Report on novel experimental approaches via Coulomb excitation measurements, on performance tests on an array of position-sensitive detectors on ion-beam applications and design studies for targets neutron production.

1. New software packages for multiple Coulomb excitation and low statistics lifetime measurements

Introduction

Coulomb Excitation is a well developed method to determine electromagnetic properties of nuclei in the ground and excited states. This experimental technique is widely applied to the unstable nuclei studies, which started to become possible with the availability of exotic beam facilities.

From early eighties a semi classical coupled-channel Coulomb excitation least-squares search code, GOSIA has been a basic tool for the data analysis. It has been developed in Rochester-Warsaw collaboration to analyse the large sets of experimental data required to unambiguously determine the many electromagnetic matrix elements involved in heavy-ion induced Coulomb excitation.

Advantages of GOSIA are:

- χ^2 fitting procedure (using a gradient method) to determine the best set of electromagnetic matrix elements,
- fast approximation method developed to speed up the analysis of the complex experiments
- extensive possibilities to take into account various geometries of experimental setup

But one can notice some difficulties in GOSIA use. Limitations of gradient method implemented in the code are:

- a susceptibility to local minima,
- a time consuming process to search for alternative solutions.

The goal of the project was to propose and implement a new minimisation technique for the Coulomb excitation data analysis.

Numerical methods

The software for Coulomb excitation analysis implements a genetic algorithm. It is a heuristic multidimensional surface search technique inspired by evolutionary biology such as inheritance, selection, crossover (also called recombination) and mutation.

The Front Line Algorithm (FLA) - the new geometric method for the objective function shape investigation in the neighbourhood of minimum was developed. It exploits samples non-uniformly generated and evaluated during the minimisation process, which are stored in a file called repository. The shape of the objective function cut at a specified threshold comes as a result.

The details of the numerical methods and their implementation one can find in the MS-136 report.

Dissemination

The new software package for Coulomb excitation experiments was presented during following meetings and conferences:

- Frontiers in Gamma-Ray Spectroscopy 2012, 5-7 March 2012, New Delhi, Indie,
- ENSAR Town Meeting, 17-20 June 2013, Warsaw, Poland,
- GOSIA analysis of Coulomb-excitation experiments at ISOLDE Workshop, 29-30 April 2014, Leuven,Belgium
- Zakopane Conference on Nuclear Physics, 30 August - 7 September 2014, Zakopane, Poland
- East–West Integrated Research Activities Workshop - Status and Perspectives of the EWIRA Laboratories, 5 October 2014, Bucharest - Magurele, Romania

The package is available on the webpage: http://www.slcj.uw.edu.pl/~pjn/Jacob/

2.Tests of an array of CVD diamond pixel detectors

Introduction

Coulomb excitation is a powerful method to study nuclear collectivity and shapes by direct measurements of dynamic and static electromagnetic moments. These studies are no longer limited to stable or long-lived isotopes thanks to availability of radioactive heavy ion beams with energies near the Coulomb barrier, and important results on nuclear structure of short-lived exotic isotopes have been recently obtained using this experimental technique.
In Coulomb excitation experiments, gamma radiation from excited states is detected in coincidence with at least one collision partner. Information on particle scattering angle allows for a proper description of the excitation process and enables Doppler correction of detected gamma rays. For forward angle scattering in the laboratory frame, however, information on particle energy or time of flight is necessary to distinguish between scattered beam particles and recoiling target nuclei. Currently used detection systems will have to be adapted to the unprecedented beam intensities from new RIB accelerators. The new gamma-ray tracking spectrometer AGATA will be well suited to work with very high counting rates thanks to the segmentation of the germanium detectors and their digital signal-processing electronics. At the same time it will provide a very high energy resolution and overall efficiency as well as precise information on emission angle of individual gamma rays due to the position sensitivity of the detectors and gamma-ray tracking. This progress in gamma-ray detection techniques must be accompanied by development of new detectors dedicated for Coulomb excitation studies of exotic nuclei.

CVD diamond detectors are currently used in high-energy physics for monitoring of intense beams. Results of tests with heavy ions at energies of several hundred MeV/amu, as well as high-energy protons and fast neutrons have shown their excellent timing properties and radiation hardness. Therefore, they are considered as attractive particle detectors for Coulex with high-intensity exotic beams. However, irradiations performed with 26 MeV protons as well as recent measurements at RBI Zagreb with 6.5 MeV carbon ions have shown that if a CVD detector was irradiated with low-energy particles that are completely stopped in the detector material, the observed radiation damage was much higher, in some cases even higher than the one of silicon. These observations should be verified, possibly with heavier ion beams.

