THE IMPACT OF THE DUTY CYCLE ON GAMMA-PARTICLE COINCIDENCE MEASUREMENTS*

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Abstract

Radioactive ion beam facilities deliver a great variety of different nuclei and thus open new possibilities for gamma-ray spectroscopy with radioactive isotopes. One of the challenges for the experimentalist is the high gamma background. To obtain nearly background-free spectra a gamma-particle coincidence measurement in inverse kinematics is well suited. Also for stable beams this method offers a lot of advantages. A crucial point for experimentalists for such kind of experiments is the duty cycle and the beam structure of the accelerator. For a typical set-up, the effect of the duty cycle and beam structure, e.g. resulting from different ion-sources, on data acquisition and thus the experiment will be shown from the experimentalist's point of view. The results will be discussed for selected accelerators, i.e. UNILAC (GSI, Germany), REX-ISOLDE (CERN, Switzerland) and ATLAS (ANL, USA).

SOURCES OF GAMMA-BACKGROUND

Radioactive ion beam facilities open new possibilities to investigate nuclear structure far from stability. A decent knowledge helps to refine theoretical models and to gain a deeper insight into the fundamental forces inside the nucleus. One of the tools of the experimentalist to deduce nuclear structure observables is γ-ray spectroscopy using γ-detectors with superior energy resolution. For small cross sections and thus not very intense photopeaks and also for highest precision it is necessary to obtain a good peak-to-background ratio. In an experiment with heavy ions, there are different sources of gamma-background, e.g. natural background radiation, beam induced radiation, X-rays from the accelerator, decay of stopped ions, unwanted nuclear reactions, etc. To minimize the influence of the first four sources a good shielding is needed. Most commonly a combination of lead, cooper and aluminum is used to reduce the effect of X-rays emitted as a consequence of gamma-induced excitation of atomic states. Furthermore a coincident measurement of the particle and the gamma helps to reduce the background substantially: If a reaction occurs there will be a certain time interval between both incidences. The particle can be the scattered ion itself, scattered target ions or particles created during a nuclear reaction. In inverse kinematics it is most likely a target like ion to gain an high detection efficiency through the focusing in beam direction.

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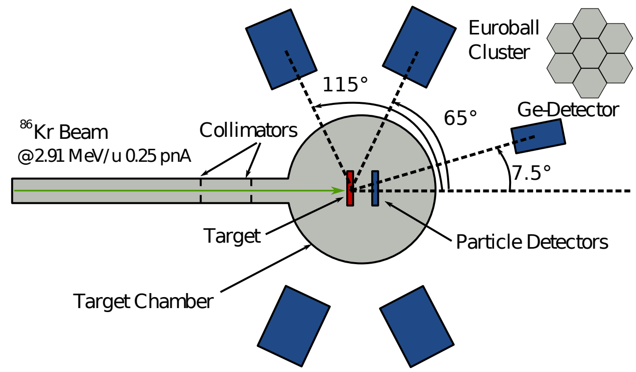

Figure 1: Setup of Experiment U242, a typical γ-particle coincidence measurement.

GAMMA-PARTICLE COINCIDENCE MEASUREMENT

A scheme of a typical setup, experiment U246@UNILAC GSI, Darmstadt is drawn in Figure 1. It was used for a gamma-particle coincidence measurement to determine g-factors and lifetimes of low-lying states. Particle detectors are normally mounted inside the target chamber and the detectors for γ-radiation outside. In this experiment four silicon PIN-diodes were placed behind the target and four Euroball cluster detectors were used to obtain γ-spectra. It was an inverse kinematics experiment, i.e. heavy ion (^{86}Kr) as projectile and a light ion as a target (^{12}C).

Creating a Coincidence Condition

To obtain a coincidence condition, a gate, called coincidence window, can be opened, when either a particle is detected or when a γ-hit is seen by one of the detectors. All hits being seen by other detectors lying inside of this window are considered as coincident. The event can be recorded and one obtains a timing between particle and gamma (see Figure 2). There are only a few sources of unwanted particles: Mainly Rutherford scattering, cosmic rays and β, α-decays. The latter one is negligible for stable beams, since the particle detectors are mounted inside the target chamber and the walls are thick enough to block these. For radioactive beams the impact of decaying the beam ions should be taken into account. Also the rate of detected cosmic rays is very small. Thus it is obvious that for stable beams nearly all detected particles are beam-induced. If no particles reach the target, the detected gammas are ignored. This leads to a significant reduction of non accelerator induced background.

