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FROM 277 MeV/u Pb⁸¹⁺ IONS**

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Doppler-Shift Assisted Fast Ion Spectroscopy: A Case Study for X-Ray Emission from 277 MeV/u Pb^{81+} Ions

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Abstract

Utilizing the different information from spatially separated segments of high-granular photon detectors the measured (LAB) energy of photons emitted by fast moving ions can be corrected individually for the Doppler effect according to the particular observation angles of each detector segment. By a redundant fitting procedure the center of mass photon energy can be determined with high precision. This new Doppler-shift assisted spectroscopy is explained for the case study of 277.4 MeV/u Pb^{82+} ions colliding with a N_2 -gas target at the heavy ion storage ring *ESR*. Spectroscopic information for hydrogenic Pb^{81+} ions is given for the ground-state transitions, for the Balmer transitions, as well as for the total K-binding energy.

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1 Introduction

A precise spectroscopy of photons emitted by fast projectiles is affected by the Doppler effect. The photon energy in the moving system, E_{CM} , can be calculated from the photon energy measured in the laboratory frame according to the formula:

$$E_{CM} = E_{LAB} \cdot \gamma \cdot (1 - \beta \cdot \cos \Theta_{LAB}), \quad (1)$$

where $\beta = v/c$ is the projectile velocity in units of the speed of light, $\gamma = (1 - \beta^2)^{-1/2}$ the relativistic Lorentz factor, and Θ_{LAB} the observation angle in the laboratory frame with respect to the beam axis. In order to determine precisely the E_{CM} energy of a photon line not only its energy E_{LAB} has to be measured accurately in the laboratory, but also the exact velocity (γ and β) and geometry (Θ_{LAB}) have to be established very carefully (see e.g. Schmieder and Marrus 1973); this is in particular true at high emitter velocities. The accuracy in the knowledge of all of these quantities determines the uncertainty for the true emission energy E_{CM} - the quantity that has to be compared with theoretical predictions. A simultaneous measurement of the photon energy at different observation angles allows via Equation 1 for a redundant and precise determination of the E_{CM} photon energy (Stöhlker *et al.* 1992a and 1993a).

The spatial energy dispersion observed in the laboratory for an originally monochromatic photon line from a fast moving source (CM -System), caused by the Doppler effect, was already exploited by Schmieder and Marrus (1973) for spectroscopic studies. Inserting a filter between photon source and detector, with a steep edge in its absorption characteristics, results in a corresponding sharp drop-off in the transmitted photon intensity at the appropriately tuned observation angle. Beyond geometrical considerations and uncertainties concerning the source velocity the resolving power of this "Doppler-tuned spectroscopy" is mainly determined by the intrinsic filter resolution, i.e. by the width characteristics of the used absorber edge. Depending on the absorber material and its edge energy this width may vary from the sub-eV region at very low edge energies up to the 100 eV region for the highest K-edge energies (for instance,

for neutral Pb atoms the K binding energy E_{Pb-K} is around 88 keV). The finally achieved accuracies, $A = E_{CM}/\Delta E_{CM}$, reported in the literature, vary from 300 to 3000 for source velocities between 2 and 45 percent the speed of light, respectively. In the upper part of Table 1 an overview is given on published experiments using the Doppler-tuned spectroscopy technique. As the Doppler dispersion gets larger at higher emitter velocities, the accuracies should increase in a first approximation with increasing β as well.

At high photon energies, where the widths for absorber edges get large, one may replace the "filter analyser" by a standard – dispersive or non-dispersive – x-ray spectrometer. However, using a standard, single device with one narrow, angle-defining slit the counting rate may shrink drastically in comparison with an integral, angular sensitive detection. By utilizing a position sensitive, non-dispersive x-ray spectrometer this drawback is avoided. Unfortunately, solid state x-ray detectors like Si(Li) or Ge(i) detectors with a proper continuous position resolution are not available commercially. However, segmented Ge(i) spectrometers allowing for a discrete position determination of the detected photons are provided already and can be exploited for a non-dispersive, Doppler-shift assisted spectroscopy of fast x-ray sources. First spectroscopic results obtained by applying this method have been reported already briefly in two letters on the Lyman α emission from fast Bi and U ions (Stöhlker *et al.* 1992a and 1993a). The spectroscopic information from the different segments of the detector is individually Doppler-shift corrected and redundantly summed up to one CM spectrum, exploiting the well-known geometrical correlations between the various detector elements. The relative accuracies achieved for the two measurements were 800 and 1700, respectively (see bottom part in Table 1). With a proper counting statistics an accuracy of about 5000 and more should be feasible in future experiments.

