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Application of Low Temperature Calorimeters for the Detection of Energetic Heavy Ions

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Abstract

The energy sensitive detection of energetic heavy ions with calorimetric low temperature detectors is investigated. The temperature readout was done with an aluminum transition edge thermometer operated at $T \approx 1.5$K. For ^{20}Ne-ions with an energy of E = 100MeV/u from the SIS accelerator at GSI Darmstadt the best energy resolution obtained was $\Delta E/E = 1.9 \times 10^{-3}$. This value corresponds to the energy spread of the ion beam of the SIS.

In a first application of such detectors the excitation of the giant resonance in lead nuclei via the reaction ^{nat}Pb(^{20}Ne, ^{20}Ne')^{nat}Pb* was investigated by separating inelastically from elastically scattered ^{20}Ne-ions in the energy spectrum. At a scattering angle $\Theta_{Lab} = 3°$ the excitation energy and the strength of the giant resonance were found to be in good agreement with theoretical predictions.

In a first test with an extracted cooled ^{238}U-beam with an energy of E = 360MeV/u from the storage ring ESR with an intrinsic beam energy spread of $\Delta E/E \leq 2 \times 10^{-4}$ an energy resolution of ΔE = 97MeV ($\Delta E/E = 1.1 \times 10^{-3}$) was measured. The baseline noise was ΔE = 17MeV. Further improvement of the energy resolution seems possible.

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I. Introduction

Calorimetric low temperature detectors may be a powerful tool for nuclear physics experiments at heavy ion accelerators. They promise high energy resolution and insensitivity against radiation damage. High energy resolution is of interest for experiments at the GSI storage ring ESR [1]. Due to beam cooling the stored beam can have a relative energy spread $\Delta E/E$ as good as 10^{-4} to 10^{-6}. In combination with a thin internal gas target experiments with very high energy resolution are possible.

The detectors discussed here were tested at the GSI heavy ion accelerators. The results with beams from the universal linear accelerator UNILAC (E = 1 - 20MeV/u) were presented in ref.2. The present contribution will focus on detector tests at the heavy ion synchrotron SIS (E = 100 - 2000MeV/u) and on a first experiment with calorimetric detectors performed at this accelerator. Furthermore, results of a recent detector test are presented where such detectors were irradiated with an extracted cooled beam from the storage ring ESR.

II. Detector Design and Experimental Setup

When constructing calorimetric detectors for the detection of energetic heavy ions it has to be realized that the conditions are different from most other applications of such detectors. The total energies of the ions at the GSI accelerators are between about 100MeV up to some 100GeV. Despite the high energies the range of these ions in matter is relatively small due to the high ionization density, thus allowing relatiely small absorber volumes.

The detectors discussed here use a thin film superconducting aluminum strip thermometer operated at $T \approx 1.5K$. The thermometer is evaporated onto a sapphire substrate of 330µm thickness and an area of approximately $2.5 \times 2.5mm^2$. Using photolithographic techniques the 10nm thick aluminum film is etched to a 10µm wide strip of a total length of 52mm in a meanderlike structure. At the transition temperature $T_C \approx 1.5K$ this leads to a resistance $R \approx 25k\Omega$ sufficiently high for conventional preamplifiers to be used for signal readout. The width of the transition was typically between 3mK and 10mK. For ion energies below 20MeV/u the substrate suffices as absorber. For the higher energies at SIS an additional cylindrical sapphire crystal is glued onto the substrate with Ge7031-varnish (see fig.1). The ions penetrate the absorber along the axis of the cylinder. The thickness of the absorber is adjusted to the range of the ions which have to be detected. A more detailed discussion of the layout and the preparation of the detectors can be found in ref.3.

For irradiation of the detectors with heavy ions we use a ^{4}He-window cryostat operated at temperatures between 1.2K and 4.2K. The detectors are mounted on a coldfinger which is temperature regulated by an electrical control circuit. The short timescale (5min) temperature stability was measured to be better than 5µK. Part of the time long-term temperature drifts up to 50µK/h were observed. During the measurements at the SIS accelerator, the ions entered the cryostat via two thin aluminum foils, one at 77K and one at 1.2K with a thickness of $20mg/cm^2$ each.

