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Highly charged ions in exotic atoms research at PSI

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Abstract

During their de-excitation, exotic atoms formed in low pressure gases reach a state of high or even complete ionization. X-rays emitted from higher n-states of electron-free atoms have well defined energies with the error originating only from the error in the mass values of the constituent particles. They served as a basis for a new determination of the pion mass as well as for a high precision measurement of the pionic hydrogen ground state shift. The response function of the Bragg spectrometer has been determined with X-rays from completely ionized pionic carbon and with a dedicated electron cyclotron resonance ion trap (ECRIT). A further extension of the ECRIT method implemented in the experiment allows a direct calibration of exotic atom transitions as well as a precise determination of the energy of fluorescence lines.

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1. Introduction

Several modern experiments in the field of exotic atoms aim at a high precision spectroscopy with reflection type crystal spectrometers. Their energy calibration as well as the determination of the response function should preferably be performed

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simultaneously to the experiment and requires well defined narrow lines at energies below 20 keV. Fluorescence lines excited, e.g. with an X-ray tube are not defined well enough in energy and are too broad to be useful. Nuclear γ transitions are only scarcely available and with the exception of the 14.413 Mössbauer transition are not defined well enough in energy. As a way out, exotic atoms with low Z themselves offer a method to solve this problem. They are de-excited directly after formation by Auger emission of electrons. A formation in low pressure gases excludes electron refilling and results in highly or even completely ionized atoms [1,2]. Completely ionized of their electrons they represent a two body system whose binding energies can be calculated from QED with high accuracy and therefore provide an excellent X-ray energy standard. In the case of antiprotonic and muonic atoms an accuracy of better than 50 ppb is achievable. Pionic and muonic atoms with $Z < 20$ provide a rich spectrum of X-rays below 20 keV. Experimentally it is only necessary to interchange targets or, if possible, to mix the calibration gas with the experimental gas in the target volume. In a case discussed below muons and pions were stopped in a specially designed target gas mixture.

The small natural line width of typically less than 10 meV can not be exploited in all cases because of Doppler broadening [3]. This broadening can be minimized for monoatomic or special molecular gases.

Some applications of well defined X-ray energies are: (i) a new determination of the pion mass involving muonic atoms as a calibration [4], (ii) a measurement of the strong interaction shift of pionic hydrogen with pionic carbon and oxygen lines as calibration [5], (iii) a test of QED calculations for spin 0 bosons by a comparison of different pionic transitions [6] and (iv) a calibration of fluorescence lines [7].

2. Pion mass

The mass of the negatively charged pion has been newly determined using pionic atom X-ray transitions calibrated with muonic X-rays. The muon mass is known to an accuracy of 0.05 ppm compared to 2.5 ppm for the pion mass [8]. The energies of the (5–4) transitions in pionic nitrogen and muonic oxygen at about 4 keV differ by only 32 eV.

The pion beam of the πE5 area at PSI was injected tangentially into the weak focussing (cyclotron-like) field of a superconducting split pair coil system. The deceleration of the pions by radially distributed thin foils guides the particles to a gas-filled target in the center, where they stop. This so-called cyclotron trap arrangement reaches an improvement of two orders of magnitude in stopping efficiency compared to the usual arrangement of stopping pions with a moderator in a linear set-up.

The decay of slow pions inside the trap results in low energy muons stopping in the target as well. The set-up of the experiment is shown in Fig. 1. X-rays emitted from the target were reflected by a spherically bent silicon crystal. The reflected X-rays were measured in a large area X-ray detector built up of six 24×24 mm^2 CCD chips [9].

For the simultaneous measurement an oxygen/nitrogen gas mixture of 90%/10% at 1.4 bar was

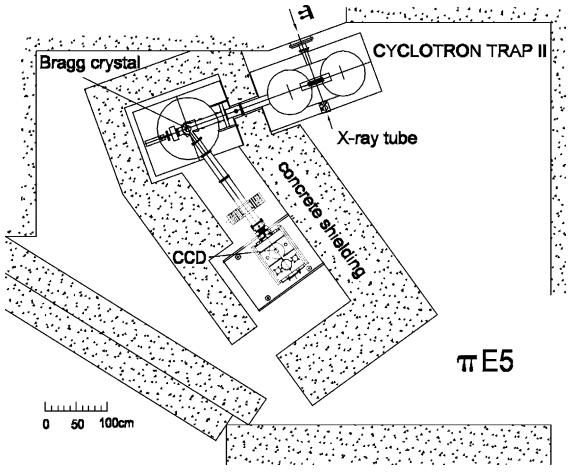

Fig. 1. Set-up of the Bragg spectrometer at the πE5 beam line at PSI.

