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Cryogenic Fast-Neutron Spectrometer

Thomas Niedermayr*
Lawrence Livermore National Laboratory
7000 East Avenue, Livermore CA 94550, USA
E-mail: niedermayr1@llnl.gov

Ionel Dragos Hau
Lawrence Livermore National Laboratory
7000 East Avenue, Livermore CA 94550, USA
E-mail: hau2@llnl.gov

Stephan Friedrich
Lawrence Livermore National Laboratory
7000 East Avenue, Livermore CA 94550, USA
E-mail: friedrich1@llnl.gov

Arnold Burger
Fisk University
1000 17th Ave. N., Nashville TN37208, USA
E-mail: aburger@fisk.edu

Uptal Roy
Fisk University
1000 17th Ave. N., Nashville TN37208, USA
E-mail: uroy@fisk.edu

Zane W. Bell
Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge TN37831, USA
E-mail: bellzw@ornl.gov

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* Speaker

We are developing high energy resolution gamma-ray and neutron spectrometers based on low temperature calorimetry for nuclear science and non-proliferation applications. Cryogenic neutron spectrometers offer very high energy resolution combined with high efficiency. Additionally, the response function is simple and the instrument is transportable. We are currently developing a fast neutron spectrometer with 0.1% energy resolution at 1 MeV neutron energy with an efficiency of 1%. The detector is composed of a cubic centimeter sized absorber which converts the neutron kinetic energy into heat through the (n,alpha) neutron capture reaction in ^{6}Li or ^{10}B. A very sensitive superconducting thermometer measures the heat rise following single neutron absorption. The detector is operated at 0.1 K at the end of a cold finger inside an adiabatic demagnetization refrigerator. We present experimental data on the development of our cryogenic fast neutron spectrometer showing excellent energy resolution with high efficiency.

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1. Introduction

Cryogenic microcalorimeter detectors operating at temperatures around ~0.1 K have been developed for the last two decades, driven mostly by the need for ultra-high energy resolution (<0.1%) in X-ray astrophysics and dark matter searches [1]. The Advanced Detector Group at Lawrence Livermore National Laboratory has developed different cryogenic detector technologies for applications ranging from X-ray astrophysics to nuclear science and non-proliferation. In particular, we have adapted cryogenic detector technologies for ultra-high energy resolution gamma-spectroscopy [2] and, more recently, fast-neutron spectroscopy [3].

Microcalorimeters are essentially ultra-sensitive thermometers that measure the energy of the radiation from the increase in temperature upon absorption (fig. 1). They consist of a sensitive superconducting thermometer operated at the transition between its superconducting and its normal state, where its resistance changes very rapidly with temperature such that even the minute energies deposited by single radiation quanta are sufficient to be detectable with high precision.

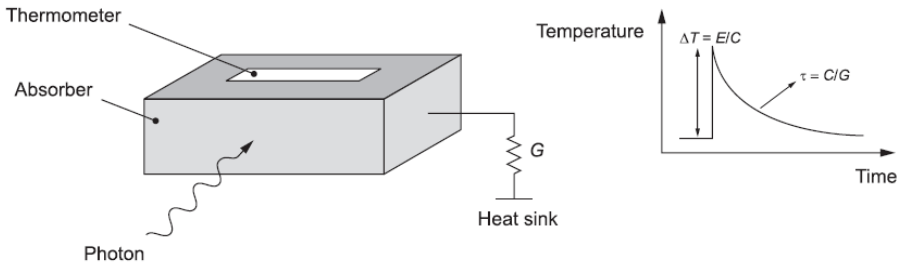

Figure 1: Basic operating principle of a microcalorimeter. An absorber with a heat capacity C is connected to a very sensitive thermometer. When a photon or particle of energy E is absorbed, the thermometer measures the temperature rise of the absorber. The heat then flows into the heat sink through a thermal link with thermal conductivity G.

The energy resolution of microcalorimeters is fundamentally limited by thermal fluctuations to $\Delta E_{FWHM} \approx 2.355\ (k_B T^2 C_{abs})^{1/2}$, where k_b is the Boltzman constant and C_{abs} is the heat capacity of the absorbing material. This allows an energy resolution below 1 keV for neutron spectrometers for an operating temperature of $T \approx 0.1$ K . The ΔE_{FWHM} does not depend on the energy of the incident photon or particle. This expression is equivalent to the familiar $(F\varepsilon E_\gamma)^{1/2}$ considering that an absorber at temperature T contains a total energy $C_{abs}T$, and the associated fluctuation are due to variations in uncorrelated (F=1) phonons ($\varepsilon = k_B T$) dominated by the background energy $C_{abs}T >> E_\gamma$.