In this paper we report on our original test experiment at the storage ring *ESR* with 277.4 MeV/u Pb^{82+} ions colliding with $N_{(2)}$ gas atoms. This case study for the x-ray emission from hydrogenic Pb ions established the new technique of an energy non-dispersive,

Doppler-shift assisted x-ray spectroscopy at a gas target. Both, details on the new technique as well as on the atomic structure of H-like Pb ions are given.

2 Experimental Technique

This test experiment has been performed at the new experimental heavy ion storage ring *ESR* during its commissioning phase: 277.4 MeV/u bare Pb^{82+} ions from the heavy ion synchrotron *SIS* were injected into the storage ring and then compressed into a small phase space volume by electron cooling. Many beam pulses from the *SIS* have been stacked within typically one hour to accumulated particle intensities in the *ESR* – in the best cases – up to about $5 \cdot 10^6$. (Presently, a factor of 10 higher stacking efficiencies are normally achieved.) Thereafter, the gas-jet target was switched on using N_2 gas with an areal density of approximately 10^{12} cm^{-2} and a relevant diameter below 3 mm (Gruber *et al.* 1989). The electron cooling was continuously in operation (at low electron currents of about 200 mA) in order to compensate for energy losses and straggling of the ions in the target. The momentum spread of the ion beam measured by the frequency spectrum of the Schottky noise induced by the coasting beam stayed narrow below $\Delta\beta/\beta = 5 \cdot 10^{-5}$ over each run. After about 15 minutes the stored ions have essentially been used up, mainly via electron capture processes in the target. Despite the narrow energy distribution for the ions in the circulating beam, the absolute value for the ion velocity could only be determined on the level of $\Delta\beta/\beta = 5 \cdot 10^{-4}$ due to the lack of knowledge of the accurate circumference of the actual beam track. Similar uncertainties are involved in the precise measurement of the acceleration voltage of the cooler which determines in the end the exact ion energy.

The dominant capture mechanism in the case studied is radiative electron capture, *REC* (Stöhlker *et al.* 1993b and 1994, see also Stöhlker *et al.* 1992b). The energy of the x rays emitted in this process corresponds to the sum of the kinetic energy of the

quasifree target electron with respect to the projectile and its final binding energy in the ion. If *REC* populates an excited level, this state cascades instantaneously down to the ground level via the emission of characteristic x rays. Here, we are mainly interested in the spectroscopy of these ground-state transitions. In any case, the bare ion is down-charged to H-like Pb^{81+} and is then separated by the next downstream dipole magnet from the coasting Pb^{82+} beam. Thereafter, behind a thin window in an adjustable pocket, the down-charged ions are detected in a position-sensitive multiwire ionization chamber (Klepper *et al.* 1992). The emitted x-rays are detected in coincidence with these ions having captured one electron. For the experimental arrangement at the *ESR* see Fig. 1. From the measured width of the down-charged ion beam, the diameter of the continuously cooled Pb^{82+} beam was deduced to be of the order of 1 mm at the gas target. Altogether, the interaction volume between gas-jet and ion beam is reasonably well defined for our spectroscopy purpose.

The target area was viewed by three Ge(i) x-ray detectors at observation angles of about 48° (forward), 90° (perpendicular), and 132° (backward) with respect to the beam direction. The forward and the 90° detectors were segmented: At 48° we used a 12 mm thick Ge(i) crystal with an active area of $2.5 \times 2.5 \text{ cm}^2$ that was divided into seven equidistant parallel stripes reducing each individual, Doppler-relevant opening angle for the observation down to 0.7° . The stripe width of 3.5 mm was comparable to the width of the x-ray source. At 90° a 5 mm thick cylindrical Ge(i) detector was installed with a total sensitive area of 275 mm^2 divided into a central segment and four wing-like quadrants. In backward direction a non-segmented, 15 mm thick Ge(i) crystal with an active area of 500 mm^2 was used. The detectors viewed the target-beam interaction region with distances of 326, 350, and 331 mm at 48° , 90° , and 132° , respectively. For the backward as well as for the forward detector a 50 μm thick Be window was installed to allow also for transmission of low-energy x rays while maintaining the ring vacuum of typically 10^{-11} mbar . (The 90° detector had to look through a 50 μm thick stainless steel

window. As the statistical uncertainties for the segments of this detector had been large, we do not use that information in the present paper.)

