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THE FIRST GENERATION OF γ-RAYS FROM HOT NUCLEI

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A method to extract spectra of first generation γ-rays from nuclear levels at high excitation energy is described. The reliability and convergence properties of the method are tested on simulated data. Some experimental first generation γ-ray spectra are presented.

1. Introduction

The γ-ray transition probability can be used to investigate nuclear structure in regions of high level density. The transition rate depends on two factors: (1) the density of accessible final states and (2) the similarities between the initial and the final state. The resulting γ-ray energy distribution will be a direct measure of these factors.

In general, the γ-decay from high excitation energy involves a cascade of transitions. With the available timing techniques there is no way to pick out the first transition in a specific cascade. The measured spectra will contain contributions from all generations of γ-rays. Unfortunately, these generations are not well separated in energy. The determination of the energy distribution of the first generation of γ-rays is further impeded by Compton scattering and pair production in the γ-counter.

In this work we present a method to extract the first generation of γ-rays from nuclei at high excitation energy, produced in reactions with two products; the daughter nucleus and a charged particle. The experimental setup is based on measuring the charged ejectiles in coincidence with γ-rays from the daughter nucleus.

The formalism of the method is presented in section 2 and tests performed on simulated γ-ray spectra are discussed in section 3. In section 4 some first generation γ-ray spectra are shown. Finally, concluding remarks are given in section 5.

2. The method

The experimental procedure has been developed at the Oslo cyclotron and is designed to study γ-radiation as a function of excitation energy. The (^{3}He, αγ) and (d, tγ) pickup reactions and the (^{3}He, ^{3}He′γ) and (d, d′γ) inelastic scattering reactions on nuclei in the rare earth region have been extensively studied. All these reactions populate states in a narrow spin window and allow an accurate determination of the excitation energy. The charged ejectiles are recorded with ΔE–E telescopes positioned at forward angles. In coincidence, γ-rays are detected with an array of several NaI counters. Details on the experimental procedure can be found elsewhere [1–3].

The present method is based on the assumption that states populated after the first γ-transition have the same decay properties as states populated directly in the particle reaction at that excitation energy. Using the reactions listed above this condition is probably fulfilled in regions of high level density. Here, the nucleus seems to attain a compoundlike system prior to γ-emission [3]. Furthermore, the γ-decay in continuum consists of statistical dipole radiation carrying a vanishing spin transfer on the average [4,5].

The method is illustrated in fig. 1. For each excitation region (bin) we produce from the particle-γ coincidences a γ-ray spectrum denoted f_i. The first generation γ-ray spectrum of the highest excitation energy (bin 1) is estimated by

$$h = f_1 - g, \tag{1}$$

where g is a weighted sum of all spectra

$$g = \sum_i n_i w_i f_i. \tag{2}$$

The coefficients w_i are unknown and represent the probability ($\Sigma\, w_i = 1$) of the decay from bin 1 to bin i. In fact, the w_i values correspond to the first generation γ-ray spectrum h, provided that h is unfolded by the response function of the NaI counters. This close relation allows a determination of w_i (and h) through a fast converging iteration procedure (see next section).

The coefficients n_i of eq. (2) are determined in such a way that the area of each spectrum f_i multiplied by n_i corresponds to the same number of cascades. Thus, for

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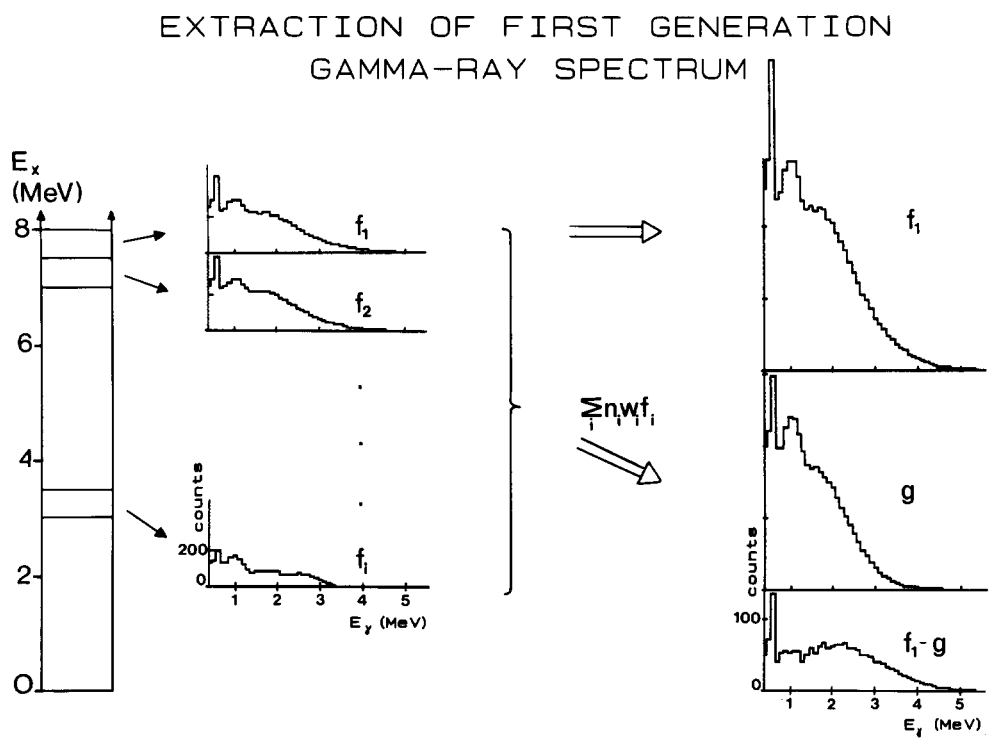