2. Neutron spectrometer development

Cryogenic neutron spectrometers offer very high energy resolution combined with good efficiency. Additionally, the response function is simple and the instrument is transportable. We are currently developing fast neutron spectrometers with 0.1% energy resolution at 1 MeV

neutron energy with an efficiency of > 1% (for 1 cm^3 92% enriched ^{6}LiF crystals). Our fast-neutron spectrometers use cubic millimeter sized boron-based and cubic centimeter sized ^{6}LiF absorbers with high sensitivity thermistors based on Mo/Cu multilayers.

In order to perform neutron spectroscopy with a microcalorimeter, we made a small volume test detector with a 1 mm^3 TiB_2 absorber [3]. As shown in fig. 2, an energy resolution of 5.5 keV FWHM was achieved for 2.79 MeV deposited in ^{10}B by thermal neutron capture. The decreased energy resolution of 10.5 keV FWHM on the 2.31 MeV line is due to the Doppler broadening of the first excited state of ^{7}Li which can be resolved due to the high energy resolution of the instrument. The liftetime of the first excited state (478 keV) of ^{7}Li was thus calculated for the first time based on the broadening of $^7Li^*$ line instead of on the broadening of the emitted gamma-ray line [4].

To increase the efficiency for fast-neutron spectroscopy, a larger absorber is required. To conserve the high energy resolution $\Delta E_{FWHM} \approx 2.355\ (k_B T^2 C_{abs})^{1/2}$, the operating temperature and the heat capacity of the absorber must remain constant, as compared with the 1 mm^3 TiB_2 detector. Both criteria can be satisfied by using a LiF absorber. At 0.1 K, the heat capacity of 2 cm^3 of LiF has the *same heat capacity* as 1 mm^3 of TiB_2 because TiB_2 is a metal while LiF is an insulator. A 3 fold increase in efficiency is thus achieved without changing the microcalorimeter thermal parameters. In order to further increase the efficiency, a 92% enriched ^{6}LiF crystal was grown, resulting in a factor 13 increase as compared to natural LiF. A further advantage to using LiF is the simplified reponse function since there is only one decay channel for the neutron capture reaction. Since Q(^{6}Li) = 4.79 MeV, discrimination against gamma-events is straightforward as they usually deposit less that 4.79 MeV in the low Z ^{6}LiF absorber. Deconvolution of the neutron spectrum is made easy because the response function is not affected by edge or geometric effects but only depends on the relevant neutron cross sections.

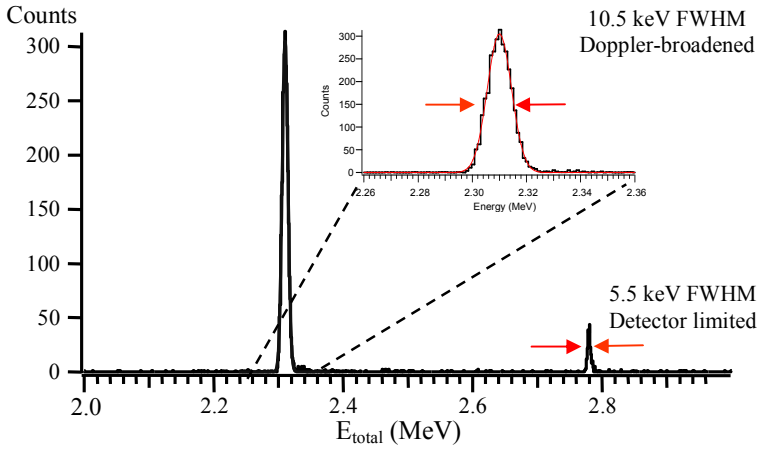

Fig. 2: Thermal neutron spectrum from a cryogenic spectrometer with a TiB_2 absorber. The two peaks correspond to the two different capture reactions in ^{10}B. The energy resolution of ~5 keV is sufficient to show the 10.5 keV Doppler-broadening due to the finite life time of the first excited state in $^7Li^*$.

A detector based on a small (0.2 cm^3) 92% enriched ^{6}LiF absorber was tested with a ^{252}Cf and ^{210}Po source. The resulting spectrum is shown in fig. 3. The large peak on the left hand side is due to low energy neutrons. This peak is the dominating feature in the spectrum due to the high absorption efficiency at low neutron energies. The broad peak on its right hand side is due to the increased absorption efficiency at 241 keV because the neutron capture reaction has a resonance at this energy. The alpha peak at 5.30 MeV shows the characteristic asymetry due to the alpha source thickness. The energy resolution is 52 keV as deduced from the alpha peak. The reduced energy resolution of 52 keV as compared to the 5.5 keV of the TiB_2 based detector is attributed to the reduced thermal coupling between the absorber and thermistor in the LiF detector design which is different from the TiB_2 detector design due to the much larger absorber volume. The energy resolution is not limited by phonon statistics (~1 keV FWHM), electronic noise (~7 keV FWHM) or position dependence (~20 keV). In order to improve the energy resolution, a new mounting design is in development in order to increase the thermal coupling between the absorber and the thermistor.