The geometry of the whole target chamber and detector arrangement was determined by laser-assisted, computer-controlled trigonometry, which resulted in a precision of $\pm 0.01^\circ$ for the mean positions of the detector segments. The electronics for all the 13 detector segments had been adjusted and individually energy calibrated by radioactive sources with a total accuracy of about 20 eV for the relevant energy region. In order to control the stability of the electronics and systematic errors each x-ray detector/segment was connected to two independent main amplifier and analyser channels. Each x-ray signal detected in a fast/slow coincidence circuit with a down-charged ion was recorded in list mode, using the GSI on-line data acquisition system (GOOSY).

At the used beam energy of 277.4 MeV/u - corresponding to $\beta = v/c = 0.6374(3)$ - the Doppler corrections are considerable: In Fig. 2 calculated relative shifts E_{LAB}/E_{CM} are plotted according to Equ. 1 as a function of the LAB observation angle. The actual measuring positions for the detectors and their segmentation are also indicated in the figure. For comparison, the relative Doppler shift at a 10 percent higher beam energy of 305 MeV/u is shown by the dashed curve. It is emphasized, that both the curves cross near an angle of 48° , i.e. at the position of the forward detector. Here, a slight variation in beam energy will influence the total Doppler shift only in second order ("relativistically Doppler-shift free angle"). On the other hand, around this angle, the shift varies most strongly with the angle. Due to this steep slope we find an appreciable variation in observation energy from stripe to stripe in the sevenfold detector. Minimizing the uncertainties in the free parameters (e.g. exact location of the interaction volume) allows via the known geometrical correlations between all the segments and the detectors, for an accurate and on-line determination of the geometry for the beam-target-detector arrangement. This is in principle also true for the beam energy.

In contrast to the 48° detection angle, the Doppler shift varies only moderately over the large opening angle of the backward detector mounted at 132° . Additionally, as at this observation angle the whole x-ray spectrum is compressed towards lower energies, this detector is in particular efficient to measure originally high-energy photons. On the other hand, we should mention that due to the relativistic transformation the actual (CM) solid angles at 277.4 MeV/u have to be corrected by factors of 0.29 and 1.81 for the LAB system at 132° and 48° , respectively.

3 Results and Discussions

For an overview on the x-ray spectrum emitted in coincidence with the down-charged hydrogenic Pb ions we display in Fig. 3 a spectrum measured by the backward detector. LAB energies are given and no correction for detector efficiency is made. We observe a practically background free spectrum with three groups of x-ray "lines": The broad REC lines at high energies, the ground state transitions or the Lyman series at medium energies, and at low energies transitions to the L shell, the Balmer series.

The most prominent REC line – the K-REC line – is caused by a direct transition of a quasifree target electron into the ground-state of the originally bare ion. From the measured centroid energy at around 138 keV we can deduce the CM energy for this transition using the well-known formula (e.g. Mokler *et al.* 1991):

$$E_{REC} \cdot \gamma(1 - \beta \cdot \cos\Theta) = E_{kin} + E_K - \gamma E_T \quad (2)$$

where E_K and E_T denotes the final (ion) and initial (target) binding energy of the active electron and E_{kin} its relative kinetic energy towards the projectile ion. Here, we have to use a mean observation angle of 132.05° resulting from the analysis of the L – K transitions observed by all the various detectors and their segments (see below). By subtracting the relative kinetic energy of the quasifree target electron with respect to the projectile we deduce for the ground-state

binding energy in Pb^{81+} a value of $101,283 \pm 170$ eV. The large uncertainty here is essentially determined by the error in β . This value agrees within -46 eV with the theoretical expectation of $101,337$ eV (Johnson and Soff 1985). We like to emphasize however, that at this high projectile energy the Compton profile of the target electrons transforms into a relatively broad line (see Fig. 3). Moreover, the exact shape of the Compton profile including the relativistically correct transformation (Ichihara *et al.* 1994), the detailed detector response functions, the efficiencies as well as second-order collision effects have to be known accurately for a precision determination of the ground-state binding energy (see e.g. Beyer *et al.* 1993, Vane *et al.* 1994, and Stöhlker *et al.* 1994). However, previously not always all the effects had been properly taken into account. The described technique is more appropriate for smaller ion velocities where it was originally proposed for by Mokler *et al.* (1991). These authors showed also the necessity to measure the REC centroid energies at a series of ion energies in order to minimize the possible systematic uncertainties in a precise determination of the binding energies.