The experimental setup at the SIS accelerator allows the detector to be irradiated directly with the heavy ion beam (reduced in intensity), or to be hit by ions scattered from a target at scattering angles up to $\Theta_{Lab} = 5°$. In the latter case the ion rate seen by the detector can easily be adjusted by changing the scattering angle. Due to the small scattering angles the primary beam had to be dumped near the cryostat. For energy calibration we used energy degraders, i.e. metal foils of known thickness. The energy loss in these foils was calculated using data from ref.4.

III. Detector Tests with Beam from the Heavy Ion Synchrotron SIS

At the SIS accelerator several detectors were irradiated with ^{20}Ne-ions with an energy of E = 100MeV/u which were elastically scattered from a lead target. Two energy spectra accumulated with different detectors are displayed in fig.2. The best energy resolution $\Delta E = 6.3$MeV ($\Delta E/E = 3.2\times10^{-3}$) was obtained with a detector with an absorber of 1mm diameter and 5mm length, leading to a total detector volume of 6mm^3 including the thermometer substrate. For a second detector with an absorber of 4mm diameter and 9.5mm length an energy resolution of $\Delta E = 8.3$MeV ($\Delta E/E = 4.2\times10^{-3}$) was obtained. In spite of the large difference in heat capacity (about a factor of 20) the obtained energy resolution in both cases was comparable. Simultaneously to the pulse height spectra, random baseline noise spectra were accumulated. For both detectors the width of the baseline noise peak was about 10 times smaller than the width of the peak due to the scattered ions. These results indicate that the energy resolution is not yet limited by thermal or electrical noise contributions which provides perspectives for the design of large solid angle detector systems.

The question of the limiting factor for the presently obtained energy resolution cannot be definitely answered, since up to now there exists no estimate for the pulse height fluctuations due to energy loss processes in the absorber. On the other hand the energy spread of the SIS beam is not very well known. It is expected to be between $\Delta E/E = 1\text{-}2\times10^{-3}$. Contributions from the energy straggling of the ions in the target (50mg/cm^2 Pb) and the windows of the cryostat (2×20mg/cm^2 Al) are estimated to be $\Delta E \approx$ 2MeV. In a recent detector test with the same configuration but with thinner target and windows (20mg/cm^2 and 2.8mg/cm^2, respectively) an energy resolution of $\Delta E = 3.8$MeV ($\Delta E/E = 1.9\times10^{-3}$) was obtained [5]. This results points to the energy straggling as limiting factor under the present conditions, but further investigation is needed.

IV. Investigation of the Giant Resonance in Lead Nuclei

The energy resolution obtained in the detector tests describes above opened the possibility to perform a first heavy ion experiment using calorimetric detectors. The cross section for the excitation of the giant resonance in lead-nuclei by ^{20}Ne-projectiles (E=100MeV/u) was investigated. Theoretical predictions indicate that the modes prominently exited in this system are the isovector giant dipole resonance (IVGDR), the isoscalar giant quadrupole resonance (ISGQR) and the isoscalar giant monopole resonance (ISGMR). The calculations were performed with the code DEIKO developed by C. Bertulani using a formalism described in ref. 6. The expected mean excitation energies (widths) of these resonance modes are 13.5(4.0)MeV, 10.8(2.2)MeV and 13.9(2.9)MeV, respectively [7,8]. Since a beam particle which has excited a giant resonance in a target nucleus essentially looses an energy corresponding to the excitation energy, the excitation of the resonance can be detected in the total energy spectrum of the scattered ^{20}Ne-projectiles.

In fig.3 an energy spectrum of ^{20}Ne-ions (E = 100MeV/u) scattered from a lead target (50mg/cm^2) at a scattering angle of Θ_{Lab} = 3° is displayed. The spectrum was accumulated during 8 hours with beam on the target for about 4 hours. Below the elastic peak (energy resolution ΔE = 6.9MeV) a bump appears which is attributed to the excitation of the giant resonance in the lead nuclei. The shoulder at the high energy side of the spectrum is most probably due to pile up, as the relative strength of this shoulder varied with the beam intensity. Further investigation of this effect is planned. The positions and the intensities of the two peaks were extracted by gaussian fits. The excitation energy of the giant resonance was deduced from the difference in peak positions to be E* = 14.0(1.2)MeV. The excitation probability $\sigma_{GR}/\sigma_{elastic}$ corresponds to the ratio of the intensities of the two peaks. From the experiment it was deduced to be $\sigma_{GR}/\sigma_{elastic}$ = 1.7(0.3)%. Both values are close to the theoretical predictions E* = 13.1MeV and $\sigma_{GR}/\sigma_{elastic}$ = 1.4 % calculated from the cross sections and excitation energies of the three giant resonance modes mentioned above, and from the cross section for elastic scattering calculated with the same code.