Fig. 1. The method used to obtain the first generation γ-ray spectrum.

singles particle spectra of constant cross-section we have $n_i = 1$. According to the experimental conditions one can choose between two normalization methods.

Singles normalization: The singles particle cross-section is proportional to the number of populated states and thus to the number of cascades. Let S_1 and S_i be the cross-sections (arbitary units) measured for bin 1 and i. The normalization factor for bin i is then given by

$$n_i = S_1/S_i. \tag{3}$$

Multiplicity normalization: The γ-ray multiplicity as a function of excitation energy can be deduced from the experiments in various ways [1,6]. Let us assume that the γ-ray multiplicity M_i of bin i is known and let $A(f_i)$ represent the area (number of counts) of spectrum f_i. Then the single particle cross-section is proportional to $A(f_i)/M_i$, and according to eq. (3) we find

$$n_i = M_i A(f_1)/M_1 A(f_i). \tag{4}$$

In cases when M_1 is well determined an area consistency check can be applied to eq. (1). Let us assume that a correction has to be introduced by substituting g with αg (α close to unity). The area of the first generation γ-ray spectrum is then

$$A(h) = A(f_1) - \alpha A(g) \tag{5}$$

and corresponds to a γ-ray multiplicity of one unit. The same value can be expressed by

$$A(h) = A(f_1)/M_1. \tag{6}$$

Combining eqs. (5) and (6) we obtain

$$\alpha = (1 - 1/M_1) A(f_1)/A(g). \tag{7}$$

Even with well determined n_i values (either by singles or multiplicity normalization) the introduction of α might be useful in order to compensate for an improper choice of the weighting function w_i.

3. The method applied to simulated γ-ray spectra

In this section we test the method on theoretical spectra. The adventage of such a procedure is that the obtained first generation spectrum can be compared to the exact solution.

The theoretical f_i spectra are calculated using a decay model based on Monte Carlo simulations. Above an excitation energy of $E_x = 2\Delta = 2$ MeV we have used a level density function according to the Fermi gas model prediction. Ground band states ($I^\pi = 0^+, 2^+, 4^+$ and 6^+) and vibrational states ($E_x = 1$–2 MeV) have also been taken into account. A detailed description of the model is given in ref. [7].

For each excitation energy (each bin i) we have simulated 2000 cascades of γ-rays. The computer code

of the decay model accumulates two types of spectra: one spectrum contains all γ-rays in the cascades and another contains the first γ-ray in each cascade. These spectra represent full energy photo-absorption events. In order to simulate NaI spectra we fold them with the NaI response function. Hence, we have access to both folded and unfolded theoretical f_i and h spectra for all excitation energies.

In fig. 2 the method is tested for singles and multiplicity normalization of the n_i coefficients. The shown spectra, which are folded, represent two typical regions of interest. In the high excitation region ($E_x = 7.7$ MeV) the γ-decay takes place within a Fermi gas and the energy distribution is of continuum type. In the lower excitation region ($E_x = 3.2$ MeV) γ-ray bumps appear due to sudden changes in the level density around 1 MeV (vibrational states) and 2 MeV (2 quasi-particle states) of excitation energy.

The agreement with the exact solution (lower part of fig. 2) is excellent for both normalizations. This is not surprising since the correct weighting function w_i, which is known from the simulations, has been applied. However, we observe small variations, mainly due to the statistical uncertainties in the f_i and g spectra. The width of bins also plays some role, however, the applied width of 0.5 MeV seems sufficiently narrow to obtain an adequate description of the true decay pattern.

