



EventGenerators

Master Thesis in Physics and Astronomy

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MASTER'S THESIS

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Abstract

This thesis describes...

Sammandrag

Denna tes beskriver...

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1. Introduction

As a part of the construction of international FAIR (Facility for Antiproton and Ion Research), the LAND experimental setup is succeeded by the R³B (Reactions with Relativistic Radioactive Beams) setup, which includes a score of new detectors. During all stages of this process—from designing and calibrating the new individual detectors and the entire setup, to analyzing the data and extracting the underlying physics—simulations are or will be used.

The R³B experiment aims to study nuclear physics, in particular the properties of exotic nuclei far from the valley of stability [1]. The experiments will be performed with radioactive beams, and the aim is to be able to determine the complete kinematics of the reaction. We will here describe a generic experiment of this kind.

The radioactive beam impinges on a target surrounded by detectors. In the case of a reaction at the target—a so called *event*—the reaction products are, ideally, identified by recording where they hit the detector, when they hit the detectors (which allows detector output to be attributed to individual events, which yields the initial and final momentum); how much energy they deposit in the detectors (yielding the charge); and their deflection in a magnetic field, which gives their charge-to-mass ratio, and thus their mass.

This is of course a simplification: the reaction products may decay in-flight, they may be deflected by interacting with the air, or a detector. This is why simulations are used, specifically Monte-Carlo simulations, since the underlying physics is non-deterministic.

While simulations are used to determine how a given reaction product propagates throughout the experimental setup, they are not necessarily needed for the actual reactions at the target, since the purpose of the experiment is to investigate those. In many cases, it is enough to simulate particles with specified initial momenta—matching the kinematic constraints of the reaction—and see how they propagate through the experimental setup: the setup should be able to identify them even if they are not the result of an actual reaction. However, since the setup in practice only should identify actual reactions products, it would be more ideal if the simulations incorporated some of the theory around the reactions to be studied. Having complete knowledge of the outgoing particle in the simulation may also tempt the person using the calibrations to overestimate the detector efficiency, since they will more easily be able to identify their particle when they know what they are looking for, and when no other processes are involved.

1.1. Event Generator for R^3B

As mentioned in the previous section, an experimental event is a reaction between the target and the beam. An *event generator*, on the other hand, is in this context a piece of code that mimics certain reactions for simulation codes. The output of such an event generator would be final state momenta and energies of the reacting particles, which can then be propagated through the simulated experimental setup.

In principle, one can think of an event generator that exactly simulates the reactions at the target and returns a final state with a probability mimic the experiment. However, there are good reasons to not implement this event generator, not all of them related to how unfeasible that project would be—considering our present knowledge of nuclear physics. In the remainder of this section, I will try to arrive at some design principles for a feasible event generator for R^3B .

!!!I AM USING 'I' HERE SINCE I BELEIVE THIS TO BE LESS OF AN OBJECTIVE CONCLUSSION. I'M NOT 100% SURE ABOUT THIS USAGE, THOUGH!!!

1.1.1. Design of an Event Generator

An event generator for R^3B needs to have certain features, that may be more or less important for more general purpose event generators. Firstly, it does not need to reproduce every feature of the experimental spectra, as long as it gives the general features. The actual experiment will determine the details. On the other hand, it needs to be easy to change the underlying model and see how this influences the resulting spectra, since quantities in the model—nuclear level densities, transition rates, etc.—is influenced by the presence of phenomenon the experimenters are actually interested in finding—such as giant resonances or halo structures—that is not directly observable in the experimental data. It should also be possible to steer the event generator to generate certain reactions, that are experimentally distinguishable, so that the event generator could be used to evaluate the detector efficiency for such reactions.

2. Theoretical Background

2.1. Nuclear Collisions

From a macroscopic perspective, nuclei can be viewed as charged particles, and thus collisions (here in a loose sense) between them is essentially governed by the Rutherford scattering formula. This is how the nucleus was discovered in the first place. However, this simple picture breaks down at higher energies, when the de Broglie wave-length ($\lambda \sim p^{-1}$) becomes sufficiently small to resolve the inner structure of the nuclei. At even higher energies, it becomes feasible to model the collision as not taking place between the two nuclei, but by individual protons and neutrons (nucleons).

This leads us to the *participant-spectator* picture of nuclear collisions, in which the collision is viewed as if taking place between a few *participant* nucleons, while the remaining *spectator* nucleons remain mostly unaffected. Such a reaction is known as *quasi-elastic scattering*, since the kinetic energy of the projectile will be much greater than the binding energy of the participants, which further motivates treating them as approximately free particles, and means that the kinetic energy will almost be conserved, hence *quasi-elastic*. !!!POSSIBLY DISCUSS LIMITATIONS!!! The collision between the participant nucleons takes place at a time scale of about 10^{-23} s [2], and is sometimes called a *fireball* or *firestreak*.

