this problem were performed at CERN, BNL (USA) and KEK (Japan) but the problem is still far from being solved.

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