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**HIGH RESOLUTION CALORIMETRIC LOW TEMPERATURE
DETECTORS FOR APPLICATIONS IN ATOMIC AND
NUCLEAR PHYSICS**

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High Resolution Calorimetric Low Temperature Detectors for Applications in Atomic and Nuclear Physics

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Summary: Low temperature calorimetric detectors may become a powerful tool for atomic and nuclear physics experiments. Such detectors are operated by reading out the temperature rise of an absorber after thermalization of the kinetic energy which is deposited by an incident particle or photon. Due to the Debye law highest sensitivity is obtained at low operating temperatures. The operating principle and the expected properties of calorimetric low temperature detectors are discussed. Such detectors promise a substantial advantage over conventional detection schemes with respect to basic detector properties, as for example energy resolution, detection threshold, resistance against radiation damage, etc.

Calorimetric detectors are developed for applications in heavy ion based atomic and nuclear physics research. The design and the achieved performance of appropriate detectors for energetic heavy ions ($E \approx 5 - 2000$ MeV/u), operated at temperatures of 1.5 - 2 K, and for hard x-rays ($E \approx 50 - 100$ keV), operated at temperatures around 50 - 100 mK, is presented. For both cases relative energy resolutions of $\Delta E/E = 1 - 2 \cdot 10^{-3}$ have been obtained, which already represents a considerable improvement if compared to conventional semiconductor detectors. Due to the achieved detector performance, which may be even improved in future, the present detectors bear a large potential for applications in basic and applied heavy ion research. A brief overview, including a few examples, is given.

1 Introduction

The success of experimental physics and the quality of experimentally determined results generally depend on the quality of the available detection systems with respect to resolution, detection threshold, accuracy, efficiency, granularity, etc. Consequently the search for improved detection techniques is always a basic part of research activities in all disciplines of physics. When focusing on atomic, nuclear, particle and astrophysics, detectors for radiation, covering photons from the visible light via x-rays to hard γ -rays, and particles, such as α -, β -radiation, light and heavy ions in a wide range of energies, and various exotic particles,

will be important.

Whereas most of the standard methods for detection of radiation are based on ionization, the rapid development of low temperature physics and techniques has allowed in the recent past for the investigation of a new detection concept for radiation, which is independent on ionization processes, namely the concept of thermal detectors. In contrast to ionization detectors, where the amount of electron-ion pairs, created by the impact of a photon or particle into an absorber, is detected, the basic concept of thermal detectors is focused on the variation of the thermal properties of an absorber due to the impact of radiation. This concept opens completely new perspectives for radiation detectors. In order to allow for a measurable change of the properties of a macroscopic piece of matter (absorber) due to the impact of a microscopic particle, and to optimize the sensitivity, such detectors make use of the drastic drop of the heat capacity of solids for low temperatures due to the Debye law. Consequently such detectors are operated at low temperatures and are therefore called "low temperature detectors". It is obvious that for the design and the optimization of such detectors the basic understanding of the solid state properties of the detector constituents, especially at low temperatures, is essential.

A large variety of different detection concepts of low temperature detectors for various applications, has been investigated in the recent years by numerous research groups all over the world. In some cases already excellent results have been reported. For a detailed overview on the field, including the different detection concepts, the physics motivations and the historical development, the reader may be referred to recent review articles [1] [2]. The present article will focus on the concept of calorimetric low temperature detectors and on their applications in heavy ion based atomic and nuclear physics. Calorimetric detectors measure the temperature rise of an absorber after the energy deposited by the incident particle is thermalized. This detector concept promises, due to its operational principle, considerable advantages over conventional detectors with respect to basic detector properties, such as energy resolution, energy threshold and flexibility in the choice of the absorber material.