However, this is just the first part of the collision. The participant nucleons may have gone unaffected through it, but the resulting system (a so-called pre-fragment) will be highly excited, and will decay to the actual fragment – often by ejecting nucleons, in this context known as evaporating them. The characteristic time-scale for these ejections vary between $10^{-21} - 10^{-16}$ s, depending on the energies and emitted particle [2].

In this picture, we thus have a two-step process to describe nuclear fragmentation. Various models to describe both steps exist in the literature, which can be combined more or less freely—they do not necessarily use the same parameters to describe the nuclei. Models which mainly use parameters like A , the number of nucleons, Z the number of protons, the total nuclear-spin J and the excitation energy E of the nucleus are termed *macroscopic*, while models that directly treat the states of individual nucleons are called *microscopic*. Examples of the former are the *abrasion-ablation model* [3], while the *intranuclear-cascade model* [4] is an example of a microscopic model. As is often the case in nuclear physics, no one model is valid of all range of nucleon number A and incident energies [5].

2. Theoretical Background

Since the focus on this report is to describe an event-generator for a physics experiment, we do not need a state of the art model (see !!!AUTOREF TO SECTION!!! for the arguments). Since the macroscopic properties of nuclei are more easily related to experimental observables, we will restrict our attention to those.

2.1.1. The fast processes—the Goldhaber model

To mimic existing code !!!CITE LEONID?!!! and to allow the user to study a reaction of their interest, the outcome of the first stage of the process is largely determined by user input: the participant projectile nucleons—the cluster—as well as its invariant mass, and the excitation energy of the pre-fragment are both specified by user input. The only specific model used is to determine the momentum of the participant system relative to the projectile, everything else is just conservation of momentum, and an isotropic cross-section. The *Goldhaber model* states that the momentum distribution is given by a Guassian with the width determined by the expectation value of the momentum of an individual nucleon, explicitly

$$\sigma^2 = \langle \mathbf{p}^2 \rangle A \frac{A_p - A}{A_p - 1}, \quad (2.1)$$

where A_p is the number of nucleons in the projectile, A in the pre-fragment, and $\langle \mathbf{p}^2 \rangle$ is the expectation value of the momentum of an individual nucleon. For a Fermi-gas, $\langle \mathbf{p}^2 \rangle$ may be written in terms of the Fermi-momentum \mathbf{p}_f as $\frac{3}{5}\mathbf{p}_f^2$ [6]. !!!THIS IS NOT THE MODEL USED IN LEONID CODE!!!

!!!LEONID USES

$$\sigma^2 = 2(M + m - M_p) \frac{mM}{m + M} = 2Q\mu(m, M),$$

where m is the mass of the participant, M_p the mass of the projectile and M the mass of the pre-fragment. If we take $Q = T = mv^2/2$, we get $\sigma^2 = m^2v^2$, which could imply that this is just the Fermi-momentum? !!!

!!!POSSIBLY MOVE NEXT TO CODE DOCUMENTATION, SINCE IT IS NOT REALLY GENERAL THEORY!!! Momentum conservation implies that

$$p_p = p_i + q_{pf} \quad (2.2)$$

$$p_i + p_t = q_i + q_t \quad (2.3)$$

where p_p is the 4-momentum of the projectile, p_t the momentum of the target, p_i the internal momentum of the cluster; q_{pf} the final momentum of the pre-fragment q_i and q_t the final momentum of the target and cluster, respectively.

Solving the above equation and squaring for p_i and squaring gives an expression for the off-shell mass of the cluster as

$$p_i^2 = p_p^2 + q_{pf}^2 - p_p \cdot q_{pf} = m_i^2 = M_p^2 + M_{pf}^2 - M_p \sqrt{M_{pf}^2 + \mathbf{p}_i^2}, \quad (2.4)$$

where we have evaluated $p_p \cdot q_{pf}$ in the rest-frame of the pre-fragment.

Since we are interested in constructing an event generator, we next transform the cluster's 4-momentum from the projectile to the laboratory frame (the projectile and target momentum is already known in the laboratory frame, the former being zero practically being a definition of that frame). The relevant gamma factor is $\gamma = 1 + T/m_p$, where T is the kinetic energy of the projectile.

