(d,pγ)-coincidence technique and its preliminary application*

An Zhu

(Open Laboratory of Radiation Physics and Technology of the State Education Commission, Institute of Nuclear Science and Technology, Sichuan Union University, Chengdu 610064)

Abstract When there exist many light elements in a sample or the sample is thick, a reliable (d,p) reaction analysis cannot be often obtained due to the interference of particle groups corresponding to different elements and even different energy levels of an element. Therefore, (d,pγ) coincidence technique is tried. By measuring a charged particle(proton) group in coincidence with its accompanying gamma rays, the background can be greatly suppressed and the interference can be effectively eliminated.

Keywords Deuteron-induced nuclear reactions, Coincidence measurement, Depth profiling analysis

1 Introduction

Deuteron-induced nuclear reactions with relatively large differential cross sections and positive Q-values are very valuable for the non-destructive analysis of light elements. As a result, (d,pγ) reaction may become one of the most important tools for the analysis of light elements. The charged particles (protons) and gamma rays emitted in deuteron-induced nuclear reactions can be detected. At present, gamma rays emitted in deuteron-induced nuclear reactions are widely utilized to determine the concentration of light elements. Most recently, this method has been deeply and in detail studied in Laboratoire de Recherche des Musées de France (LRMF) in the case of ^{12}C(d, pγ)^{13}C reaction.[1] Unfortunately, the disadvantage of detecting gamma rays is that most information on the concentration depth profile, which is of essential importance in some studies, is lost. In contrast, if the emitted charged particles (protons) are detected, the important information on the depth profile can be extracted. High sensitivity can be attained if the charged particles (protons) of interest can be separated from background particles which might be protons or alpha particles arising from competing reaction channels. However, when there exist many light elements in a sample or the sample is thick, a reliable analysis cannot be often obtained due to the interference of particle groups corresponding to different elements and even different energy levels of an element. In these cases, p-γ coincidence technique, in which a charged particle(proton) group in coincidence with its accompanying gamma rays is measured, is quite useful.

In the past, PIXE-RBS coincidence technique was developed to extract the depth profile of light elements in the matrix consisting of heavier elements.[2] In our own knowledge, p-γ coincidence technique was seldom applied in nuclear reaction analysis. Recently the p-γ coincidence technique was exploited and presented in Ref.[3].

In LRMF, a large number of works of art and archaeological objects are analyzed annually using the Accélérateur Grand Louvre d'Analyse Elémentaire (AGLAE) IBA facility. In most cases, they are thick samples in which there often exist some light elements interesting in archaeology and fine arts studies, for example, C, N, O, S, P, etc. Therefore, the p-γ coincidence technique is very necessary in LRMF. In this paper, we analyzed the ^{16}O and ^{14}N elements by using ^{16}O(d,p$_1$γ) and ^{14}N(d,p$_5$γ) reactions due to their relatively large differential cross sections in comparison with other reaction channels.

2 Experimental

The experiment was performed with an

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external milli-beam for archaeometric application on the AGLAE IBA facility at LRMF based upon a 2 MeV Pelletron 6SDH2 tandem accelerator from National Electrostatics Corporation.[4~8] In the experiment, the generating voltmeter was calibrated with the classical narrow resonance $^{27}Al(p,\gamma)^{28}Si$ at 992 keV, FWHM=0.1 keV, the energy spread of the beam was found to be less than 700 eV.

The gamma rays were registered by an Ortec HPGe detector (50 mm diameter and 59 mm long) with an efficiency of 22.7% relative to NaI(Tl) and an energy resolution of 1.7 keV at 1.33 MeV. The gamma ray detector was placed at 90° with regard to the deuteron beam and close to the samples. The charged particles (protons) were detected at an average scattering angle of 165° by an annular surface barrier detector with a depletion depth of 300μm. The incident energy of deuteron beam is 1.8 MeV. In front of this detector, a Mylar foil with a thickness of 38μm was used to stop the elastically scattered deuterons. The annular charged particle detector was installed in a specially-designed nozzle which was described in detail in Ref.[9]. Targets and detector system were placed in ^{4}He gas-jet circumstance.

The experimental set-up and an electronic circuitry used in the experiment are shown in Fig.1. The electronic circuit consists of a slow part, which is used for energy analysis of the emitted protons, as well as a fast system, involving a constant fraction timing discriminators (CFD) and a time-to-amplitude converter (TAC). Coincidence of the electronic circuit was adjusted by use of ^{227}Ac source which emits spontaneously gamma rays and alpha particles.

The data acquisition system employed in our experiment is MPA/PC multiparameter system, manufactured by Fast ComTec Communication Technology, Germany. With the data acquisition system, the pulses from gamma- and particle detectors, which are in coincidence with each other, can be stored in a computer, and we can easily obtain coincidence particle (proton) spectra by setting digital windows on the gamma rays corresponding to the light elements of interest.