The present project was motivated by a new generation of heavy ion facilities which started operation about one decade ago at GSI Darmstadt. The combination of the heavy ion synchrotron SIS, the radioactive beam facility FRS, and the experimental storage ring ESR allows for a new generation of heavy ion experiments in atomic and nuclear physics. They include high resolution experiments with heavy ion beams of excellent beam qualities ($\Delta E/E \leq 10^{-4} - 10^{-6}$) due to beam cooling in the ESR and using thin internal targets, experiments with radioactive beams which need efficient isotope identification, and high resolution x-ray spectroscopy on highly charged heavy ions. Such experiments demand for x-ray and heavy ion detectors with highest energy resolution and detection efficiency, not available with conventional detection schemes.

2 Operation Principle and Properties of Calorimetric Low Temperature Detectors

The detection principle of a calorimetric low temperature detector is schematically displayed in fig. 1. An incident particle (or photon) with energy E is stopped in an absorber, leading primarily to ionization and production of high energy phonons. After the decay of electronic excitations the main part of the incident energy will be converted into heat (thermal phonons), leading to a temperature rise ΔT of the absorber. The observed thermal signal is read out by a thermometer coupled to the absorber. Finally the deposited heat is transferred via thermal coupling to the heat sink. The time development of the observed thermal signal $\Delta T(t)$ is in first approximation described by

$$\Delta T = \frac{E}{C} \cdot \exp\left(-\frac{t}{\tau}\right), \quad (2.1)$$

where $C = c \cdot m$ is the heat capacity of the absorber, m denotes its mass, and c its specific heat. The dynamic behaviour of the detector is determined by the thermal time constant $\tau = \frac{C}{k}$. The amplitude of the thermal signal being inversely proportional to the heat capacity C , it is obvious that a high sensitivity of the detector is achieved by minimizing the specific heat c of the absorber:

$$c = c_e + c_l = \alpha \cdot T + \beta \cdot \left(\frac{T}{\Theta_D}\right)^3, \quad (2.2)$$

where c_l denotes the contribution of the lattice, and c_e the one of the conducting electrons. For normal metals c_e is proportional to T , and therefore dominates the heat capacity at low temperatures. The highest sensitivity is therefore expected for dielectric solids, where $c_e = 0$, and c_l may become - due to the T^3 -dependence of the Debye law - very small at low temperatures for materials with high Debye temperature Θ_D . Alternative materials are superconductors, operated at $T \leq T_c$, where $c_e \sim \exp(-\frac{T}{T_c})$ vanishes exponentially with decreasing temperature. Besides the constraint of small specific heat the absorber material is also to be optimized with respect to rapid and complete thermalization of the deposited energy. For the absorber mass a reasonable compromise between sensitivity and detector efficiency and solid angle has to be found for each individual application.

As thermometers for reading out the temperature rise ΔT of the calorimetric detector thermistors may be used. For a thermistor the change of temperature is converted to a change of resistance. Biasing the thermistor with a constant current the change in resistance leads to a voltage pulse. Thermistors reach their highest sensitivity for high dR/dT . Two types of thermistors are most frequently used. One choice is a semiconductor thermistor, which consists of a small piece of highly doped and compensated Si or Ge and provides for low temperatures a steep rise of the resistance with decreasing temperature due

Figure 1 Schematic view of the operational principle of a calorimetric low temperature detector.

to the mechanism of hopping conductivity [3]. Alternatively a superconducting phase transition thermometer may be used, which consists of a thin film of a superconducting material, operated at the phase transition between the normal and the superconducting state.

The coupling k to the heat sink has to be chosen sufficiently weak to allow the temperature rise of the absorber to appear, thus the thermal decay time τ should be long as compared to the thermalization time. On the other hand, a compromise between the complete detection of the thermal signal and a short decay time τ may be found in cases where a high rate capability of the detector is needed.

