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Nuclear Physics: Estimating the Mean Lifetime from Partially Observed Events

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Abstract

In nuclear physics, one important property of particles to identify is their mean lifetime. The arrivals and subsequent radioactive decays (departures) of single radioactive nuclei can be detected by cutting-edge particle detectors. When there is inconsistency between arrivals and departures and only partial observation of departures, problems arise. Experiments in which the arrival rate is set very low to allow for matching of arrivals and departures are inefficient. An estimation technique that works for a wide range of arrival rates is what we propose. An initial estimator and a method for correcting numerical bias are combined in this approach. The method provides accurate estimates regardless of the arrival rate, as demonstrated by examples and simulations based on data on Lutetium isotope 155 alpha decays. The estimation technique makes it possible to make use of all of the data gathered by the particle detector, which has the practical advantage of allowing for more precise estimates and, in some instances, shorter experiments.

Keywords: Nuclear physics • Radioactive decays • Physics's laws

Introduction

The classic illustration of a time-varying Poisson process is radioactive decay. Physics's laws can be used as a direct basis for the statistical model: The lifetimes follow an exponential distribution with a mean that is equal to the inverse of the decay rate, and the decay events are independent of the decay rate. Because it is sensitive to the structure of the underlying quantum mechanical states, the mean lifetime is one of the most important characteristics of particles in nuclear physics that must be identified. For instance, a radioactive alpha decay that lasts longer than a straightforward model predicted is caused by a significant shift in nuclear structure from the initial to the final state. In particle physics, a well-known statistical problem is estimating the mean lifetime in various experimental configurations [1].

Literature Review

Numerous modern experiments simultaneously measure decays and the continuous production of radioactive species. This is made possible by cutting-edge particle detectors and data acquisition systems that are able to identify not only the arrivals of single radioactive nuclei to a detector but also the radioactive decays of those nuclei. The arrivals and decays, which are collectively referred to as departures, are unmatched, implying that there is no physical connection between them. We can only say that a certain arrival and departure form a pair if the arrival rate is low and the mean lifetime is short because only one departure has been observed between two consecutive arrivals [2].

When some arrivals or departures are mislabeled or only partially observed, problems arise. Due to the particle detector's structure, we focus on experiments in which not all departures can be detected. For instance, since the alpha radioactive nuclei that are implanted into a detector following fusion reactions are typically located very close to the surface of the detector, approximately half of the departures do not occur because the alpha particle escapes from the detector. We have an uneven number of arrival and departure times that cannot generally be linked to one another because of the lack of matching. This paper addresses the issue of estimating the mean lifetime from such data. Because matching an arrival to a departure before the next arrival only causes a negligible bias, experimenters typically prefer setups with a low arrival rate compared to the decay rate. However, this strategy may result in a poor utilization of the measurement capacity. A high arrival rate makes it impossible to match, but a high number of events per second make it possible. The goal of this paper is to come up with a strategy that can also be used with a high rate of arrivals in the event that there are no matching arrivals and departures [3].

The data were gathered in the Accelerator laboratory of the University of Jyväskylä as part of an experiment to measure the charged particle radioactivity of 160Os produced in a fusion evaporation reaction (unpublished data). Technical description of the physical data collection Liukkonen used the K130 cyclotron's beam of 304 MeV 58Ni to bombard a self-supporting 106Cd target with a thickness of approximately 1 mg/cm^2. Over 14.6 hours, the average beam intensity of 3 pnA (19 109 particles/s) was utilized. The radioactive 155Lu was one of the fusion evaporation reaction's byproducts [4].

Using electric and magnetic fields, the recoil-mass spectrometer MARA was used to separate the unreacted primary beam from the fusion evaporation residues, or arrivals in this paper. A gaseous multi-wire proportional counter (MWPC) transmission detector is used to first detect the recoils at the focal plane of MARA. The recoils are then implanted into a double-sided silicon strip detector (DSSD), which has 192 72 strips running horizontally and vertically, respectively. The DSSD has a total area of 128 x 48 mm^2 (width x height). The event can be assigned to a virtual pixel because an ionizing particle causes a local simultaneous signal in both the horizontal and vertical strips of the DSSD. Time to amplitude converter (TAC) modules use the time differences between charge signals read through delay lines from opposite ends of wireplanes to determine the horizontal and vertical transmission positions of recoil passing through the MWPC detector. The DSSD covers half of the possible decay directions, resulting in a 50% detection rate, and the directions of the decay products (departures) of the implanted recoils (arrivals) are random. The experimental setup is schematically depicted in. A self-triggering data

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acquisition system employing analogue to digital converter (ADC) modules and field-programmable gate array (FPGA) chips records all detector events in MWPC and DSSD. FPGA chips employing a moving window deconvolution algorithm calculate the voltage signal generated by charge integrating preamplifiers' kinetic energy and radioactive decay for recoils implanted into the DSSD [5,6].

There are three types of events observed in the DSSD: background, recoils (arrivals), and decays (departures). A recoil is a DSSD event if the DSSD energy and flight time between the MWPC and DSSD are contained within a two-dimensional gate, and both horizontal and vertical positions were successfully recorded at the MWPC. The probability of classifying recoil as background was 8.7% because of the last condition. A decay event, which can be alpha, beta, or proton radioactivity in this reaction, is a DSSD event with energy between 500 keV and 10,000 keV and no signal at MWPC. The remainder of the events are categorized as background [7].

Discussion

When arrivals and departures are not matched and when departures are completely missing at random, we have proposed a method for estimating the mean lifetime. The approach is derived from nuclear physics experiments aimed at determining the expected lifetime of particles. The estimation is based on the physics-based assumption that lifetimes are distributed exponentially. The estimation does not require information regarding the matching of arrivals and departures because of the exponential distribution's memoryless property. If the assumption of an exponential distribution can be supported, the method could theoretically be used to solve other issues. The mean lifetime can be accurately estimated from partially observed departures, as demonstrated by simulations and real-world data examples. An initial estimator and a method for correcting numerical bias are combined in the estimation method. In order to locate an impartial estimator in the minimum contrast estimation, the noisy binary search can be utilized because the exponential distribution only has one parameter. A different initial estimator based on a different thinning strategy could be used with the same bias correction method. In our examples, the probability of observing a deviation was known, but the data could also be estimated [8,9].

An intriguing relationship exists between the arrival rate and the estimate's standard error, as shown by the simulation results. The arrival rate ought to be either very large or equal to the decay rate if the activity time is fixed (the setup of the second simulation experiment). However, there are some drawbacks to the second scenario: First, in real-world experiments, very high arrival rates are typically practically impossible to achieve. Second, it is absolutely necessary for the activity period to be shorter than the follow-up period. Thirdly, as depicted in Figure 6, once a saturation point has been reached, increasing the amount of time spent on the activity may have little effect on estimates' accuracy. As a result, it would appear that an optimal design should have an arrival rate that is equivalent to the expected decay rate if any prior information on the mean lifetime is available. This empirical observation's theoretical justification remains a mystery [10].

Conclusion

The estimation of a particle's mean lifetime may only be one of several experiments' objectives in nuclear physics. This indicates that the arrival rate might not be as optimal as it should be for a specific estimation task. Fortunately, the proposed estimation strategy can be utilized across a broad range of arrival rates. All DSSD strip data will be able to be used as a result of this. The proposed estimation method easily multiplies the amount of data that is accessible in comparison to approaches that only make use of the strips where the arrival rate is sufficiently low to allow for the matching of arrivals and departures. The estimates will be more accurate as a result, and the required accuracy can be achieved in a shorter experiment.

Conflict of Interest

None.

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