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CASSPERR: A γ–γ cascade detector for resonant nuclear reaction analysis

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ABSTRACT

Resonant nuclear reaction analysis (RNRA) is sometimes the only technique able to quantify elements in a matrix containing other elements. Background due to cosmic rays and natural radioactivity has limited traditional RNRA to samples with relatively high concentrations of the measured element, or to facilities with large amounts of passive shielding. Many nuclear reactions of interest in RNRA produce excited states in the resulting nuclei that then de-excite by product-specific sequences of photon emissions. The CAScade SPEctrometer for Resonant Reactions (CASSPERR) selects only events that match the desired combination of photon emissions. Rejection of other events greatly reduces the background, thus improving the signal to noise ratio (SNR). Since it is constructed from available commercial components, CASSPERR opens RNRA to typical ion beam analysis facilities. The design, operation and evaluation of CASSPERR with applications to materials science are currently under investigation.

1. Introduction

Auger Electron Spectroscopy (AES) and Secondary Ion Mass Spectroscopy (SIMS) are typical methods for determining elemental concentrations in a material. Both methods require measurement of known standards to obtain quantitative results and may have strong secondary matrix sensitivities. In addition, both methods are surface-sensitive-only techniques. Depth profiles are obtained from sputtering which removes layers of the sample. The sputtering affects depth resolution and may also contaminate the spectra from which the results are determined [1]. Ion beam analysis techniques offer nondestructive alternatives to AES and SIMS and in many cases can provide direct quantitative results without matrix effects [2].

Resonant nuclear reaction analysis (RNRA), an ion beam analysis technique, has potential advantages over AES and SIMS for certain elements or types of measurements. For example, RNRA is capable of detecting and quantifying the depth profiles for hydrogen [2,3]. Advantages of RNRA include quantification of concentrations without the need for comparative measurements to external standards. Also, the formation of surface oxides and other surface contaminants do not affect the quantitative analysis with NRA. Minimum detection levels (MDL) of 10–100 parts per million atomic concentration (ppm-ac) are often achievable [4,5].

Although it is a powerful tool, the relative use of RNRA is small compared to other ion beam analysis techniques such as Rutherford backscatter spectrometry because RNRA data is acquired sequentially – i.e. collecting data at incremental energies (depths). The data collection time can be reduced either by increasing the efficiency of detection or increasing the signal to noise ratio (SNR). The most commonly used method to reduce the noise is to passively shield the detector from the background (typically cosmic rays or naturally-occurring, low-level radioactive elements). The volume of shielding required to decrease the noise from these interfering backgrounds occupies too much space for easy implementation at most ion beam facilities. Active shielding via coincidence rejection requires that a cosmic ray interact with both the detector and the coincidence shield. The low probability for both interactions to occur limits the effectiveness of this coincidence rejection technique [6].

Sum coincidence spectrometry, also known as gamma–gamma coincidence counting and gamma cascade spectrometry, is a common technique used in nuclear decay studies [7,8], in neutron activation analysis [9–26], in applications that use radionuclides [27–30] and charged particle activation analysis [31,32]. Singru [33] suggested that this technique be applied to (p,$\gamma\gamma$) reactions. Complex, multi-detector configurations have been used to measure such cascades [34,35]. The development, characterization and

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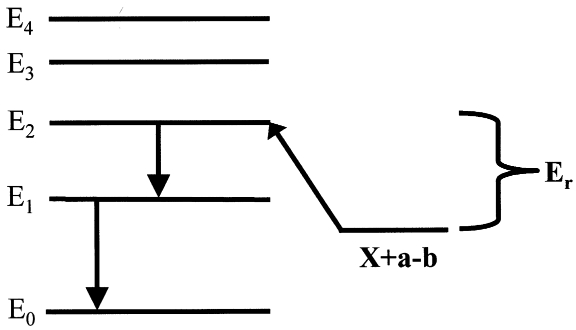

Fig. 1. Example diagram illustrating a resonant nuclear reaction between reactants X and a to form products Y and b. Y then decays from its excited state (E_2) through an intermediate state (E_1) to the ground state (E_0) by the cascade emission of characteristic γ-photons.

possible materials science applications of a two detector system – the CAScade SPEctrometer for Resonant Reactions (CASSPERR) – based on this technique are presented herein.

2. Instrumentation

2.1. Physics of γ-cascades from resonant nuclear reactions

Nuclei have structured energy levels. In RNRA, an ion with energy (E) enters the sample and interacts with a sample nucleus to form an excited product nucleus. An enhancement of the reaction cross section, a resonance, occurs when the ion energy plus the mass excess energy (mass of reactants minus the mass of the products in energy units) matches an energy level in the product nucleus. The decay to the ground state of the product nucleus proceeds through the emission of a product-specific sequence of characteristic high-energy (MeV) gamma photons as shown in Fig. 1 [36]. CASSPERR is designed to accept only those events that match the specific decay sequence for the reaction of interest.