The L-, M-, ... REC populate excited states in the projectile L-, M-, ... shell, respectively, where at the used ion energies low angular momentum states (s states) are preferred (Ichihara *et al.* 1994). These excited states cascade radiatively down to the ground state. Due to the high nuclear charge of the Pb nucleus, transitions to the ground state are very fast; even the M1 dipole transitions have to be considered as prompt. The corresponding E1 and M1 transition rates are of the order of $2 \cdot 10^{16} s^{-1}$ and $5 \cdot 10^{13} s^{-1}$, see for example Mokler *et al.* 1994. For instance, the $2^2P_{3/2} - 1^2S_{1/2}$ transition, i.e. the Lyman- α_1 line, is pure whereas for the "Lyman α_2 line", i.e. $2^2P_{1/2} - 1^2S_{1/2}$ transitions, strong contributions from M1 transitions $2^2S_{1/2} - 1^2S_{1/2}$ have to be considered. According to Ichihara *et al.* (1994) we calculated the primary population for the various L states and found that the M1 transitions contribute as much as about 73 % to the line at the $Ly - \alpha_1$ region. This value is only slightly changed by side feeding cascades. The total Lyman- α intensity is dominantly be determined directly by the L REC. The $Ly - \beta$ and

higher *Lyman* transitions are caused by REC to higher shells ($n > 2$) which contributes also via cascades to the Balmer lines observed at low x-ray energies.

As was pointed out already, one of the advantages of the use of the segmented detector is the small individual opening angle and, thus, the small Doppler broadening. Due to the large angular dispersion of the Doppler shift for the forward detector at 48° (cf. Fig. 2) we are able to treat the spectra measured by the different stripes individually. In Fig. 4 x-ray spectra are shown for the two outermost and the middle stripe of the sevenfold detector for the case studied: $277.4 \text{ MeV/u } Pb^{82+}$ on N_2 . Only the region around 100 keV is displayed where in the LAB-frame the Lyman- α_1 and $-\alpha_2$ transitions in hydrogenic Pb^{81+} ions appear. At the given conditions we find a differential shift of about 1.3 keV per degree. It is obvious, that there is absolutely no way to resolve these two lines for a non-segmented detector covering the same total solid angle as the used one and at a typical resolution of about 500 eV . Knowing the actual geometry we can transform the spectra for each stripe to the emitter system and then, sum them up redundantly to one well resolved CM spectrum.

The actual target/detector arrangement including beam geometry was determined by (i) optimizing the resolution in the summed-up CM spectrum for the sevenfold detector, (ii) incorporating the energy information from the lines of all the spectra obtained for each segment and all the eight segments and detectors – in particular also from the backward detector – and (iii) utilizing the precise knowledge on the geometry of the detectors relative to each other and on their segmentation. An "on-line" angular accuracy of 0.05° was achieved for the actual geometry during the measurement, delivering centroid angles of 47.82° and 132.05° for the forward and backward detectors, respectively. This result agrees fairly well with the one determined independently by trigonometry, using the ESR coordinates of the gas-jet centre as a reference. The natural condition used for the best fit is that in the CM system the spectra for all the detectors as well as their segments yield within statistical fluctuations the same centroid energies. The accuracy of this procedure

depends sensitively on the statistical uncertainties in the different LAB spectra.

Fig. 5 shows the summed-up CM spectrum for the sevenfold forward detector resulting from this fitting routine minimizing the total uncertainties. A very clean - practically background-free - spectrum is obtained for the energy region between 10 and 100 keV. As can be seen, the lines are nicely resolved manifesting the effectiveness of the described technique. The *REC* lines lying at higher energies are not visible for the forward detector as its efficiency drops beyond 120 keV considerably. The lines at the Lyman emission region are well separated. Also the Balmer series observed at low x-ray energies displays well resolved lines. In the following, the x-ray emission from the Balmer region is briefly discussed first (cf. Fig. 6). Then, the spectroscopic information from the Lyman- α emission region will be described in more detail (see Table 2).