V. First Detector Test with Cooled Heavy Ion Beams from the Storage Ring ESR

Recently calorimetric detectors were tested for the first time with a cooled heavy ion beam extracted from the GSI storage ring ESR. During a relatively short beamtime the detectors were tested with ^{238}U-ions with E = 70MeV/u and E = 360MeV/u. The experimental setup was the same as described above but the window of the cryostat was changed. Because of the large energy loss in matter for such very heavy ions leading to a large energy straggling, the metal foils were replaced by a system of 4 narrow (1.5mm ×30mm) collimators. For the 70MeV/u uranium ions we obtained an energy resolution of ΔE = 23MeV ($\Delta E/E = 1.4\times10^{-3}$) with both, a detector with a superconducting transition edge thermometer (absorber size: ∅4mm, length 9.5mm) and a detector with a germanium thermometer as described in ref. 9 (absorber size: ∅3mm, length 6mm). The baseline noise was ΔE = 12MeV and ΔE = 5MeV, respectively. For the higher beam energy only the detector with the transition edge thermometer was able to stop the ions. The energy resolution obtained here was ΔE = 97MeV ($\Delta E/E = 1.1\times10^{-3}$) with a slightly increased baseline noise of ΔE = 17MeV. In both cases the energy spread of the beam inside the storage ring was determined from Schottky spectra of the circulating beam to be better than $\Delta E/E$ = 2×10^{-4}. The extraction process is assumed not to increase the energy distribution, but this has to be confirmed in future experiments. For the present experiment the beam resolution did most probably not limit the measured energy resolution because we achieved only a poor temperature stability during this measurement.

We conclude that the energy resolution $\Delta E/E = 1.1\times10^{-3}$ obtained for ^{238}U-ions with an energy of E=360MeV/u is already an improvement compared to conventional heavy ion detectors. Further improvement seems to be possible. In order to investigate the intrinsic limitation for the energy resolution of the detectors we plan to perform further test measurements with extracted high quality ESR beams.

Acknowledgements

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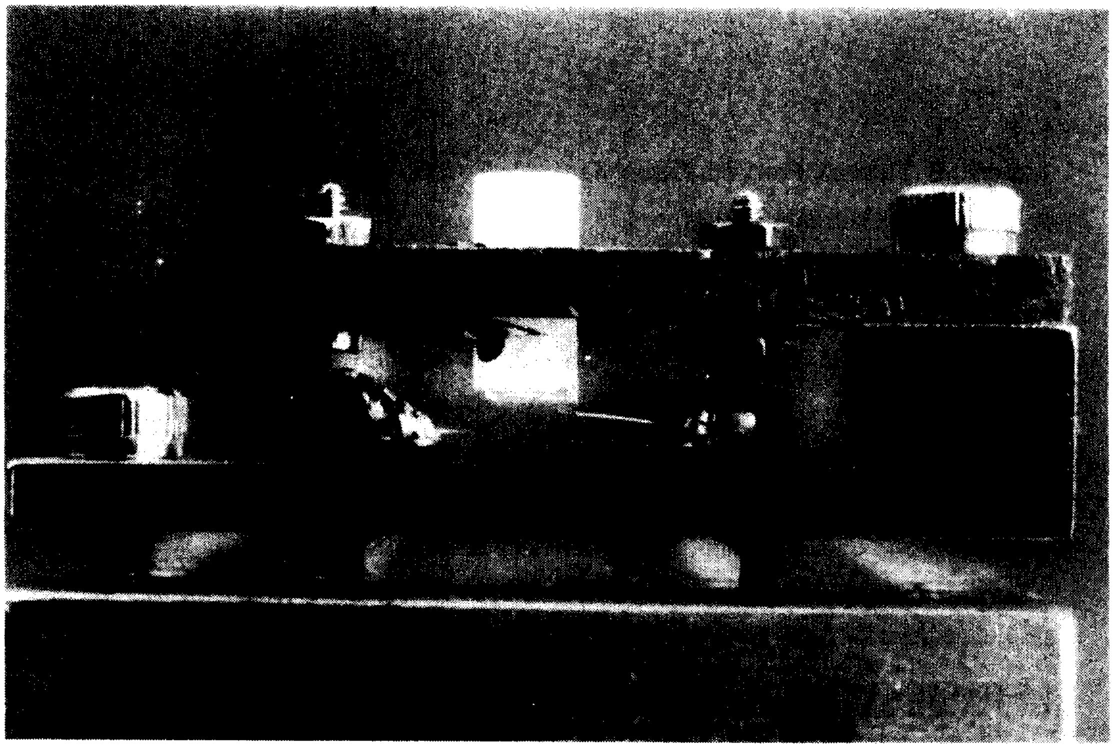