Due to their operational principle the potential advantage of calorimetric detectors over conventional ionization detectors are:

- The smaller energy gap ω for the creation of an elementary excitation, leading to a better counting statistics. Whereas the energy gap for producing an electron-ion pair in a conventional semiconductor detector is of the order of a few eV, the excitation energy of thermal phonons is of the order of $\omega \leq 10^{-3} - 10^{-4}$ eV. This results in a potentially better energy resolution and lower energy threshold, both decreasing with $\sqrt{\omega}$.
- The more complete energy detection. For ionization detectors substantial losses in the ionization signal up to 60 - 80 % appear due to direct phonon creation and charge recombination (the latter effect is specially dominating for very heavy ions due to the extremely high charge densities). In contrast, for calorimetric detectors principally the whole deposited energy, besides small losses (see below), is finally transferred into heat after the decay of the initial electronic excitations.
- The flexibility in the choice of the absorber material. As compared to semiconductor detectors, a much wider variety of materials are expected to fulfill the above conditions for absorber materials. The absorber material may therefore be optimized with respect to radiation damage (mainly for heavy ion detectors) and absorption efficiency (mainly for x-ray detectors).
- The small noise power at low operating temperatures.

The theoretical limit of the intrinsic energy resolution, which may be achieved with calorimetric low temperature detectors under optimum conditions (optimum filtering, no loss processes), is determined [4] by the contributions of the

thermodynamical fluctuations of the energy content in the absorber (also called phonon noise) and the Johnson noise of the thermistor:

$$\Delta E = \xi \cdot \sqrt{k_B \cdot T^2 \cdot C} \quad . \quad (2.3)$$

Here k_B denotes the Boltzmann constant, and ξ is a dimensionless factor of the order of 1 - 3 which contains the information about the thermistor and the thermal coupling. Relation 2.3 corresponds to the thermodynamical limit. Note that for cases, where only the lattice contributes to the heat capacity, ΔE decreases with $\sqrt{T^5}$.

In special cases even for thermal detectors the energy resolution may be also affected by the statistical fluctuations of small amounts of energy which do not contribute to the thermal signal. Such loss processes are due to photons, escaping from the absorber, or long living excitations in the absorber, such as Frenkel pairs, metastable electronic states, etc., which are not thermalized within the time constant τ of the calorimeter. A detailed discussion and theoretical predictions for such effects are given in [5]. Especially for the case of calorimetric detectors for heavy ions, where the stopping process drastically affects the lattice structure of the absorber, we expect that the limit of the intrinsic resolution will be determined by such stopping processes, and thus by the solid state properties of the absorber material.

3 Calorimetric Detectors for Energetic Heavy Ions

Calorimetric low temperature detectors may become a powerful tool for nuclear physics experiments at heavy ion accelerators. They promise high energy resolution and relative insensitivity against radiation damage. In contrast, conventional heavy ion detectors, such as semiconductor detectors and ionization chambers, which operate on charge collection, provide relative energy resolutions for the heaviest ions of about $\Delta E/E \approx 10^{-2}$. They are limited by the high ionization density leading to recombination effects, short lifetimes of the detectors due to radiation damage and the statistics of the created electrons. High resolution magnet spectrographs are capable of achieving resolutions as good as 10^{-3} , but at the cost of very limited solid angle and thus detection efficiency.

When constructing calorimetric detectors for the detection of energetic heavy ions it has to be realized that the conditions and detector parameters with respect to absorber size, incident energy, energy resolution, amount of radiation damage, etc. are different by orders of magnitude from those of most other applications of such detectors [1, 2]. The GSI accelerator facilities provide heavy ion beams of all ion species in a wide energy range from kinetic energies around

Figure 2 The setup of a calorimetric detector with a semiconducting germanium thermistor is schematically displayed on the left side of the figure (for details see text). The corresponding $R(T)$ characteristics is shown on the right side.

the Coulomb barrier ($E \approx 5 - 20$ MeV/u) up to relativistic energies ($E \approx 100 - 2000$ MeV/u), corresponding to total energies of about 100 MeV up to some 100 GeV. Despite the large total energies the high specific energy loss of heavy ions in matter leads to relatively small ranges (0.5 - 20 mm in most cases, except for very light relativistic ions), thus allowing relatively small absorber volumes. This makes low temperature detectors, which reach their highest sensitivities for small absorber sizes, attractive for the detection of heavy ions. Due to the relatively high incident energies, already operating temperatures around 1.5 K will allow sufficient sensitivity of calorimetric detectors for heavy ions, thus reducing the demands on low temperature technology.