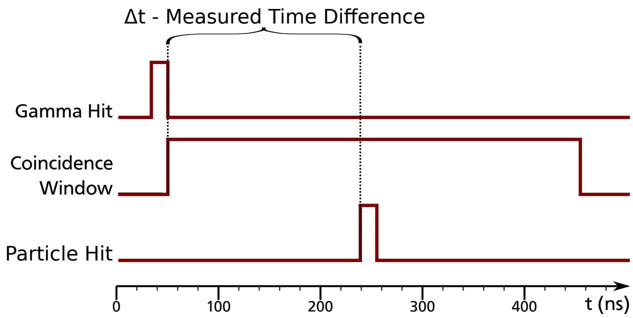

Figure 2: Coincidence condition and the definition of the time delay in respect to the coincidence signal.

The coincidence window should be long enough to compensate variations of the timing signals of the detectors, but short enough to avoid the accumulation of other events. A typical width, chosen in the example experiment, is about $t_{\text{coinc}} = 400$ ns. During this time only one coincident event should occur, since otherwise it would be hard to obtain a reliable relation between the particle and the gamma. Since the duration of the reaction and the deexcitation of the nucleus is often on a shorter time scale than the electronics is able to detect, the recorded distance in time between these should be the similar for each single reaction. The gate used in analysis for each reaction can be shorter than the coincidence window. This helps to further reduce the background, since the actual used true coincidence gate is shorter. The time distance between a random coincidence, i.e. a particle is detected, but not the corresponding gamma, is equally distributed over the coincidence window. This can be used, to further decrease the amount of background, especially the beam-induced background: Putting a gate on a time difference, where just random coincidences were observed, one can create a spectrum with random gammas. This spectrum can be subtracted from the obtained true coincidences and the background peaks should disappear.

DAQ and Influence of the Duty Cycle

After detection the data acquisition system (DAQ) needs to store the recorded event or at least needs to move it to a buffer. During this time the DAQ is blocked and can not accept any further events. Events can only measured during the time, particles arrive at the target. Thus the duty cycle $D_{\%}^{\text{exp}}$ plays an important role for the theoretical limit of the counting rate, which can be estimated through the following equation:

$$\overline{n_{\text{max}}} \leq \frac{D_{\%}^{\text{exp}}}{t_{\text{dead}} + t_{\text{coinc}}} \,. \qquad (1)$$

From this equation it is obvious, that for such kind of experiments the duty cycle must be as close as possible to 100 %. For high repetition rates the theoretical maximum is a little bit higher, since the dead time might overlap with the no-beam time.

This estimation takes into account, that a new coincidence occurs directly after the dead time. This is just possible when there is a high rate of both particles and gammas. This leads directly to an high rate of random coincidences.

To avoid to an increasing amount of random coincidences, it is necessary to limit the rate of emitted particles and gammas. The rate of reactions highly depends on the actual particle rate on the target. In a coincidence measurement the rate of detected good events can be estimated by the formula:

$$n_{\text{true}}(t) = n_T(t) \cdot \sum_{\text{reactions}} \sigma_i \varepsilon_{i,\text{p}} \varepsilon_{i,\gamma} \varepsilon_{\text{DAQ}}(t) \overline{p_{\text{2nd incident}}} \,. \qquad (2)$$

Here n_T denotes the rate of particles on the target, σ_i the integrated cross section for each reaction, $\varepsilon_{i,p}$ and $\varepsilon_{i,\gamma}$ the detection efficiency for the for particle and gamma and $\varepsilon_{\text{DAQ}}(t)$ the efficiency of the DAQ. Additionally only gammas arriving at the same time and one particle should be detected, which is taken into account by the last factor. The rate of detected good events is not proportional to the rate of particles. An higher rate decreases the efficiency of the DAQ through the dead time after each event. Furthermore, there is also an increased probability that a second incident occurs and it is not possible to obtain a valid timing relationship. Therefore the rate of reactions per second and thus the current has to be limited.

Hence a constant rate of particles at the target is preferred. If the bunch structure significantly differs from a rectangular-shaped, either the amount of random coincidences is increased or the achievable event rate is decreased.

COMPARISON BETWEEN SELECTED ACCELERATORS

The arguments stated above indicate that a DC beam as provided e.g. by a tandem accelerator suits best for gamma-particle coincidence measurements. For bunched beams the rate is limited by the duty cycle. The duty cycle itself can be limited by accelerator structures itself or by the source. Therefore the duty cycle varies even for one specific accelerator. Here only typical beams, being available for the experimentalist are discussed.

The ATLAS accelerator (ANL, USA) can operate in CW-Mode with a repetition rate of 12.125 MHz. This is orders of magnitude higher than a typical DAQ can handle, thus it offers DC like conditions for the experimentalist.