Since the collision between the target and the cluster is easier to do in their zero-momentum (ZM) frame, we also need to transform between the laboratory and that frame. This is readily done by noting

$$\bar{\mathbf{P}} = \mathbf{p}_i + \mathbf{p}_t = \gamma(\beta_{\text{ZM}})\bar{m}\beta_{\text{ZM}} = \bar{E}\beta_{\text{ZM}} \implies \beta_{\text{ZM}} = (\mathbf{p}_i + \mathbf{p}_t)/\bar{E}, \quad (2.5)$$

where \bar{E} etc. denotes the energy of the system of both particles. Since we want the β between the lab and the ZM frame, we evaluate all the quantities in the lab frame

$$\beta_{\text{ZM}} = \frac{\mathbf{p}_i}{E_c + m_t}. \quad (2.6)$$

The scattering between target and cluster is back-to-back in the ZM frame, and we generate the scattering angle from an isotropic $\frac{d\sigma}{dt}$, which in practice means that the Mandelstam variable t is a uniform random number. The ZM energy, momentum and scattering angle can be readily expressed in term of the invariant Mandelstam variables

$$E_c = \frac{s + m_i - m_t}{2\sqrt{s}} \quad (2.7)$$

$$|\mathbf{p}_c| = \sqrt{E_c^2 - m_i^2} \quad (2.8)$$

$$\cos \theta = \frac{t - m_i^2 - m_c^2 + 2E_c^2}{2|\mathbf{p}_c|^2}. \quad (2.9)$$

A random polar angle ϕ in $[0, 2\pi]$ is then generated, which together with $|\mathbf{p}_c|$, θ and E_c fix the ZM 4-momentum of the cluster, and also the target by $\mathbf{p}_t = -\mathbf{p}_c$. Using (2.6), these results are boosted to the lab frame, in which we now have an expression for all the relevant momenta.

2.2. The slow process – decay of a compound nucleus

There are at least two models for the decay of a compound nucleus popular in the literature, the Hauser-Feshbach and the Ewing-Weisskopf formulas. Both aim to describe how a compound nucleus in a given macro-state (E^* , J , Z , A) will decay.

The older Ewing-Weisskopf formula, which this work is based on, gives the probability of decaying by evaporating a particle ν as

$$\frac{d^2 P_\nu}{dE_f dt} = \frac{1}{h} \frac{\rho(E_f, J_f)}{\rho(E_i, J_i)} \sum_{S=|J_f-S|}^{|J_f+S|} \sum_{l=|J_i-S|}^{|J_i+S|} T_l(\epsilon_\nu), \quad [7] \quad (2.10)$$

2. Theoretical Background

where P is the probability, E_f the final-state energy, J_f the final-state spin, ρ the level densities and $\epsilon_\nu = E_f - E_i - B_\nu$ the kinetic energy of the evaporated particle, B_ν being its binding energy. s is the intrinsic spin of the evaporated particle, S is the spin of the system consisting of the final state nucleus and evaporated particle, with l being the orbital angular momentum of that state with respect to its center of mass. The sums give all the way to couple these while conserving the total angular momentum $\mathbf{J}_f + \mathbf{s} + \mathbf{l} = \mathbf{S} + \mathbf{l} = \mathbf{J}_i$. T_l is the transition probability. By integrating over E , we get $\frac{dP_\nu}{dt} = \Gamma_\nu$, which is roughly proportional to the probability to decay through the channel ν , $P_\nu = \Gamma_\nu / \Gamma_{\text{tot}}$.

Provided that the characteristic life-time of the system is short compared to the time resolution of the experimental setup, we may essentially treat the decay-widths as probabilities, since – as far as the experiment is concerned – the decay may as well take place instantaneously. Note that the system may undergo multiple decays before it reaches its ground-state, and that time-scale of this entire decay chain must be short by the experimental standards. The time-of-flight resolution of the future R³B setup will be in the picosecond range (10^{-12} s) [1], which is well above the time-scales of single evaporation given by Gaimard and Schmidt ($10^{-21} - 10^{-16}$ s) [2]. Hence we will view Γ_x as the probability to decay by a given process in an unspecified but short time step.

Since we are interested in simulating a decay chain, we want more information than merely the decay by a given particle. We thus take a step back from (2.11), and undo the summation over l

$$\frac{d\Gamma_{\nu,l}}{dE_f} = \frac{1}{\hbar} \frac{\rho(E_f, J_f)}{\rho(E_i, J_i)} \sum_{S=|J_f-s|}^{|J_f+s|} T_l(\epsilon_\nu), \quad (2.11)$$

which finally gives us the decay probability (per unit energy) from an initial state (E_i, J_i) to a final state (E_f, J_f) by emitting a particle ν with angular momentum l .

