

PALACKÝ UNIVERSITY OLMOUC
FACULTY OF SCIENCE
JOINT LABORATORY OF OPTICS

MASTER THESIS

Development of a spectrometric chain for
the detection of low-energy gamma
radiation using semiconductors.



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DECLARATION

I hereby declare that I elaborated this bachelor thesis independently under the supervision of Mgr. Leo Schlattauer Ph.D., using only information sources referred in the Literature chapter.

In Olomouc November 4, 2023

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Introduction

Chapter 1

Gamma rays properties and matter interaction

1.1 Gamma emission

1.2 Passage of radiation and particles through matter

Interaction of a particle (radiation) with another particle (atom, nuclei, free electron) or with continuous matter can result into many types of reactions and effects - scattering of a particle from incident direction, creation of new particles and nuclei, annihilation of incident particle etc. It mainly depends on particle's energy, electric charge, spin and mass, but also on the properties of target particle or matter. The physical quantity describing the probability of a specific interaction of particle with single point target is known as the cross section. Normalized to the unit solid angle - differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{1}{F} \frac{dN_s}{d\Omega} \quad (1.1)$$

Where F is a particle flux, Ω is a solid angle and N_s is the average number of scattered particles per unit time. And the total cross section is given by integration:

$$\sigma = \int \frac{d\sigma}{d\Omega} d\Omega \quad (1.2)$$

However, to characterize the interaction probability of particle with continuous matter, which contains many interaction centres (defined by their density), other assumptions have to be made. The average number of scattered particles is given by:

$$N(\Omega) = FAN\delta x \frac{d\sigma}{d\Omega} \quad (1.3)$$

and integrated:

$$N_{tot} = FAN\sigma\delta x \quad (1.4)$$

The A is a total area perpendicular to the flux, δx is the material thickness and N is the density of interaction centres.

Depending on the type of particle

Heavy charged particles (such as alpha particles, protons, muons, pions) lose their energy mainly due to the atomic electrons collisions. Due to their mass which is much higher than the mass of electrons ($M \gg m_e$) they collide with, the direction of their path is left unchanged. The loses of energy per unit path is defined as stopping power $\frac{dE}{dx}$. The stopping power for the heavy charged particles is given by Bethe-Bloch formula which relates stopping power and particle's energy. However the Bethe-Bloch formula doesn't apply on low energies (Lindhard-Sharf nuclear loses) and on higher energies (bremsstrahlung radiation). The change of their path direction is possible by the second process with lesser probability - by the elastic scattering from nuclei.

Electrons and positrons have much smaller mass than the heavy charged particles, and thus the direction of their path is changed due to the movement in an electric field of nucleus. The bremsstrahlung radiation loses are mayor yet at low energies. However, the energy lost due to the collisions also comes to play - it is guided by special Bethe-Bloch formula, which takes the path direction change into account.

Other interaction effects are also possible (Cherenkov radiation emission, nuclear reactions), but they are rare or does not affect the particle's energy as those previously mentioned.

The interaction of neutrons is totally different due to the lack of charge.

This thesis, which is described more detail in following chapter.

1.2.1 Gamma matter interaction

1.3 Photoelectric effect

1.4 Compton scattering

1.5 Pair production

Chapter 2

Gamma rays detection

2.1 Properties and parameters of detectors

2.1.1 Gaseous detectors

2.1.2 Scintillation Detectors

2.1.3 Detectors based on semiconductors

Chapter 3

Semiconductor Detectors

3.1 Principle and parameters

3.2 Construction scheme of Instruments for gamma detection based on semiconductors

3.2.1 XR-100CdTe X-Ray and Gamma Ray Detector

3.2.2 MIMOS 2

3.3 Available semiconductor sensors

3.4 Hamamatsu detectors

3.5 OPF420 PIN diode

Chapter 4

Detector pulse analysis

Chapter 5

Mössbauer effect and spectroscopy

Mössbauer effect is a physical effect, which can under certain circumstances occur on atomic nuclei. It consists of recoilless resonance emission/absorption of gamma photons by nuclei of source/absorber with discrete nuclear energy levels. This effect has a wide field of application - mainly the Mössbauer spectroscopy, which is a nuclear experimental technique and a special type of gamma spectroscopy, which uses the appropriate nuclei in studied sample as sonds of local electric and magnetic fields.

This technique is capable of providing many unique information in material research, geology, chemistry and biology - study of phase and chemical composition of solid materials such as steel, study of local magnetic fields and spin states, in-situ measurements of phase transitions. The main disadvantage of this technique is the fact that there is not an appropriate radiation source for many isotopes. The mayor significance has iron and its isotope ^{57}Fe with possible radiation source ^{57}Co (which decays into an excited state of ^{57}Fe), which allows Mössbauer spectroscopy to be employed on many fields, including the steel industry.

5.1 Physical concept

In previous chapters was mentioned, that the atomic nuclei are quantum systems with discrete energy levels (analogous to the energy levels of electron shell), thus upon deexcitation or excitation they emit/absorb gamma photon with energy equal to the difference between the levels. For the free, stationary nucleus, the emitted/absorbed energy spectra follow the shape of Lorentzian curve.

However, this energy may be altered - due to the momentum conservation law, some part of the gamma photon energy is transferred to the kinetic energy of nucleus, crystal as whole body or is transformed into lattice vibrations (phonons). Due to this fact, the emission and absorption energy spectra may be different and without any overlaps, which prevents the resonance effects from happening.

In the case of free, stationary nuclei, momentum and energy transfers are so high, that the emission and absorption spectra are shifted to different directions by large energetic values, which makes the resonance absorption impossible to observe. However, the nucleus bounded into the crystal lattice is a different case - the crystal as whole body will absorb the momentum. If we consider, that the entire crystal has much larger mass than the nucleus, the energy transfer into crystal's kinetic energy will be very small - the gamma photon energy remains nearly unaltered. Thus this can be considered as recoilless emission/absorption and the energy spectra have overlap, which makes the resonance absorption (Mössbauer effect) observable.

It also worth mentioning, that there is also a third case - the free nuclei in thermal motion. The velocity of nuclei is guided by Maxwell's statistics and the spectra become widened by Gaussian shape. At higher temperatures, this effect may result into spectra overlap and makes the resonance absorption observable. However, this technique is not much developed yet and has only a little field of application.

5.2 Mössbauer spectroscopy

- perturbation theory, what results into the fact, that every phase or chemical constitution has its own Mössbauer spectrum.

5.2.1 Interaction of nuclei with local fields

The main properties of nucleus which cause the interactions with local electric and magnetic fields are: atomic number Z , quadrupole momentum Q and its spin I along with its projections.

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5.3 ^{57}Fe spectroscopy

One of the isotopes, on which we are capable to observe a Mössbauer effect is ^{57}Fe .

- Source of 14.4 keV gamma - ^{57}Co radioactive nuclei built-in crystal lattice - mostly in a rhodium matrix.
- Transducer for doppler modulation with PID regulation for precise velocity and energy control.
- detector of transmitted/backscattered gamma radiation, conversion electrons or RTG along with evaluation electronics including amplifiers, MCA's etc.

This thesis is mainly devoted to the application of semiconductor detectors for detection of the 14.4 keV gamma photons in transmission geometry.

It is also necessary to consider, that the ^{57}Fe isotope have relative abundance only 2.21% [**compounds**]. Although this fact, the spectra are still measured with very respectable precision and efficiency, which makes the Mössbauer spectroscopy very sensitive measurement method.

Conclusion

The work on thesis was both very hard and experiencing, and thus it can be compared to have to chug a bottle of 50% vodka - get sick, get experienced.