2.2. Construction

CASSPERR is constructed from two gain-matched, 7.62 cm diameter by 7.62 cm long, cylindrical NaI(Tl) detectors (A and B, respectively). Each detector is connected to a photomultiplier tube (PMT), a preamp and a spectroscopic amplifier (Amp). The bipolar output of each amplifier is connected to an analog-to-digital converter (ADC) and multichannel analyzer (MCA). Energy spectra for standard radioactive sources are collected with detector A. The same sources are used to collect spectra with detector B. The gain and focus on PMT-B and the gain on Amp-B are adjusted until the energy spectra from detector B best match those from detector A for ^{60}Co. The gain matching is checked for γ-photon energies up to 11 MeV with the ^{27}Al(p,γ)^{28}Si reaction.

The gain-matched, bipolar outputs of Amp-A and Amp-B are disconnected from the energy ADC/MCA and connected to a summing amplifier. The output of the summing amplifier is connected to a timing single channel analyzer (TSCA) that is gated on the total energy of the cascade for the selected reaction. The TSCA output serves as the input for a gate signal of a linear gate. The bipolar output of Amp-A is also connected to the signal input of the linear gate through a delay amplifier. In this arrangement, known as the sum-coincidence mode and shown in Fig. 2, the output of the linear gate corresponds only to those γ-photons due to de-excitations of the product nucleus and to chance coincidences of random events. The linear gate output is connected to the energy ADC/MCA.

2.3. Evaluation

A comparative evaluation of CASSPERR in two modes, single-detector mode and sum-coincidence mode, was performed with ^{60}Co, ^{137}Cs, ^{22}Na and the natural background as sources. Detectors A and B were placed 7.62 cm away from and on opposite sides of the sources. In single-detector mode, the bipolar output of Amp-A was connected directly to the energy ADC/MCA to avoid differences between the electronics. In sum-coincidence mode, the TSCA was set with a resolution-limited ±102-keV window around the 2.50-MeV sum-energy of the 1.17-MeV plus 1.33-MeV γ-photon cascade from the ^{60}Co source. The low-energy tail of the naturally-occurring 2.61-MeV ^{208}Tl peak extends into the resolution-limited, high-energy side of the 2.50-MeV window and thus, provides a good indicator of background suppression.

Spectra were collected with no source present to quantify the natural background suppression of the sum-coincidence mode. Spectra collected in the single-detector mode suffer from the typical interfering background and Compton scattered events. As shown in Fig. 3, the ^{40}K and ^{208}Tl full-energy peaks (FEP) and their associated Compton continua are easily identified in the single-detector mode yet they are absent in the sum-coincidence mode. The 2500-keV peak in the sum-coincidence mode of Fig. 3 is not a true coincidence peak. It is due to events where the total energy that corresponds to the TSCA-gated sum-energy window is solely deposited in detector A (shown in Fig. 2) and no energy is deposited in detector B during the allowed coincidence time. The background suppression factor (BSF) is the ratio of the count rate in single-detector mode to sum-coincidence mode with only the nat-

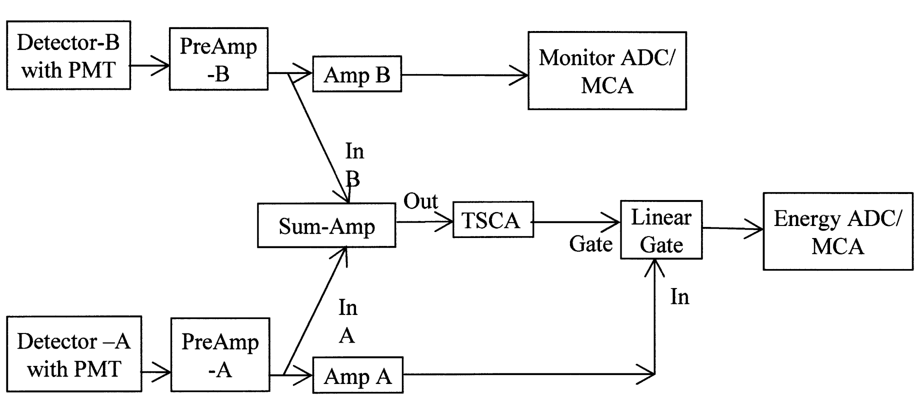

Fig. 2. The schematic for the CASSPERR in sum-coincidence mode. Sum-Amp is a summing amplifier. TSCA is a timing single channel analyzer. Delays are introduced as needed such that the cascading γ-photons produce a gate signal in coincidence with an input signal at the linear gate. ADC/MCA is an analog-to-digital converter connected to a multichannel analyzer. The monitor ADC/MCA provides a means to simultaneously operate in the single-detector mode and sum-coincidence mode.