Fig.1: Photo of a calorimetric low temperature detector for relativistic heavy ions mounted on a copper support. The cylindrical sapphire absorber (diameter: 3mm, length: 6mm) is irradiated with heavy ions from above. Ist thickness is sufficient to stop ^{20}Ne-ions with energies up to 120MeV/u. The transition edge thermometer is glued onto the bottom side of the absorber.

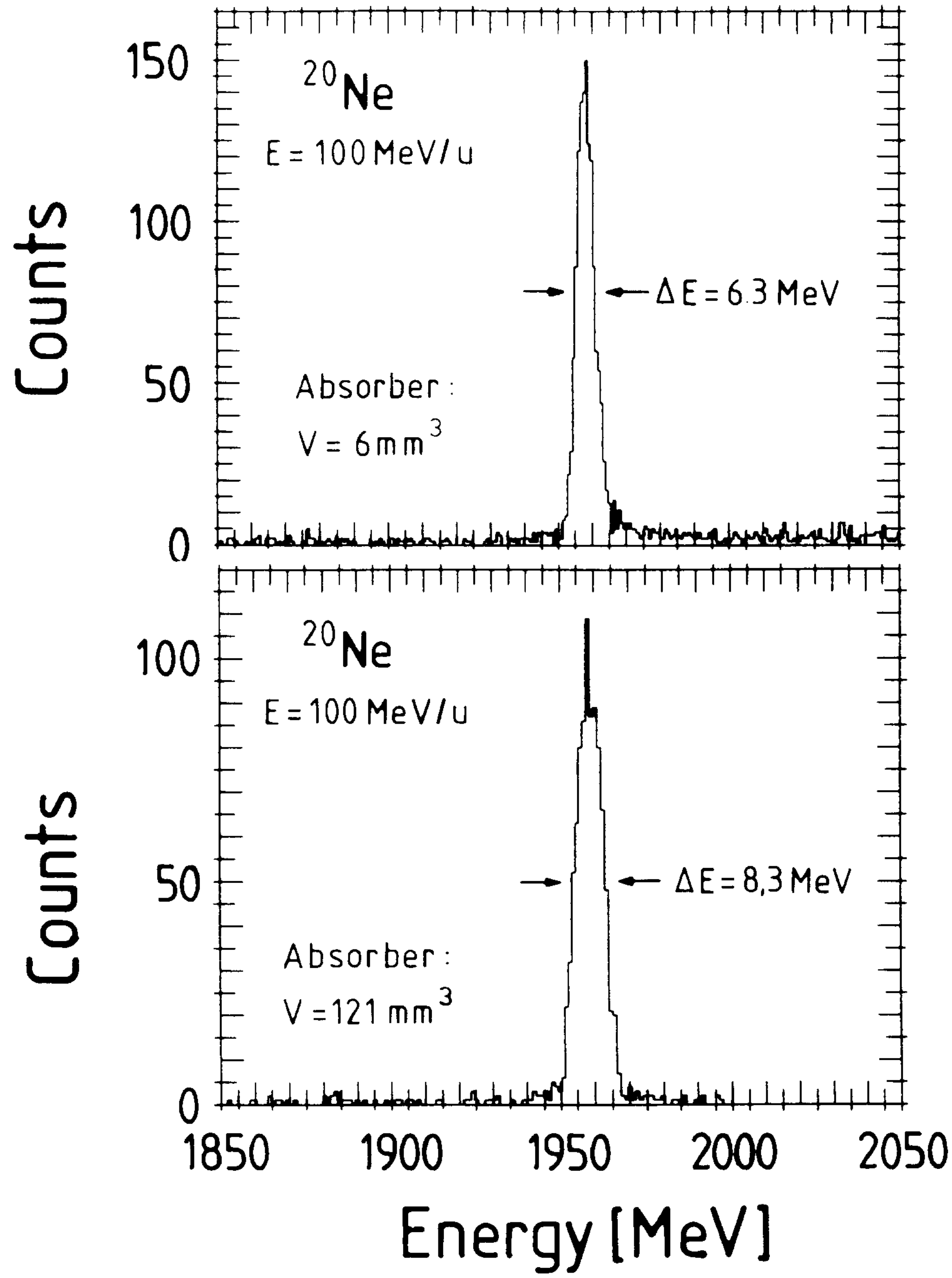

Fig.2: Energy spectra obtained for 100MeV/u ^{20}Ne-ions using transition edge calorimeters with different volumes of the