The spectral region for the Balmer lines is shown in an enlarged scale in Fig. 6. For comparison also a simulated spectrum is inserted at the top of the figure. The initial (n, l) population as well as the angular distribution of the emitted photons are not easy to incorporate reliably into a simulation calculation for a spectrum. Nevertheless, we find a reasonable accordance between measured and calculated spectra. For our simulation we calculated the (n, l) population caused by REC into higher shells using the nonrelativistic theory of Stobbe (1930). The transition rates were computed according to the GRASP code (Dyall *et al.* 1989). For the L-shell binding energies we used the tabulated values from Johnson and Soff (1985); and for the higher shell we solved the Dirac equation. From a comparison of both the two spectra we conclude that the Balmer spectrum is dominated by $n^2S_{1/2} - 2^2P_{3/2}$ transitions. This is obvious as at our ion energies *REC* populates preferentially s states and only to a smaller extent higher angular momentum states (Ichihara *et al.* 1994). However, an appreciable contribution from $n^2P_{1/2} - 2^2S_{1/2}$ transitions, particularly for $n = 3$, is also observed (see Fig. 6). All the other possible transitions into the L shell contribute less according to their population.

Now we discuss the less complex Lyman- α region, cf. Fig. 5. Here, we have to consider first the accuracy achieved by the least square fit procedure. As this case study had been performed during the initial commissioning phase of the *ESR* in 1992, the x-ray measurements had been taken over an extended period of days at relatively low numbers of stored ions. Moreover, during day times accelerator- and ring- related experiments were performed, before tuning the *ESR* back on the conditions needed for the x-ray experiment. This introduced unpredictable systematic errors into the analysis of the spectra summed over all the individual measuring periods. Hence, despite the good overall statistics seen for instance in the spectrum shown in Fig. 5, we have to place a large systematic uncertainty for our extracted x-ray energies even if we select for the data analysis the most reliable runs only.

For the spectra summed over all reliable measuring times, the fitting procedure gives relatively precise values for the centroid energies of the x-ray lines. Including calibration uncertainty, stability of the detector and electronic arrangement, and possible long-time drifts we place as a conservative estimate a total uncertainty of 35 eV on the precision of the extracted centroid energies. In addition, we have to add the errors caused by the slightly varying experimental conditions. Assuming $\Delta\beta/\beta = 5 \cdot 10^{-4}$ we have to introduce an uncertainty of 38 eV. The uncertainty in $\Delta\Theta$ of 0.05° gives an error of 53 eV. With an independent summation of all the errors involved, the E_{CM} energies of the lines observed are accurate within 75 eV. The experimental values extracted for the lines in the *Lyman* - α transition region are given in Table 2.

These experimental results are compared with the theoretical values given by Johnson and Soff (1985). As was already pointed out, the *Ly* - α_2 line is blended with the "prompt" M1 transition. Assuming a calculated population of the $p_{1/2}$ and $s_{1/2}$ levels by *REC* of 27 % and 73 %, respectively, we yield an expectation value for the centroid energy of the composed line of 75,309 eV, which has to be compared with the measured value given in Table 2. For the comparison with theory, the error has to be increased due to the un-

certainty in the population distribution. Cascades from higher shells are not expected to change this population significantly.

Despite the imperfections in doing this experiment during the initial commissioning at the *ESR*, the experimental accuracy is already remarkable: If we subtract from the measured transition energies the corresponding *Dirac* values, a ground-state *Lamb* shift for hydrogenic Pb^{81+} of 290 ± 75 eV is obtained, which has to be compared with the theoretical value of 245 eV (Johnson and Soff 1985). Similarly good - and presently already better - accordances are found for neighbouring very heavy hydrogenic species (see e.g.: Xe by Briand *et al.* 1989, Dy by Beyer *et al.* 1993, Au by Beyer *et al.* 1994a, Bi by Stöhlker *et al.* 1992a and U by Stöhlker *et al.* 1993a and Beyer *et al.* 1994b). For all very heavy, one-electron ions investigated up to now, the measured ground-state transition energies confirmed the predictions for the ground-state *Lamb* shift, see e.g. the survey given by Mokler *et al.* 1993).