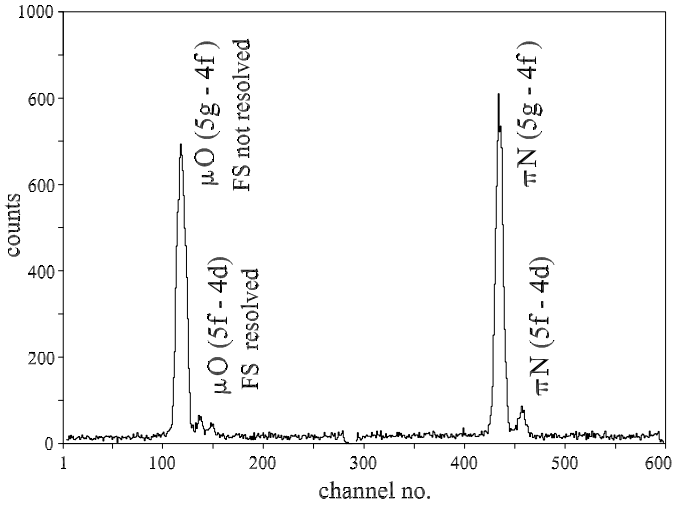

Fig. 2. Simultaneously recorded spectra of the pionic oxygen and nitrogen (5–4) transitions in the O_2/N_2 gas mixture. One channel corresponds to 102 meV.

used. More than 8000 events were recorded for both the μO and the πN(5g–4f) transition as shown in Fig. 2. Using the μO calibration line the value of the pion mass was determined with an error of about 1.7 ppm. A second energy calibration has been performed by using the copper fluorescence radiation as described for a preliminary experiment [10]. An accuracy of about 2 ppm is expected here so that a total error of about 1.3 ppm can be expected for the final result.

3. Pionic hydrogen

The new pionic hydrogen experiment at PSI aims at a substantial improvement in the determination of the isospin separated values for the scattering lengths in the pion nucleon system [5]. The scattering lengths can be extracted from a measurement of the strong interaction shift and width of the ground state of the pionic hydrogen atom. A drastic improvement in luminosity and in background suppression has been achieved recently as compared to a previous experiment [11]. The experiment has started with a study of the pressure dependence of the groundstate shift, measuring the 3–1 transition. As calibration line the πO(6h–5g) transition nearby was chosen. The aim of these measurements is to identify or to exclude molecular effects which could falsify the shift value attributed to the strong interaction [12]. A typical πH(3p–1s) spectrum is shown in Fig. 3 for a pressure of 4 bar. No pressure dependence has been found for the energy of the πH(3p–1s) transitions. Therefore on the present level of accuracy the molecular formation neither impedes the shift nor the width measurement. Preliminary results are in agreement with the value of the previous experiment performed at 15 bar equivalent density [11].

4. ECRIT

The final goal of the pionic hydrogen experiment is a determination of the strong interaction width with a factor of five improvement, which requires a well determined response function of the crystal spectrometer. The use of X-rays from exotic atoms alone is not sufficient because of their limited rate. The search for a more versatile method resulted in the set-up of a 6.4 GHz ECRIT X-ray source [13]. X-rays from hydrogen-like atoms as well as M1 X-rays from helium-like

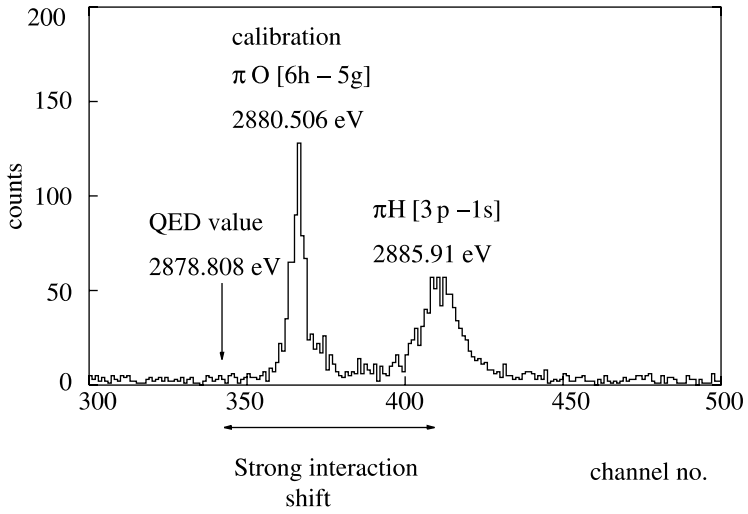

Fig. 3. The 3–1 transition in pionic hydrogen together with a pionic oxygen calibration line πO(6h–5g) and the satellite transition πO(6g–5f). The strong interaction effects are immediately visible as a broadening compared to the oxygen line and as a shift compared to the QED position. One channel corresponds to 145 meV.

atoms have natural line widths negligibly small compared to the expected resolution of the Bragg crystals. They are, however, broadened by Doppler effect, which for 3 keV X-rays contributes less than 50 meV, which is a factor of almost 10 times smaller than typical widths of the response function of the Bragg spectrometers used.