Experiments

Several tests of single-crystal CVD detectors with alpha radiation sources where performed in the Institute of Nuclear Physics of Polish Academy of Sciences in Kraków and in the Heavy Ion Laboratory University of Warsaw. Goals of these short measurements were to check properties of various detectors and applicability of experimental electronic solutions.
Main experimental studies on the properties of diamond detectors employs a high energy proton beam from Cyclotron Centre Bronowice in Kraków and ^{32}S beam form cyclotron U200P in Warsaw. Response of single-crystal CVD detectors on the protons were used to design and check the performance of a new developed electronics. Heavy ion beam from Warsaw cyclotron allows to test spectroscopic properties and time resolution of the diamond detectors.

In total 10 different single-crystal CVD detectors were tested.

Two 5 days experiments were performed in Heavy Ion Laboratory in Warsaw: 14-18 October 2013 and 3-8 November 2014. The first measurement was focused on the spectroscopic performance of CVD detectors and second to determine the time resolution of diamonds' response on heavy ions.

Details of the experimental methods and obtained results can be found in the MS-138 report.

Conclusions

The tests of scCVD detectors performed in Heavy Ion Laboratory on the ^{32}S beam at energy of 90 MeV showed that further development on diamond detectors is required.

Nevertheless one can conclude as follows.

a) Timing performance of the detectors is very promising. The measured width of a timing spectrum is determined by the energy loss in the target, but the result is much better the resolution of Si detectors.
b) The polarisation effect observed in with the heavy ion beam shows that scCVD detector cannot be used at a high rate. The farther studies of the effect are required.
c) The quality of scCVD detectors is unstable and spectroscopy of heavy ions with them is difficult at a present state of technology.

3. Performance tests of position sensitive detectors for 3D imaging

The possibility to use diamond detectors in ion beam analysis applications has been explored for coincident elastic scattering technique. This technique is based on the concept of irradiation of transmission samples by ion microbeam and detection of both scattered and recoiled nuclei in coincidence. In this way a 3D analysis of elements similar in mass to the mass of the projectile ion could be performed.

The most important requirement on the experimental setup for this technique is capability to measure combined energy of scattered and recoiled nuclei and to perform a reliable coincidence measurements minimizing a false coincidence events. Additional characteristics of the coincidence setup that would be beneficial for sensitive analysis are also:

- High solid angle of detector system due to its perspective application in ion microprobe setup where the ion beam currents are generally low. Since the increase of solid angle implies kinematic broadening of the detected energy distributions, segmented or position sensitive detector are needed.
- High timing resolution increases capabilities of the detection system to reject false coincidences and in the case of multielement analysis it can be employed to resolve contributions of different scattering/recoil combinations. Diamond detectors offer generally better timing in comparison to silicon.
- Radiation hardness of such a detector system is also very important requirement as MeV energy heavy ions degrade detector characteristics rather fast. It was expected that diamond may be beneficial material due to generally accepted characteristic that it is more radiation tolerant than silicon in the case of high energy (GeV) particles.

Performance tests

In order to determine capabilities of CVD diamond detectors to replace silicon detectors for ion beam analysis and in particular in elastic scattering coincidence setup that uses microbeam of C or O ions (which offer the widest range of elements for the analysis), the heavy ion nuclear microprobe facility at the RBI has been used.

Performance tests consisted of

- diamond detector radiation hardness measurements,
- studies of their timing properties
- possibility to obtain position sensitivity without using a strip detector approach,
- feasibility study for coincidence measurements 3D analysis applications using CVD diamond detectors.

Details of the experimental methods and obtained results one can find in the D-12.2.2 Report.

Conclusions

On the basis of the performance tests within this task the following conclusions can be made:

a) Radiation hardness of single crystal CVD diamond detectors for detection of MeV energy ions (protons, C and O ions) is not better than silicon and therefore radiation hardness of diamond cannot justify the replacement of silicon by diamond.
b) Timing properties of diamond detectors are surely better than silicon and moreover they have a negligible leakage current. However, in the case of coincident scattering, the timing properties could not be utilized for the low energy range of C ions

available at the RBI microprobe. Higher energy in detector (of the order of 10 MeV) would give better results, which is unfortunately too high for the most of analysis applications.

c) Both, the radiation hardness and superior timing properties are advantageous for very thin diamond detectors (e.g. 6 micrometers thick diamond membrane detector). Such detectors may be used as a trigger for transmitted ions that induce signals in other detectors using other processes (e.g. STIM – scanning transmission ion microscopy, IBIC- ion beam induced charge, SIMS – secondary ion emission spectroscopy, etc.). It is clear that in these cases diamond would be superior to silicon.