3.1 Design and Development of Calorimetric Heavy Ion Detectors

Within the present project two types of calorimetric detectors for heavy ions with different thermometers, one on the basis of a semiconducting germanium thermistor, and the other on the basis of a superconducting phase transition thermometer have been developed. A detailed discussion of the layout and the preparation of these detectors may be found in [6][7][8][9].

The first type of calorimeter is prepared on the basis of a germanium thermistor. It consists of a $3 \times 1 \times 0.5$ mm³ germanium crystal, heavily doped and compensated with indium (2×10^{17} atoms/cm³) and antimony (1×10^{17} atoms/cm³), which provides a strong temperature dependence of the resistance at low temperatures (see right part of fig. 2). At a typical operating temperature around $T = 1.7$ K the resistance is $R = 600$ k Ω with a $\frac{dR}{dT} = -2.6$ M Ω /K, corresponding to a thermistor sensitivity $\alpha = \frac{1}{R} \cdot \frac{dR}{dT} = -4.3$ K⁻¹. The germanium crystal was glued onto a copper support with GE-7031 varnish, as illustrated in the left part of fig. 2. The electrical contacts were formed by thermal pressure bonding of 25 μ m diameter gold wires. As absorber a sapphire crystal ($2 \times 1 \times 0.33$ mm³) was glued with GE-7031 varnish onto the germanium thermistor. Sapphire is

Figure 3 The setup of a calorimetric detector with a superconducting aluminum thermometer is schematically displayed on the left side of the figure (for details see text). The corresponding $R(T)$ characteristics is shown on the right side.

a suitable absorber material because of its low heat capacity ($\Theta_D \approx 1000$ K). The thermistor is biased by a battery through a load resistor ($R_L = 10$ M Ω). The voltage signal due to the impact of an ion is read out by a voltage sensitive preamplifier and further amplified by a shaping amplifier (shaping time: 100 μ s).

The second type of calorimeter consists of a superconducting thin aluminum film, which is operated in the region of the phase transition between the super- and the normalconducting state, and again a sapphire absorber. The setup, shown schematically in fig. 3 (left side), is very similar to the one for the germanium calorimeter (fig. 2), the only difference being that the aluminum thermistor is evaporated on top of the sapphire substrate. The thickness of the aluminum film of about 10 nm was adjusted to provide a narrow transition width for high sensitivity. In order to match the resistance of the microstrip to conventional preamplifiers, the aluminum film was patterned in a meander-like structure by photolithographic techniques. It consists of 51 connected strips of 10 μ m width and 1 mm length each. A typical observed $R(T)$ characteristics is displayed in fig. 3 (right side). The phase transition appears at a temperature of $T_c = 1.488$ K with a width of $\Delta T = 2.9$ mK and an impedance of $R(T_c) = 52$ k Ω , yielding a sensitivity of $\alpha(T_c) = \frac{1}{R} \frac{dR}{dT} = 404$ K $^{-1}$.

For both types of calorimeters the absorber thickness was adjusted to the individual experimental conditions, i.e. to the range of the heavy ions, by glueing additional sapphire absorbers onto the sapphire substrate, as illustrated in fig. 3.

3.2 Experimental Setup and Results on the Detector Performance

The experimental setup used for detector tests is shown in fig. 4. A pumped 4 He window cryostat, operated at temperatures between 1.2 K and 4.2 K, was used to cool down the detectors to their operating temperature. The detectors are

Figure 4 Schematic view of the experimental setup for heavy ion detection (for details see text).

Figure 5 Preamplifier signal due to the impact of a 11.4 MeV/u ^{136}Xe ion onto the germanium calorimeter.

mounted on a cold finger (see insert in fig. 4) which is temperature regulated by an electrical control circuit. A temperature stability of about 5 - 10 μK is reached. The cryostat was connected to a scattering chamber at one of the beamlines of the GSI facilities. Both, scattering chamber and cryostat, are mounted on a movable arm, allowing the detectors to be irradiated either by Rutherford scattered ions from thin target foils, or by the direct beam at reduced intensity.