4 Summary and Future Developments

In this paper the new technique of a *Doppler*-shift assisted fast ion spectroscopy was described. Already this early feasibility study established the superior power of exploiting the spatial (angular) energy dispersion caused by the *Doppler* effect in combination with granular solid state detectors having a good energy resolution. This was demonstrated by the spectroscopy of the *Lyman* and *Balmer* x-ray lines emitted from fast hydrogenic Pb^{81+} ions. The ground-state *Lamb* shift was determined with an accuracy of 75 eV and compares nicely with the prediction given in the literature. Also, the ground-state binding energy measured directly via the K - REC line agrees well with the expectation value. Additionally, for the first time the *Balmer* series has been observed for a very heavy hydrogenic ion. Also in this case a good accordance with a simulated spectrum has been found.

For this first in-ring case study of 277 MeV/u Pb^{82+} ions colliding with light gas atoms the achieved accuracy, $A = E/\Delta E = 1000$, is

only moderate due to the limiting boundary conditions during the initial phase of the *ESR* commissioning. In a second experiment with U^{92+} ions performed a month later, the accuracy was already increased by almost a factor of two, see Table 1 and Stöhlker *et al.* (1993a). With the present operation at the *ESR*, providing high intensities of more than $5 \cdot 10^7$ stored ions even for the heaviest species, accuracies of 5000 to 10000 should be possible exploiting the described *Doppler*-dispersion assisted spectroscopy using granular solid-state detectors. This technique allows in particular to determine simultaneously x-ray lines over a wide energy region (*Lyman*– and *Balmer*– as well as *REC*– lines) resulting in an additional redundancy for – and, thus, a better accuracy in – the structure of these very heavy, highly-charged ions. We emphasize that employing a gas target the x-ray background is completely negligible even for the low-energy photons.

Compared to the use of a non-segmented solid state detector – at a detection angle of 0° or 180° in order to reduce the *Doppler* dispersion (Beyer *et al.* 1994) – the *Doppler*-shift assisted technique with high-granular solid state x-ray detectors results with an especially high confidence level for the extracted transition energies and their accuracies; this is due to the systematic redundancy in the information from the different detector segments. In particular, the uncertainties in ion beam energy and in observation geometry can be determined on-line with high precision. Using the geometrical correlations between the segments – the shifts in the spectra for the different segments are not independent – these uncertainties are included and minimized in our redundant fitting routine.

The classical *Doppler*-tuned spectroscopy utilizing the absorber technique may provide for the determination of ground-state transition energies absorbers with slightly narrower edge widths than the corresponding energy resolution of solid state detectors. However, large area x-ray detectors with an extremely good position resolution (best two-dimensional ones) have to be used. These detectors have to have a good efficiency and should distinguish additionally against background effects, for instance against photons from Comp-

ton events. Using more than one absorber material with different edge energies at different angles the redundancy of our *Doppler*-dispersion supported spectroscopy can probably be incorporated into the classical *Doppler*-tuned technique. It will depend on the development of two-dimensional x-ray detectors with an ultimate position resolution and high detection efficiencies whether the slight resolution advantage of the absorber technique will result in more accurate transition energies. High pressure gas detectors with large volumes, Compton suppression, and a three dimensional position resolution for the detected x rays are being developed elsewhere (Dangendorf *et al.* 1991).

On the other hand, there are also very challenging developments of solid state x-ray detectors - like calorimetric cryo-detectors (McCammon *et al.* 1993) - which may improve the energy resolution drastically. These detectors are still small in size; however, there is no objection to arrange several of these detectors to one high granular assembly. Such a special arrangement will combine the superior technique of the *Doppler* dispersion assisted spectroscopy with the best energy resolution available for non-dispersive x-ray spectrometers (detectors). Depending on the finally achieved energy resolution - e.g. using new calorimetric detectors - and on the capability to cover large solid angles for a good overall counting statistics, the accuracy of this technique may get compatible with the one postulated for the best high-resolution crystal spectrometers, where at the same time the overall detection efficiency for the *Doppler*-shift assisted method is better. Additionally, the applied coincidences between x-rays and charge-state of the ions is crucial for background- and satellite-free x-ray spectra. We have the definite hope, that this new technique in combination with the development of new x-ray detectors will allow to determine the ground-state transition energies for the heaviest highly-charged ions even with an accuracy on the eV level or below; a level that is of relevance for the subtleties of the *QED* contributions in those heavy systems.