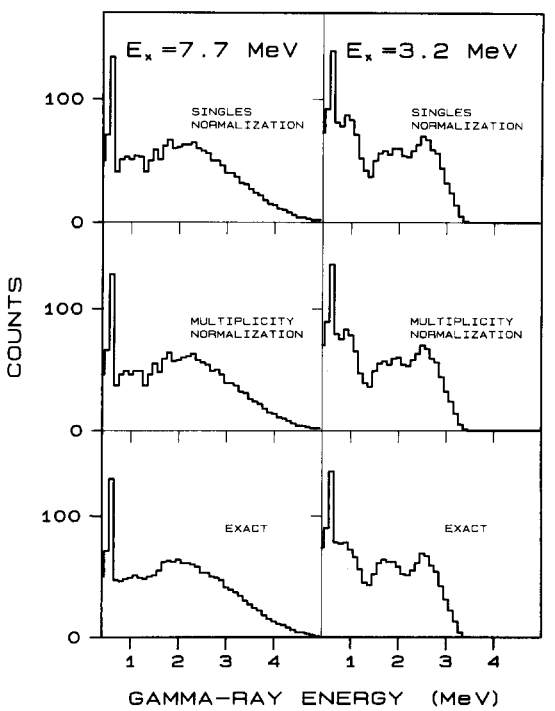


Fig. 2. First generation γ-ray spectra from 7.7 MeV and 3.2 MeV of excitation energy.

The dependence on the weighting function w_i is demonstrated in fig. 3. With different choices of w_i (see left part) we find that the shape of the first generation spectra (right part) remains almost the same. The most striking effect is a change in area which can be understood in the following way: Take for instance the weighting function with the lowest energy centroid (middle part of fig. 3). The g spectrum is in average built up of spectra from high excitation energy. Thus, this spectrum represents higher multiplicity and more counts. The result is that the difference spectrum $h = f_1 - g$ contains too few counts. In such cases the area correction procedure (eqs. (5) and (7)) can to some extent compensate for these effects. However, a better treatment is of course to find the correct weighting function and apply it to the data.

The weak dependence of the first generation γ-ray spectra for various weighting functions w_i can be utilized to find the correct w_i itself. The following iteration procedure is suggested:

(1) Apply a trial function w_i.
(2) Deduce h.
(3) Transform h to w_i (i.e. unfold h, make h having same energy calibration as w_i, normalize area of h to 1).
(4) If w_i (new) $\approx w_i$ (old) then finished, else proceed with (2).

We have tested the convergence of this iteration procedure on spectra from the continuum region ($E_x = 7.7$ MeV). In fig. 4 the centroid of the unfolded first

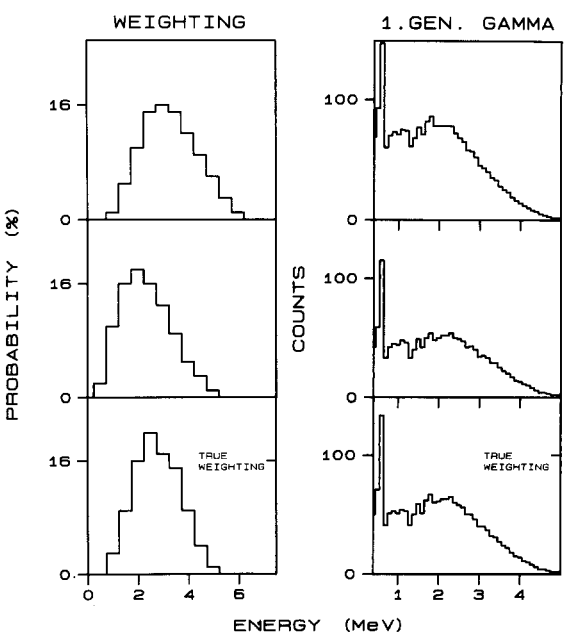


Fig. 3. First generation γ-ray spectra obtained with various weighting functions w_i.