In several measurements the detectors were tested with various heavy ion beams (^{20}Ne ... ^{238}U) with various energies ranging from 5 MeV/u up to 360 MeV/u. For both types of detectors excellent results were already obtained. In fig. 5 a preamplifier signal for the impact of a 11.4 MeV/u ^{136}Xe ion onto the germanium calorimeter is displayed. From the observed pulse height a temperature rise of the calorimeter of $\Delta T = 9.5$ mK at an operating temperature of $T = 1.7$ K is detected. The decaytime of about $\tau = 250$ μsec is determined by the thermal coupling to the heat sink and allows for count rates of about 1 kHz. An energy spectrum [6] for 11.6 MeV/u ^{209}Bi ions from the UNILAC linear accelerator, again taken with the germanium calorimeter, is displayed in fig. 6 (left side). The baseline noise was determined with a pulser, coupled to the preamplifier, to be $\Delta E = 2.2$ MeV. For the incident ^{209}Bi ions a clean spectrum showing a narrow gaussian peak with a width of $\Delta E_{FWHM} = 4.3$ MeV is obtained, which corresponds to a relative energy resolution of $\Delta E/E = 1.8 \cdot 10^{-3}$. This result already represents a considerable improvement if compared to conventional ionization detectors, in particular for such very heavy ions. Similar results are obtained for the superconducting aluminum calorimeter [7]. For 4.8 MeV/u ^{58}Ni ions an energy resolution of $\Delta E/E = 1.6 \cdot 10^{-3}$ was obtained.

In further test measurements the present detectors were also bombarded with relativistic heavy ions, obtained from the heavy ion synchrotron SIS. In fig. 6

Figure 6 Energy spectra obtained for 11.6 MeV/u ^{209}Bi ions with the germanium calorimeter (left side), and for 100 MeV/u ^{20}Ne ions with the aluminum calorimeter (right side). The relative energy resolutions achieved are $\Delta E/E = 1.8 \cdot 10^{-3}$ for the ^{209}Bi ions and $\Delta E/E = 1.9 \cdot 10^{-3}$ for the ^{20}Ne ions.

(right side) the results, taken with the aluminum calorimeter, are displayed. For 100 MeV/u ^{20}Ne ions a relative energy resolution of $1.9 \cdot 10^{-3}$ is obtained [9], again representing for these high energies a considerable improvement as compared to conventional detectors. Of special interest was a comparison, where data were taken [8] with two detectors of same type, but with different absorber sizes ($V = 6 \text{ mm}^3$ and $V = 121 \text{ mm}^3$). In spite of the large difference in heat capacity the energy resolution was comparable. This indicates that the resolution was not limited by the sensitivity of the detector, and provides perspectives for the design of large solid angle detector systems.

When summarizing all the results it turns out that the obtained relative energy resolutions of $1.6 - 1.9 \cdot 10^{-3}$ are very similar, independent on the ion species, the ion energy, the type of detector and absorber size. These findings indicate that the present limitation in energy resolution is not determined by the intrinsic detector resolution due to sensitivity, thermal or electrical noise contributions, heat capacity, statistics of the energy loss processes, etc. (see section 2), but most probably by the quality of the heavy ion beams from the UNILAC and SIS accelerators, namely the energy spread of these beams, which is expected to be of the order of $\Delta E/E \approx 1 - 2 \cdot 10^{-3}$. Consequently, in a recent experiment [9] the detectors were tested with cooled heavy ion beams, extracted from the storage ring ESR. The energy spread of the beam was determined from Schottky spectra of the circulating beam to be better than $\Delta E/E = 2.4 \cdot 10^{-4}$. The resulting energy spectrum, obtained for the aluminum calorimeter, is displayed in fig. 7. For a 360 MeV/u ^{238}U beam a relative energy resolution of $\Delta E/E = 1.1 \cdot 10^{-3}$ was achieved, which represents the up to date best result for heavy ions.

