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Nuclear Instruments and Methods in Physics Research A 589 (2008) 472–483

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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A new analysis method to determine β-decay half-lives in experiments with complex background☆

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Received 2 November 2007; received in revised form 18 February 2008; accepted 19 February 2008
Available online 18 March 2008

Abstract

This paper reports the first application of a new technique to measure the β-decay half-lives of exotic nuclei in complex background conditions. Since standard tools were not adapted to extract the relevant information, a new analysis method was developed. The time distribution of background events is established by recording time correlations in backward time. The β half-lives of the nuclides and the detection efficiency of the set-up are determined simultaneously from a least-squares fit of the ratio of the time-correlation spectra recorded in forward and in backward time, using numerical functions. The necessary numerical functions are calculated in a Monte-Carlo code using the known operation parameters of the experiment and different values for the two free parameters, half-life and detection efficiency, as input parameters.

PACS: 21.10.Tg; 02.50.−r; 02.60.Cb; 02.70.Uu

Keywords: Exotic nuclei; Half-lives; Statistical analysis

1. Introduction

The half-life is a fundamental property of radioactive nuclei, carrying important information on their intrinsic structure. For the β decay, the situation is particularly complex, because it may populate a large number of levels in the daughter nucleus. Theoretical predictions are still rather uncertain, and therefore experimental work on this field is most important. This is even more the case, since β decay plays a decisive role in several astrophysical processes. A prominent example is the r-process nucleosynthesis [1,2], which relies on the β-decay properties of very neutron-rich nuclei along the r-process path. The present work deals with a measurement on β half-lives of nuclei close to the 126-neutron shell south of lead. This region is of exceptional interest to understand how the nuclear structure evolves on the neutron-rich side beyond the doubly magic nucleus ^{208}Pb, which is rather well understood in terms of the shell model. There has been little progress for nuclei in this region in the past due to the difficulty in producing and identifying these nuclides. This is in contrast to lighter elements, which are well populated by fission of actinides. The main reason for the progress achieved in the present experiment was the choice of a novel production mechanism: the nuclides of interest were produced by cold fragmentation using relativistic heavy-ion beams [3].

The nuclei of interest were available as secondary projectiles. They were identified in flight and implanted into an active catcher. The basic information for determining their half-lives, the implantation times and their subsequent decays were registered. Due to the time structure of the beam from the SIS18 heavy-ion synchrotron, the implantations, the β decays, and background events from several sources are influenced by the repetition rate and the length of the beam pulses.

A number of well-established methods for the extraction of half-lives from measured raw data exist, from which the

☆This work forms part of the Ph.D. Thesis of T. Kurtukian-Nieto.

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0168-9002/$ - see front matter
doi:10.1016/j.nima.2008.02.098

one that is best suited for the specific nature of the data as determined by the experimental approach may be chosen. Unfortunately, we found that none of these established methods are suited for the specific conditions of the present experiment. The complex time structure of the registered events due to the periodic operation conditions of the synchrotron accelerator, which provided the relativistic heavy-ion beam of our experiment, required the development of a new numerical analysis method. The benefit of numerical methods has been proven already previously in the correlation analysis of heavy-element data to cope with complex experimental conditions and to take nuclear-property systematics into account [4].

In this paper we will give a short review on the characteristics of the raw data provided by different experimental approaches and on the essential conditions and parameters of the well-established analysis methods. This survey will demonstrate the need for development of a new mathematical model for extracting half-lives of nuclear species produced in the present experiment. The following chapters will give a detailed documentation of the new analysis method we have developed and investigate its strengths and limitations. The individual steps of the analysis are presented and its success is demonstrated.

2. Experimental approaches for measuring half-lives

The technique of choice for measuring half-lives will depend on the lifetimes themselves and on the production of the nuclei investigated. There are essentially two typical classes of experimental conditions for measuring half-lives[1]:

2.1. Activation method

In the first type of experiment, it is possible to produce a large number of nuclei in a given time period, which is short compared to their half-life. This is the case if the nuclide in question can be produced with high cross-section. In this case, the experiment consists of an activation phase and a recording phase. These phases might be repeated several times. After the activation time, the decrease of the number of nuclei in the sample is registered. This can be done either by determining the decay rate or by counting the number of nuclei still present. These two quantities are coupled by the continuity condition.

There exist some variants of the activation-type experiment. First, the decays are registered; secondly, the number of nuclei still present in the probe is determined as a function of time. In both cases, the spectrum follows an exponential function. For very long half-lives, the decay rate is approximately constant during the experiment, and the value of the half-life can be obtained directly from the ratio of the number of detected decays per time unit to the total number of nuclei in the sample. Background may consist of nuclei with other half-lives (contaminations, daughter nuclei) or a constant rate of parasitic events.

2.2. Delayed-coincidence method

Another type of experiment is characterised by short half-lives and/or low production rates. If the rate of produced nuclei is lower than the inverse of its half-life, it is convenient to record the time of production and look for the time of the consecutive decay. These time differences are sorted into a spectrum.

In this case, there are roughly three different variants on recording the data: One may record all events that look like a decay, after any produced nucleus, or one may record all events that look like a decay, after the last produced nucleus, or one may record only the first event that looks like a decay, after the last produced nucleus.

In 'simple' experimental conditions, the average production rate is constant. That means that there is no time structure in the production rate. Independently from the recording options mentioned above, the 'true' correlations follow an exponential distribution. Also in delayed-coincidence experiments, background may exist, consisting of nuclei with other half-lives, decays of daughter nuclei, and a constant rate of parasitic events. A constant background rate appears as a constant rate if all events are registered, but as an exponential distribution if the time scale refers only to the last produced nucleus.

The condition that the rate of produced nuclei is lower than the inverse of its half-life should consider an eventual position sensitivity of the experiment. If the detector, which registers the produced nuclei and the decays, is subdivided, the situation is equivalent to a number of independent experiments with lower rate, corresponding to the granularity of the detector.

The background conditions of the experiment are very much influenced by how well the nuclei as well as their decay are specific for a certain decay process. Best conditions are met if the nuclei are completely identified in mass and atomic number and if the decay is unambiguously identified, e.g. by its energy lines in alpha and gamma decay, using a high-resolution detector. In this case, the decays of many different species can be investigated simultaneously without any interference. Such an experiment is equivalent to a number of experiments with different nuclear species. Still the identification of either the nucleus or the decay is helpful for improving the experimental conditions, mostly in terms of background conditions. Since the β spectrum has the property of being continuous, β decay is not specific enough to be attributed to a specific nucleus, increasing the probability of a random correlation.

[1]We only consider experimental approaches which rely on directly recording the times of individual events. Exploiting indirect signatures of decay times like Doppler shift of gamma rays during stopping the nuclei of interest are beyond the scope of the present paper.