Targets used in our experiment are Kapton foil ($C_{22}H_{10}N_2O_4$) with a thickness of 8μm and a patina sample interesting in archaeological studies.

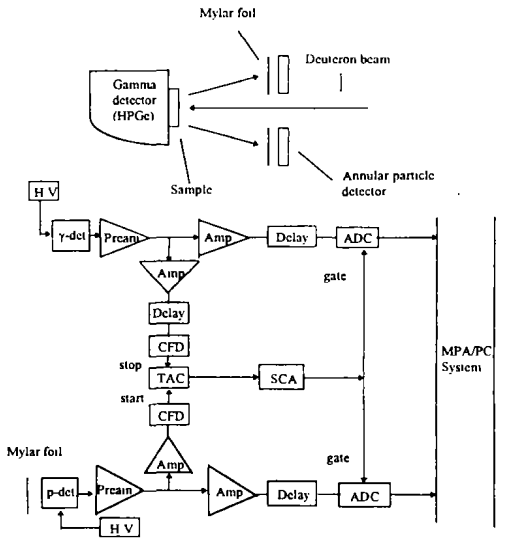

Fig.1 A schematic diagram of experimental set-up and electronic circuit used in the experiment

HV-high voltage; preamp- preamplifier; Amp-main amplifier; CFD- constant fraction timing discriminator; TAC-time to amplitude converter; SCA- single channel analyzer; ADC- amplitude digital converter.

3 Results

3.1 Kapton foil

Fig.2 shows the ungated gamma spectrum of the Kapton sample. In Fig.3, the proton peak corresponding to $^{12}C(d,p_0)$ is quite more intensive than the other peaks from the reactions of deuterons with ^{16}O and ^{14}N. When digital windows are set on the gamma peaks of $^{14}N(d,p_5\gamma)$ and $^{16}O(d,p_1\gamma)$ respectively, we can obtain the coincidence particle(proton) spectra(solid lines) shown also in Fig.3. From Fig.3, it is obvious that the proton peaks of $^{12}C(d,p_0)$ and $^{16}O(d,p_0)$ in the coincidence spectra have been suppressed to almost zero, the remaining protons from $^{12}C(d,p_0)$ reaction are fully caused by accidental coincidences. Also, we can see that neither oxygen nor nitrogen can be accurately analyzed if the proton peaks corresponding to them cannot be separated. The above analysis of Kapton foil indicates that the p-γ coincidence technique is necessary and successful in this case.

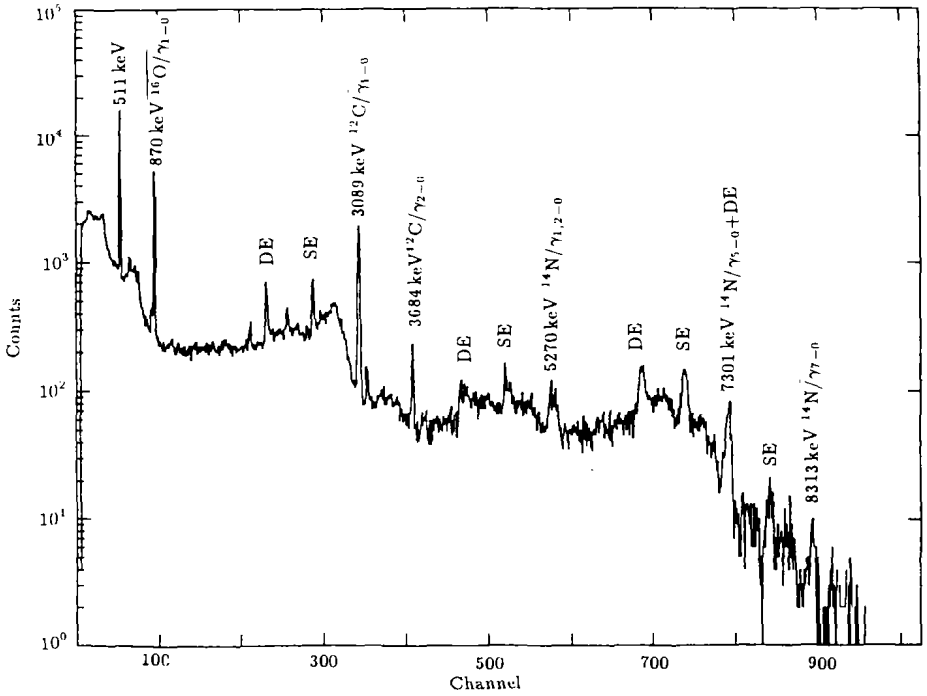

Fig.2 Ungated gamma spectrum from a kapton foil at a deuteron energy of 1.8 MeV SE and DE represent single escape peak and double escape peak, respectively