The question whether with this result the intrinsic limit of the detector resolu-

Figure 7 Energy spectrum for a cooled ^{238}U beam with $E = 360$ MeV/u which was extracted from the ESR storage ring. The obtained relative energy resolution is $\Delta E/E = 1.1 \cdot 10^{-3}$.

Figure 8 Energy spectrum observed for scattering of a 100 MeV/u ^{20}Ne beam from a lead target. The bump due to the excitation of the giant resonance in lead is indicated by the label GR.

tion is reached remains open at present. It may be answered by further systematic investigations of the energy resolution dependent on the ion species and on the absorber materials. Such investigations, which are planned for the future, may also provide quantitative results on the solid state properties of the absorber materials, as the amount of lattice imperfections due to Frenkel pairs, radiation damage, and of metastable electronic states, etc. are expected to finally limit the intrinsic energy resolution of calorimetric detectors for heavy ions.

3.3 Applications of Calorimetric Heavy Ion Detectors

The excellent performance of calorimetric heavy ion detectors which was already obtained opened the possibility for a first application in a heavy ion experiment [9]. The excitation of the giant resonance, which is a collective vibrational mode of nucleons in nuclei [10], was investigated for the lead nucleus by separating inelastically from elastically scattered ions in the spectrum for scattering of 100 MeV/u ^{20}Ne ions from a lead target. In contrast to standard detection techniques [10], where all decay products of the giant resonance have to be detected, thus requiring a rather extended and complicated experimental setup, the present method allows a relatively simple setup, but requires high energy resolution. In fig. 8 the measured energy spectrum for ^{20}Ne ions, scattered from a lead target at a scattering angle of $\Theta_{\text{lab}} = 3^\circ$, is displayed. Below the elastic peak a bump appears which is attributed to the excitation of the giant dipole resonance in the lead nuclei. The positions and the intensities of the two peaks were extracted by gaussian fits. The resulting excitation probability and excitation energy are within the errors in good agreement with theoretical predictions [9]. In future

we aim to continue such investigations, the excitation of single giant resonances of different multipolarities, and especially of higher order modes, so called multiphonon giant resonances, being of particular interest [10].

Besides this example, calorimetric detectors bear, due to their excellent performance, which may be even improved in future, a large potential for possible applications in basic and applied heavy ion research. A few examples are:

- Elastic and inelastic nucleus-nucleus scattering: Here high energy resolution is required to isolate elastic scattering from low lying excited states, or vice versa. The physics motivation is the precise determination of nuclear potentials (example: low energy heavy ion Mott scattering, such as $^{208}\text{Pb} + ^{208}\text{Pb}$, to investigate effects of the QED), or the investigation of various excitation modes in nuclei (examples: giant resonances, as discussed above, multiphonon excitation of low lying excited states, such as the 3^- state in ^{208}Pb).
- Experiments with radioactive beams: The investigation of nuclear reactions with radioactive beams requires isotope identification of the beam-like reaction products. With a relative energy resolution of $\Delta E/E = 1 \cdot 10^{-3}$ a mass identification via an energy / TOF measurement will allow the separation of masses up to the heaviest isotopes, and replace the standard $B \cdot \rho$ / TOF method with solid angle limiting magnet spectrometers. An application of calorimetric detectors for the VAMOS spectrometer, presently under construction at the SPIRAL facility at GANIL, France is planned.
- Production and identification of heavy elements: In such experiments [11] calorimetric detectors may be applied for isotope identification (see above), and for high resolution detection of the fission fragments.
- Monitor for the energy spread of ion beams: A possible application could be the investigation of the energy distribution after heavy ion channeling in crystals.