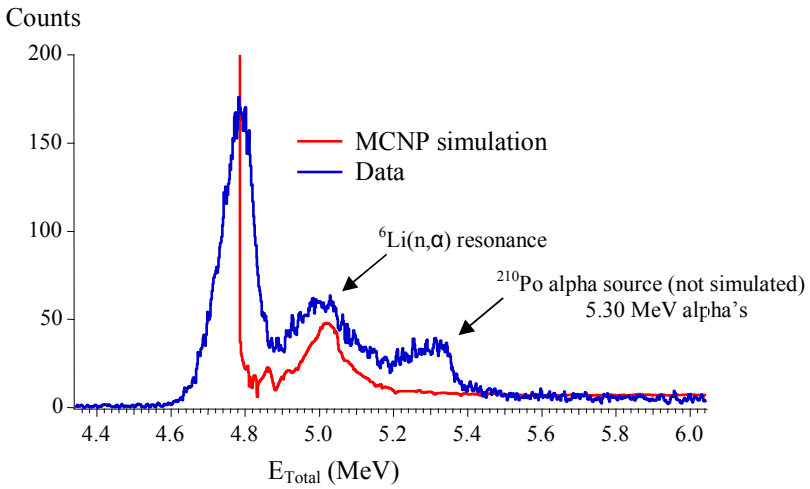

Fig. 3: Fast-neutron spectrum from weak ^{252}Cf and ^{210}Po sources with 52 keV FWHM resolution using a 92% enriched ^{6}LiF absorber crystal. The broad peak, shifted by Q= 4.79 MeV to ~5 MeV is due to increased absorption by ^{6}Li at 0.241 MeV. The alpha peak at ~5.3 MeV is due to ^{210}Po. In red is the expected spectrum of a ^{252}Cf source simulated with MCNP, not taking into account the alpha source.

The current challenge for microcalorimeters is their necessarily small effective pixel area, ~1 cm^3 for neutron spectrometer pixels, and their slow decay time, ~10 ms for neutron spectrometers. The pixel size is limited by the requirement for low C_{abs} for high energy resolution; the decay time is set by the intrinsically weak thermal coupling between materials at low temperatures. Both issues can be addressed by fabricating large detector arrays, which is currently addressed by our group for gamma-ray microcalorimeters. Additionnaly, digital signal processing permits operation of microcalorimeters at much higher counting rates. The expected

count rate of a 36 channel neutron spectrometer will be of a few kHz. This will enable high-precision neutron spectrometry with high statistics, as simulated for Pu analysis in fig. 4.

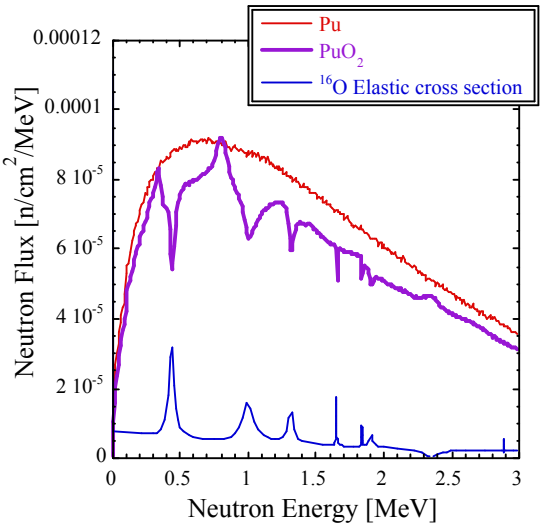

Fig. 4: MCNP simulation of the neutron spectrum of a Pu and a PuO_2 source for a spectrometer resolution of 10 keV. In red is the spontaneous fission spectrum (Watt distribution) of Pu, in purple the spontaneous fission spectrum of Pu modified by the presence of oxygen and in blue the elastic scattering cross section of oxygen. From the structure of the PuO_2 spectrum, the presence and quantity of oxygen can be derived. Neutron microcalorimeter arrays will allow the detection of light elements in a heavy-element matrix from spectral features at nuclear resonance energies, even through thick shielding.

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References

[1] Ch. Enss, *Cryogenic Particle Detection*, Topics in Applied Physics **99**, Springer, ISSN: 1437-0859 (2005)
[2] M. F. Cunningham, *High-resolution operation of frequency-multiplexed transition-edge photon sensors*, Appl. Phys. Lett. **81** 159 (2002)
[3] T. Niedermayr, *Microcalorimeter design for fast-neutron spectroscopy*, Nucl. Instr. Meth. A **520** 70 (2004)
[4] I. D. Hau, *Lifetime of the first excited state of ^7Li*, to be submitted