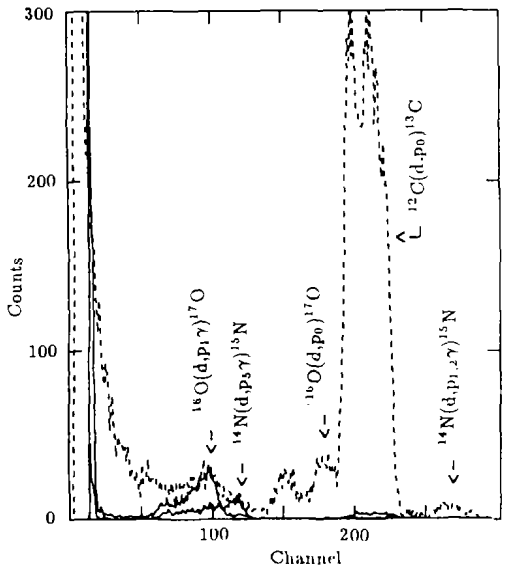

Fig.3 Ungated particle (proton) spectrum (dashed line) and coincidence spectra (solid lines) of $^{14}N(d,p_5\gamma)^{15}N$ and $^{16}O(d,p_1\gamma)^{17}O$ from a Kapton foil at deuteron energy of 1.8 MeV

3.2 Patina sample

The coincidence particle (proton) spectra are obtained when the digital windows are set on the gamma peaks corresponding to $^{16}O(d,p_1\gamma)$ and $^{14}N(d,p_5\gamma)$, respectively. It can be seen from Fig.4 that the other proton peaks, corresponding to $^{16}O(d,p_0)$, $^{12}C(d,p_0)$ and $^{14}N(d,p_{1,2})$, have been greatly suppressed and that it is quite important to separate the contributions between $^{16}O(d,p_1\gamma)$ and $^{14}N(d,p_5\gamma)$ in order to accurately analyze oxygen and nitrogen elements. Especially for nitrogen element, the p-γ coincidence technique is very crucial for the accurate analysis because its small peak is strongly interfered by the peak of $^{16}O(d,p_1\gamma)^{17}O$ reaction. In addition, by this p-γ coincidence technique, the background around channel 50 has also been suppressed, this is very important for accurately analyzing the depth profiling of ^{16}O and ^{14}N elements. After obtaining the charged particle (proton) spectra for the elements of interest by p-γ coincidence technique, the information of depth

profiling for these elements can be reliably extracted by standard reference target method[10] or spectrum simulation method.[11] By comparing the coincidence particle (proton) spectra of patina sample and Kapton foil, we can discover that the concentration of the element nitrogen in patina sample is mainly distributed on the surface.

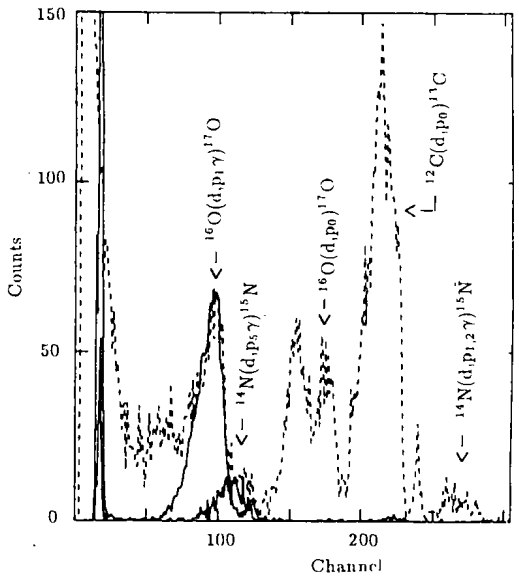

Fig.4 Ungated particle (proton) spectrum (dashed line) and coincidence spectra (solid lines) of $^{14}N(d,p_5\gamma)^{15}N$ and $^{16}O(d,p_1\gamma)^{17}O$ from a patina sample at a deuteron energy of 1.8 MeV

4 Conclusion

According to the results described above, the p-γ coincidence technique is quite effective in cases where the ungated particle spectrum obtained by a single measurement becomes too complicated to be reliably analyzed due to the existence of a number of light elements excited by (d,p) reactions or to the reason that the sample analyzed is thick. In this report, the technique was investigated and applied to the analysis of oxygen and nitrogen. However, this method is general and can be applied to the analysis of other elements only if appropriate p-γ coincidences exist. In addition, the background below channel 25 in particle spectra should be reduced so that the accidental coincidences can be further eliminated. Of course, accidental coincidences can also be reduced further either by improving the timing or by lowering the ion beam current reasonably.

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