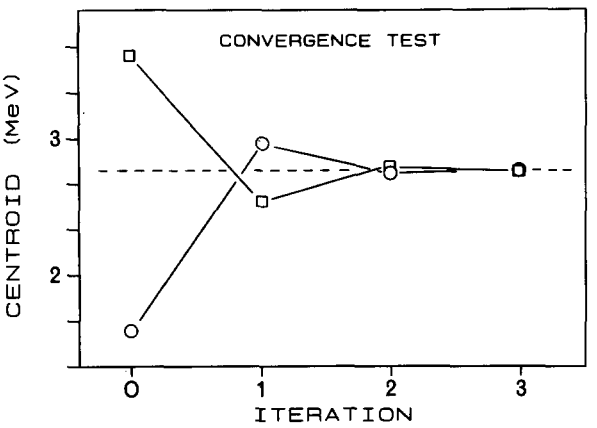


Fig. 4. The γ-ray energy centroid of the unfolded first generation spectra deduced in the iteration procedure (see text).

generation spectrum is shown for each iteration. As trial function we have used a constant distribution with a width of 3 MeV. Two tests have been performed, one test with the trial function 1.2 MeV below (circles) and one with the trial function 0.8 MeV above (squares) the exact centroid (broken line). Already in the first iteration the centroids in both cases are as close as ~ 0.2 MeV from the correct value. In the next iteration the deviation is reduced to ~ 0.03 MeV. Excellent agreement is obtained in the third iteration. However, taking into account experimental uncertainties the solution after second iteration is fully acceptable.

The convergence has also been tested for the decay within a regime of states with abrupt changes in the level density. Here, prominent decay routes appear as γ-ray bumps in the spectra. Fig. 5 demonstrates that the unfolded first generation γ-ray spectrum, even in this case, is reproduced almost perfectly after second iteration.

It is interesting to notice from fig. 5 that the convergence is faster for the higher energy part of the spectrum. This means that the high energy part is less dependent on other generations of γ-rays and is therefore most reliable.

4. Experimental first generation γ-rays

The extraction of the experimental first generation γ-ray spectra can imply some difficulties. From a statistical point of view the spectra contain about the same number of counts as used in the simulations above. Furthermore, the n_i factors can easely be determined with an accuracy of 3–4%. However, the experimental conditions can introduce severe systematical errors. The

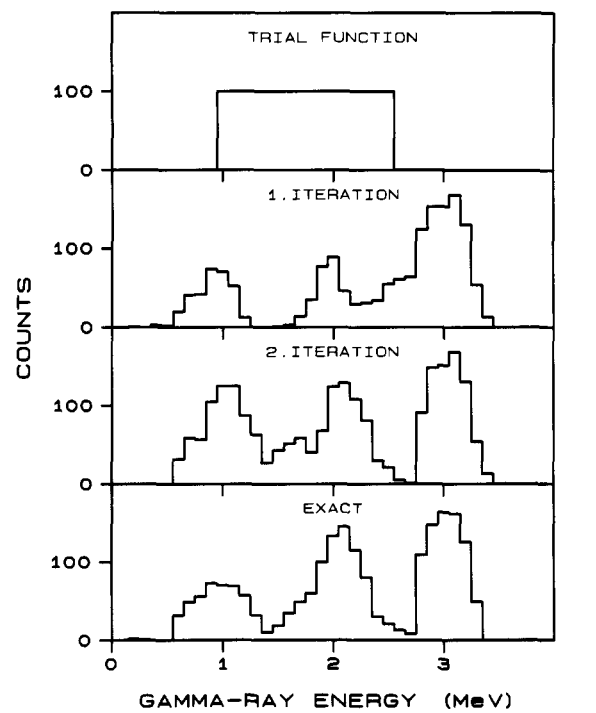


Fig. 5. First generation γ-ray spectra. The iteration procedure is applied in a region with abrupt changes in the level density (E_x = 3.2 MeV).

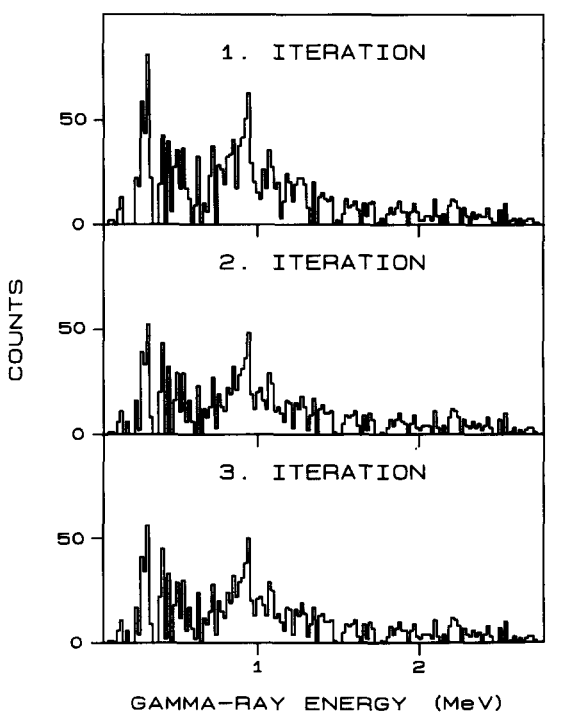


Fig. 6. Experimental first generation γ-ray spectra from E_x = 2.7 MeV measured in the ^{163}Dy(^{3}He, αγ)^{162}Dy reaction. A fast convergence is observed.