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Figure captions

Figure 1: Experimental arrangement at the heavy ion storage ring *ESR*: A continuously cooled beam of 277.4 MeV/u bare Pb^{82+} ions traverses a N_2 gas jet target. Down-charged ions are detected behind the next down-stream ring magnet. The target area is viewed by three Ge(i) x-ray detectors, where two of them have a high granularity. The x rays are measured in coincidence with the down-charged hydrogenic Pb^{81+} ions.

Figure 2: Relative Doppler shift E_{LAB}/E_{CM} as a function of the (LAB) observation angle Θ_{LAB} for 277 and 295 MeV/u ions (full and dashed curve, respectively). For comparison, the positions for the x-ray detectors at the *ESR* gas jet are indicated as well as their granularities.

Figure 3: X-ray spectrum seen by the backward (132°) Ge(i) detector for 277.4 MeV/u $Pb^{82+} - N_2$ collisions. The x rays are measured in coincidence with the down-charged Pb^{81+} ions. (LAB energies are given; for line assignment see text.)

Figure 4: The Lyman transition region for Pb^{81+} seen by the two outermost and the middle stripe of the forward (48°) x-ray detector. The three spectra (LAB energies) correspond to mean observation angles of 45.65° , 47.82° , and 49.99° . (For the other experimental conditions see Fig. 3.)

Figure 5: X-ray spectrum transformed to the center of mass reference frame for transitions in hydrogenic Pb^{81+} . The spectrum is summed over all CM spectra from the seven stripes of the forward (48°) detector. For the Lyman α region the contributing transitions are indicated in the insert.

Figure 6: Expanded view of the Balmer region for the CM spectrum shown in Fig. 5. For comparison a simulated spectrum is inserted. The main transitions contributing to the x-ray lines are also indicated.

Table captions

Table 1: X-ray spectroscopy techniques exploiting the Doppler-shift dispersion at fast ion beams: The upper part of the Table gives experimental data for the conventional "*Doppler-tuned spectroscopy*", in the lower part results utilizing the new "*Doppler-shift assisted spectroscopy*" technique are presented. The first collumn for the ion species shows also the number of electrons for the ionic sequence studied; the velocity (second collumn) is given in units of the speed of light; for the transitions investigated the involved main shells (third collumn) and the region for the CM energies (fourth collumn) are indicated; $E_{CM}/\Delta E_{CM}$ represents the achieved accuracies (fifth collumn); the last collumn shows the literature references.

Table 2: Ground-state transition energies for L-shell excited Pb^{81+} ions: The experimental results are compared to the predictions of Johnson and Soff (1985).

Table 1: Doppler- shift dispersion exploiting spectroscopy

Z - #e	v/c	n ₁ -n ₂	E _X /keV	E _{CM} /ΔE _{CM}	Ref.
⁶ C - 4	0.02	L - M	0.3	600	Huddle and Mowat 1982
¹⁷ Cl - 2,3	0.05	K - L	2.7	900	Schmieder and Marrus 1973
¹⁸ Ar - 2	0.15	K - L	3.1	300	Cocke et al. 1974
³⁶ Kr - 1	0.20	K - L	13.0	(3000)	Mokler et al. 1978
⁹² U - 3	0.43	L - L	0.3	3000	Schweppe et al. 1991
⁸² Pb - 1	0.63	K - L	80.0	1000	this work
⁸³ Bi - 1,2	0.40	K - L	80.0	800	Stöhlker et al. 1992a
⁹² U - 1	0.70	K - L	100.0	1700	Stöhlker et al. 1993a

Table 2: Ground state transition energies (eV)

TRANSITION	EXPERIMENT	THEORY	EXP - THEO.
L _y α ₁ : 2 ² P _{3/2} -1 ² S _{1/2}	77,890 ± 75	77,935	-45 ± 75
L _y α ₂ : 2 ² P _{1/2} -1 ² S _{1/2}	75,246 ± 75	75,281	
M1 : 2 ² S _{1/2} -1 ² S _{1/2}		75,320	-63 ± 80

Fig 1

Fig 2

277 MeV/U $\text{Pb}^{82+} \Rightarrow \text{N}_2$

Fig. 3

277 MeV/u $\text{Pb}^{82+} \Rightarrow \text{N}_2$

X-Ray CM-Energy (keV)

Fig 6