In a set-up similar to Fig. 1 the cyclotron trap was replaced by the ECRIT. The M1 transition $1s2s\,^3S_1$–$1s^2\,^1S_0$ at 3104 eV of helium-like argon shown in Fig. 4 was used for a determination of the response function of Bragg crystals. Restricting the surface of the Bragg crystals from a radius of originally 95 to 40 mm resulted in the theoretical resolution [15]. The nominal configuration during experiments with exotic atoms excludes the crystal surface at a horizontal distance of >30 mm from the center. For this configuration the resolution decreased by a about 20% [14].

4.1. A combined set-up: ECRIT plus exotic atoms

Pionic atoms can be produced with an order of magnitude higher intensity than other exotic atoms but have the drawback of a factor of about 20 less well determined mass. X-rays from an ECRIT can be used to improve this situation combining them with pionic X-rays in a double source set-up. In the following it is assumed that a calibration of a pionic X-ray with E_{EX} (Bragg angle Θ_{EX}) is required. In order to avoid systematic errors, the angular position of the detector should not be changed and its focal position should only minimally be adjusted. The first requirement is fulfilled for an ECRIT source emitting X-rays with an energy E_X and the corresponding Bragg angle Θ_X. It is placed at an angle $180 - 2 \times \Theta_X$ deg with respect to the detector arm opposite to the target for exotic atoms. The Bragg crystal must then be rotated by $180 - \Theta_X - \Theta_{EX}$ deg and the focal position of the detector must be shifted by $R_C \times (\sin\Theta_X - \sin\Theta_{EX})$, with R_C being the curvature radius of the crystal.

As an example, the calibration of a pionic carbon (5–4) transition with an energy of 2973 eV measured with a quartz [1 1 0] crystal at a Bragg angle Θ_B of 58.1° is considered. With present intensities of pions stopped in CH_4 the position of the (5–4) transition can be determined to about 300 ppb after about three weeks of measurements. An obvious choice for calibration is the $K\alpha_2$ X-ray from hydrogen-like chlorine at 2962 eV (Bragg angle 58.5°), which is known with an accuracy of 200 ppb. A rotation of the Bragg crystal of 63.4°

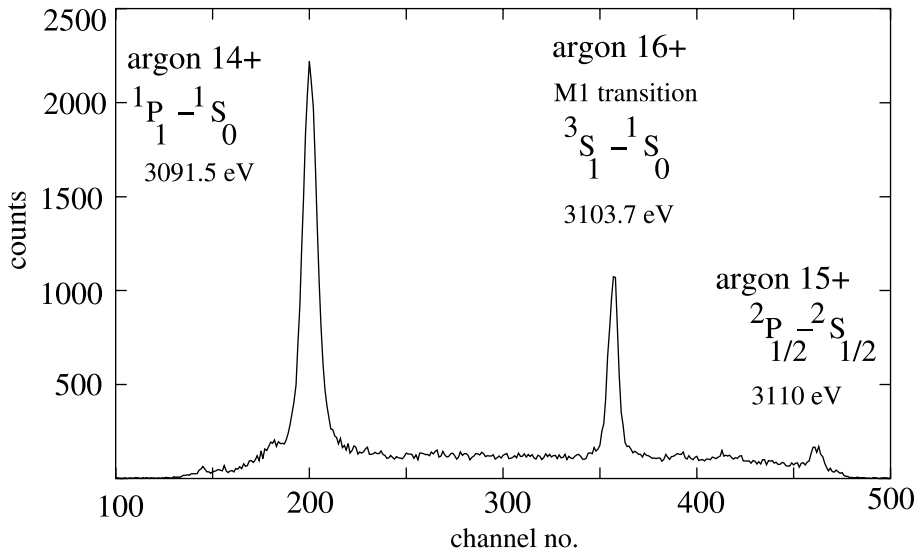

Fig. 4. The spectral region for argon X-rays from Ar^{14+}, Ar^{15+} and Ar^{16+} (M1 transition) as emitted from the PSI ECRIT source. The M1 X-ray line is used to calibrate the response function of a Bragg spectrometer (Johann mounting) equipped with spherically bent crystals. One channel corresponds to 79 meV.

and a detector shift of 11 mm is required to switch from measurement to calibration. The shift can be performed with lateral movements of less than 1 μm corresponding to a systematic error of 40 ppb. The rotation can be controlled with state of the art angular encoders with an accuracy of 1 ppm for large angle differences. An excitation of Kα fluorescence X-rays of argon with energies at 2956 eV near the pion target as well as near the ECRIT at the same distance from the crystal permits a calibration of the angular encoder to less than 100 ppb. A well determined pion mass provides then a dense distribution of X-ray standard transitions emitted from different gases. This fact can be used in turn to calibrate less well known X-ray transitions of hydrogen and helium-like ions and can be extended to calibrate fluorescence X-rays as well.

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