At UNILAC (GSI, Germany) the duty cycle is limited to 25 %. This leads to a significant lower maximum counting rate. Furthermore the repetition rate varies a lot for different ion sources. It can reach up to 50 Hz. In this case the bunch structure has to be taken into account. Long pulses of 5 ms length provide a quite constant rate of particles during the bunch.

The beam structure of REX-ISOLDE (Cern, Switzerland) is, in contrast to the stable beams of UNILAC and ATLAS, very complex: The normal extraction process out

Table 1: Comparison between ATLAS, UNILAC and REX-ISOLDE [1, 2, 3, 4, 5, 6]. See text.

	ATLAS	UNILAC	REX -ISOLDE
acc. Duty Cycle	100 %	25 %	10 %
exp. Duty Cycle	0.25 %	25 %	0.075 %
typ. Repetition Rate	12 MHz	50 Hz	3 – 9 Hz
max. Event Rate	20 kHz	5 kHz	150 Hz
typ. Event Rate	1 kHz	250 Hz	7.5 Hz
Measurement time	7 h	28 h	39 d

of the EBIS source leads to a structure, with a sharp peak and a long tail with lower intensities. The slow extraction is more suited for gamma-particle coincidence measurements, but is still demanding. A typical example for these structures is drawn in Figure 3. The maximum repetition rate of the accelerator is 50 Hz with a duty cycle of 10 %, but the extraction from the source typically has a smaller rate with 3-10 pulses per second, so the duty cycle at the experiment is even lower. To overcome the limited event rate at REX-ISOLDE, at experiments like Miniball a dead-time free DAQ is used, where the readout is performed in the time interval between two EBIS pulses.

In Table 1 the properties of the selected accelerators are summarized. The experimental duty cycle is given by the fraction of time, where beam is on target. The maximum event rate is calculated for an experiment similar to example above, with the choices for the coincidence window $t_{\mathrm{coinc}} = 400$ ns and dead time $t_{\mathrm{dead}} = 50$ µs. Since the absolute efficiency is not taken into account the actual rate is even lower: Experience show, that for a setup as shown in Figure 1 it is about the factor of 20 lower. For this experiment one needs around 10^5 counts per Peak to extract the lifetime and the g-Factor. The fraction of events for populating the 2_1^+ peak of ^{86}Kr is just 0.4 %. To compare the different accelerators the required beam time for this setup and peak is also given.

CONCLUSION

Gamma-particle coincidence measurements offer a great tool to obtain nearly background-free spectra, but the duty cycle and the bunch structure limit the achievable event rate. A precise knowledge of the duty cycle and beam structure is important for the experimentalist to plan experiments. The limited duty cycle and the disadvantageous beam structure of REX-ISOLDE is very challenging. Here the experimentalist needs to increase significantly the efficiency. Furthermore upgrades to higher duty cycles especially for radioactive beam facilities will significantly reduce the measurement time and thus will enhance the possibilities to study new effects in nuclear structure physics.

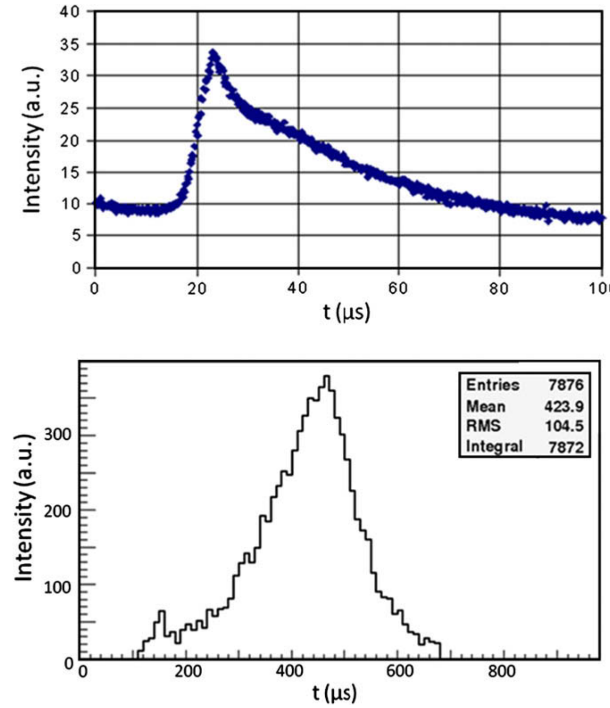

Figure 3: Time structure for an extracted bunch from EBIS at REX-ISOLDE. Top: normal extraction. Bottom: slow extraction mode [1].

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