sapphire absorbers (upper part: V=6mm^3, lower part: V=121mm^3). The energy resolutions observed correspond to relative resolutions of ΔE/E = $3.2 \cdot 10^{-3}$ (upper part) and ΔE/E = $4.2 \cdot 10^{-3}$ (lower part).

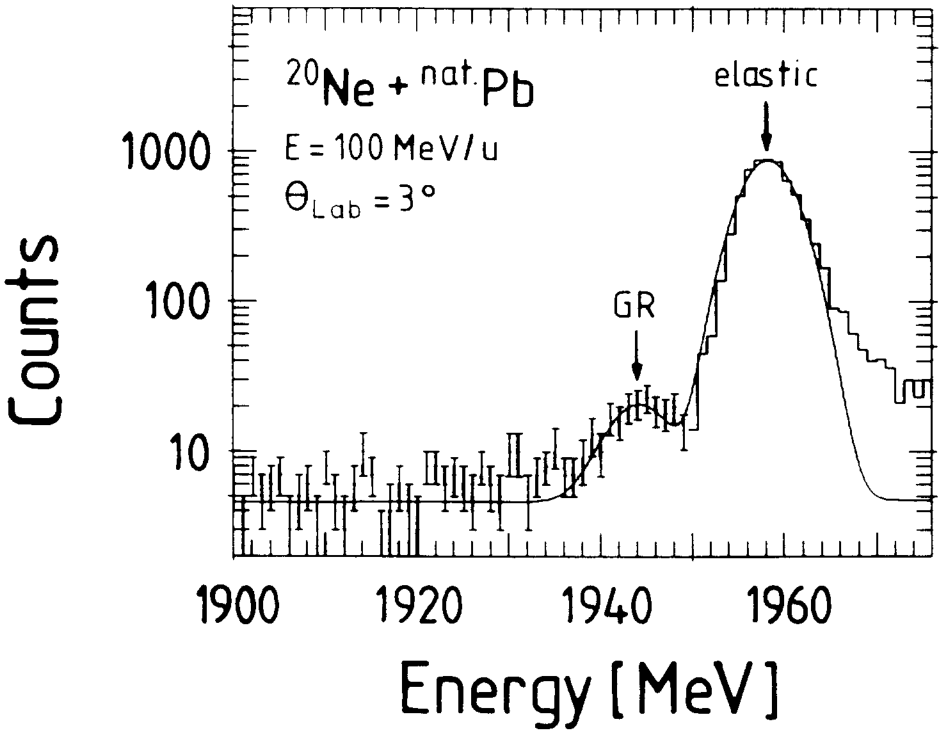

Fig.3: Energy spectrum observed for scattering of a 100MeV/u ^{20}Ne-beam from a lead-target at Θ_{Lab} = 3°. The position of the bump due to the excitation of the giant resonance in lead is indicated by the label „GR". The solid line represents the result of gaussian fits to the data.