4 Calorimetric Detectors for Hard X-Rays

Besides the detection of heavy ions the concept of calorimetric detectors also provides considerable advantage for x-ray spectroscopy. Whereas the worldwide activities on calorimetric heavy ion detectors are still very scarce, a lot of activities with various motivations and potential applications for x-ray detectors exist [1][2]. Most of these developments are restricted to the energy range $E_\gamma \leq 10$ keV. Relativistic heavy ion beams, now available at GSI Darmstadt, allow to prepare highly stripped ion beams of very heavy ions with correspondingly high electronic transition energies of the order of $E_\gamma = 50 - 100$ keV. Consequently, there is a demand for high resolution detectors for such "hard" x-rays.

Figure 9 Level scheme for hydrogen like U^{91+} according to various atomic models. The numbers on the right indicate the electronic binding energies.

4.1 Motivation: Precise Determination of the Lamb Shift in Hydrogen Like Very Heavy Ions

About fifty years ago it became evident that for small distances between electric charges the classical Coulomb interaction potential is not completely correct. The precise experimental test of the theoretical predictions by quantum electrodynamics (QED), then developed, is still - at least for high Z systems - one of the outstanding and most challenging problems of atomic physics. In the hydrogen atom, or in hydrogen like ions, the QED corrections give rise to the so called Lamb shift, which is a small deviation of the binding energies from those predicted by the relativistic Dirac-Coulomb energy (see fig. 9). Whereas in light systems, where QED predictions were confirmed to a high precision, the higher order effects are almost negligible, they increase strongly with higher Z . On the other hand, the theoretical predictions of QED, which are usually performed in series expansions in $Z\alpha$ (α being the fine structure constant), become most critical for the heaviest systems, where $Z\alpha$ approaches values close to unity. Therefore a precise determination of the Lamb shift in hydrogen like very heavy ions represents one of the most sensitive tests of QED in strong electromagnetic fields, not accessible otherwise. The level scheme of the U^{91+} ion is displayed in fig. 9. The binding energy of the $1s$ -energy level is about -132 keV, thus yielding transition energies for the Lyman- α lines of about 100 keV. The $1s$ Lamb shift is predicted to be $L_{1s} = 463$ eV.

To determine the $1s$ Lamb shift of heavy ions the transition energies of the Lyman- α transitions are to be measured with high accuracy and compared with theoretical predictions from the Dirac theory. Such experiments are performed at the storage ring ESR [12][13]. A beam of bare U^{92+} ions is injected and interacts with an internal gas target. This may lead to the capture of one electron and to the population of a $2p$ state, which promptly decays to the $1s$ state. The emitted Lyman- α x-rays are detected by detectors surrounding the internal target. The latest experimental results on the $Z = 79$ and $Z = 92$ systems are compared with theoretical predictions in [12]. The experimental results agree well with the theoretical predictions, but the experimental errors (± 13 eV) are about one order of magnitude larger than the theoretical ones (± 1 eV). Thus the

Figure 10 Schematic view of one pixel of the calorimetric x-ray detector.

Figure 11 Schematic view of the side arm of the $^3\text{He}/^4\text{He}$ dilution refrigerator (for details see text).

experimental accuracy has to be improved considerably for a more stringent test of QED. One major contribution to the experimental error is the poor energy resolution of $\Delta E \approx 800$ eV obtained with Ge-detectors, which must be improved to reach an absolute accuracy of about $\Delta E = \pm 1$ eV. This was the motivation for the design of a low temperature calorimetric detector for the present application.

4.2 Development of Calorimetric X-Ray Detectors and First Results

As compared to calorimetric detectors for heavy ions, appropriate detectors for x-rays with essentially the same detection principle are developed. On the other hand, due to the by orders of magnitude smaller incident energies, x-ray detectors are to be operated at considerably lower temperatures ($T \leq 100$ mK), and are drastically limited in the absorber volume in order to reach sufficient sensitivity. To meet the experimental conditions required by the Lamb shift experiment the calorimetric detector should, among others [13], fulfill the following constraints:

- a relative energy resolution of $\Delta E/E \leq 1 \cdot 10^{-3}$ for $E_\gamma = 50 - 100$ keV,
- a total detection efficiency (including detector solid angle) of $\geq 10^{-6} - 10^{-5}$, which may be reached with a photopeak efficiency of $\geq 30\%$ and an active detector area of ≥ 100 mm².