ν can in principle be any particles. However, the photon must be treated differently as it is massless and thus fully relativistic – which makes the distinction between l and the intrinsic spin unnatural – and removes a polarization state. With this in mind, we get

$$\frac{d\Gamma_\gamma}{dE_f} = \frac{1}{\hbar} \frac{\rho(E_f, J_f)}{\rho(E_i, J_i)} \sum_{l=|J_f-J_i|}^{|J_f+J_i|} T_l(\epsilon_\gamma) \quad (2.12)$$

$$\Rightarrow \frac{d\Gamma_{\gamma,l}}{dE_f} = \frac{1}{\hbar} \frac{\rho(E_f, J_f)}{\rho(E_i, J_i)} T_l(\epsilon_\gamma), \quad (2.13)$$

where $l > 0$ is an integer.

Although ν could be any particle, it becomes more appropriate to model the decay as a fission process if ν becomes sufficiently heavy in relation to the compound nucleus. Fission is usually modeled as a transition first to a *transition state*, beyond which the nucleus will inevitably fission [8]. The present work does not include fission, and we will thus not discuss its details here. Swiateck discussed the possibility of treating particle

emission and fission in an essentially symmetric fashion, by using a transition state formalism also for lighter particles [?]. !!MAY BE INTERESTING TO SAY SOMETHING ABOUT THIS. FIND SOURCE ON WHY THIS APPROACH ISN'T USED!!

We will now describe models for the level density ρ and transition probability T_l .

2.2.1. Level densities

The level density $\rho(E, J)$ enumerates the number of levels of a given nucleus in an energy range $[E, E + dE]$ with a given spin J . We have in our notation suppressed the dependence on A and Z . We use the following expression

$$\rho(E, J) = \frac{\exp(\beta U + a/\beta)(1 - \exp -a/\beta)}{\sqrt{1 - \frac{1}{2}U\beta \exp -a/\beta}} \frac{2J + 1}{\sqrt{2}48} \frac{\beta}{U^{3/2}} \frac{1}{\sqrt{\Theta_{\perp}^2 \Theta_{\parallel}}} \quad (2.14)$$

where $U =$

3. The Code

The CODEZ code, based on CODEX [9], contains models for the various quantities needed in statistical models. It is written to be easily extendable and to a large extent modular, so that the various models can easily be replaced. Details on the specific models may be found in the corresponding sections below. To achieve this modularity, the code is written in C++ and makes use of *object-oriented* programming concepts.

The program is roughly structured as follows: Decay processes are specified by model objects, which contain models for calculating transition probabilities to possible final states. “Probabilities” here refers to $d^2P_\nu/dtdE$, roughly the probability to decay to a final state in energy interval dE during the time dt by the process ν . The probabilities need not be normalized. The model objects implement a function that for a given energy discretization tabulates specific information about the decay, along with the corresponding cumulative probability. A complete table of transition probabilities and final states is generated by looping over all model objects.

A de-excitation step may then be performed by drawing a random number between 0 and the final cumulative probability, and looking up the corresponding decay in the table. Several one-step decays may thus be performed with little extra computational costs, which is valuable when verifying models.

3.0.2. Transition Probabilities

The transition probability $d^2P_\nu/dtdE$ from an initial state i to a final state f by the process ν is roughly given by

$$R \equiv \frac{d^2P_\nu}{dtdE} = \sum_j \frac{\rho_f}{\rho_i} T_{\nu,j}(E_i, E_f). \quad (3.1)$$

Here, ρ is the nuclear level density for the initial and final states, $T_{\nu,j}(E_i, E_f)$ the transmission coefficient, with j being a collective index describing the different ways a process may carry the nucleus from i to f .

Glossary

intro an introduction, page 1

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A. Appendix 1

B. Code

```
struct spec_POS_t
{
    SPEC_FLOAT(_dx,          2.5, "cm", "full_width_x_of_active_volume")
    ;
    SPEC_FLOAT(_dy,          2.5, "cm", "full_width_y_of_active_volume")
    ;
    SPEC_FLOAT(_dz,          0.03, "cm", "full_width_z_of_active_volume");
    SPEC_FLOAT(_lgheight,    2, "cm", "lightguide_height_over_active_
        volume");
    SPEC_FLOAT(_lgheadd,     0.70, "cm", "size_of_square-shaped_lightguide-
        heads");
    SPEC_MEDIA(_type,        "plastic", "", "POS_active_volume_material.");
    SPEC_MEDIA(_lgtype,      "plastic", "", "Lightguide_material");
};
```

```
#include "auto_gen/spec_info_pos.hh"
```

```
#define UNUSED_PARAM(x)
```

This function is called when GGLAND creates the detector.

```
gg_geom_obj *make_POS(void *vspec, uint32_t UNUSED_PARAM(mask_set)
, const transform_matrix *loc_rot
, det_name_no_info *name_no)
{
```

C. Svenska här