The present detector design was developed in close collaboration with D. McCammon et al., Univ. Madison, Wisconsin, USA and S.H. Moseley, C.K. Stahle et al., NASA, Goddard Space Flight Center, Greenbelt, USA. Both research groups work since many years on the development of low temperature microcalorimeters for x-ray astronomy in the energy range $E_\gamma = 1 - 10$ keV, and have already obtained excellent results [14]: $\Delta E = 7.3$ eV for $E_\gamma = 5.9$ keV. The detector modules for the present setup consist of silicon thermistors, which are used as thermometers, and of x-ray absorbers glued on the top of the thermistors by

Figure 12 Energy spectrum obtained with a calorimetric detector at an operating temperature of 60 mK with a $0.3 \text{ mm}^2 \times 66 \text{ }\mu\text{m}$ Sn absorber for 59.6 keV photons. An energy resolution of $\Delta E_{FWHM} = 121 \text{ eV}$ for the photopeak (right side) and of $\Delta E_{FWHM} = 72 \text{ eV}$ for the K_{α} escape lines (left side) is obtained.

means of an epoxy varnish. A schematic view of a detector pixel is displayed in fig. 10. The pixel is made from a wafer of silicon containing an implanted thermistor, the implanted leads and the support beam providing the thermal isolation. Thermistor arrays [15], consisting of 36 pixels each, are provided from the collaborating groups from Madison and Goddard. The final detector concept foresees three calorimeter arrays, the active area of 1 pixel being about 1 mm^2 .

For the Lamb shift measurement the experimental setup was optimized with respect to energy resolution and detection efficiency for hard x-rays at the experimental area of the ESR. In order to reach sufficient photopeak efficiency, the absorber should be a high Z material and should have a volume of $V \geq 1 \text{ mm}^2 \times 40 \text{ }\mu\text{m}$. Systematical tests of suitable absorber materials, fulfilling also the conditions of low heat capacity, as well as rapid and complete thermalization, were recently performed [16][17]. Promising materials are Sn, HgTe and Re. To obtain a reasonable detection solid angle the detector arrays have to be located as close as possible to the interaction zone at the internal target of the ESR. To realize this concept a special $^3\text{He}/^4\text{He}$ -dilution refrigerator with a side arm which fits to the internal target geometry was designed in cooperation with Oxford Instruments. A schematic view of the system is displayed in fig. 11. The detector arrays are mounted on the cold finger at the end of the side arm and can be irradiated through a system of aluminum coated mylar windows. In order to suppress low-frequency microphonics the first amplifier stage was positioned close to the detectors inside the side arm of the cryostat. It consists of cooled FET's, operated at a temperature of about 125 K, which have the purpose to reduce the relatively high impedance of the detectors. In agreement with the specifications the cryostat reaches a base temperature of 11.5 mK, and a cooling power of $400 \text{ }\mu\text{W}$ at 11.5 K. The operating temperature of the detectors may be chosen between $T = 50 \text{ mK}$ and $T = 100 \text{ mK}$.

The detector performance presently achieved is already close to fulfill the

demands of the Lamb shift experiment. The best results were obtained with Sn as absorber material. The energy spectrum obtained for a detector with a $0.3 \text{ mm}^2 \times 66 \text{ }\mu\text{m}$ Sn absorber for 59.6 keV photons, provided by an ^{241}Am source, is displayed in fig. 12. For the photopeak at 59.6 keV an energy resolution of $\Delta E_{FWHM} = 121 \text{ eV}$ is obtained, whereas for the K_α escape lines, which may also be used for an accurate energy measurement of higher energy x-rays, a resolution of $\Delta E_{FWHM} = 72 \text{ eV}$ was measured. These results may be compared to the theoretical limit of the energy resolution for a conventional semiconductor detector which is about $\Delta E \approx 380 \text{ eV}$ for 60 keV photons .

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