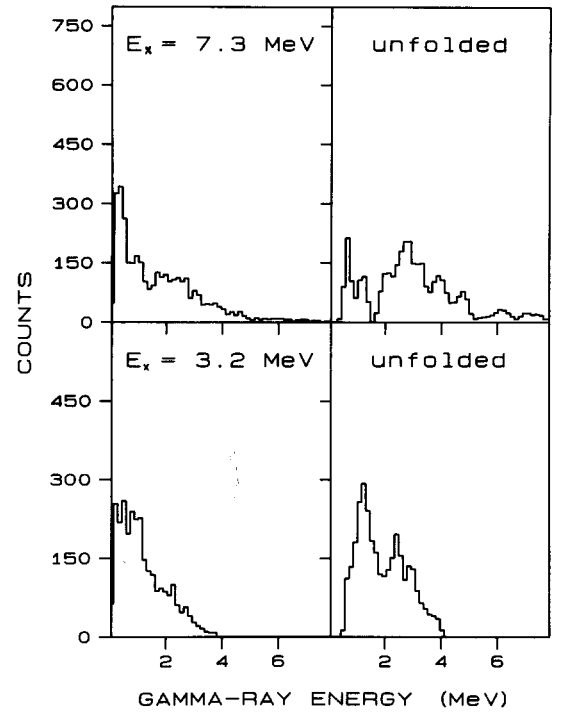
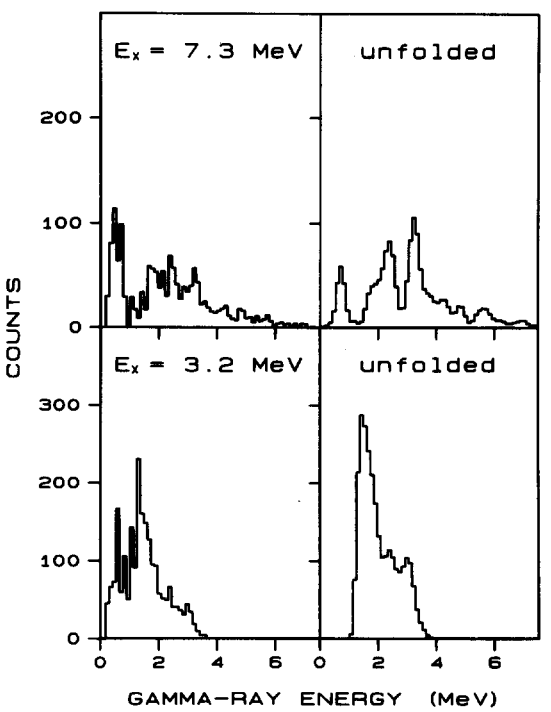


Fig. 7. First generation NaI γ-ray spectra (left) and unfolded spectra (right) deduced from the ^{163}Dy(^{3}He, αγ)^{162}Dy reaction with $E(^3\text{He}) = 45$ MeV. The excitation energy window has a width of ~ 1 MeV.



measurements should run with minimal pileup effects both for the particle-counters and the γ-counters. It is important to use highly enriched targets without any contaminations. Also isomeric states in the level scheme can complicate the analysis.

In fig. 6 is shown first generation γ-ray spectra from an excitation energy of 2.7 MeV. The data are taken from the ^{163}Dy(^{3}He, αγ)^{162}Dy reaction with a beam energy of 45 MeV. In the first iteration a trial weighting function w_i according to the Fermi gas model prediction has been chosen. The procedure has converged after second iteration, as expected from the tests in sect. 3.

Figs. 7 and 8 show the final results of both the NaI and the unfolded γ-ray spectra for ^{162}Dy and ^{170}Yb, respectively. The excitation regions are typical for the decay in high and low level density regimes. The shown unfolded spectra demonstrate the problem of proper unfolding of spectra with few counts. However, the results are very encouraging with respect to future experiments with higher statistics.

5. Conclusion

A method to extract first generation γ-ray spectra has been described, tested and applied to data from the (^{3}He, αγ) reaction. The weighting function neccessary in the subtraction of other generations of γ-rays can be found in a fast converging iteration procedure.

The method works well in various excitation regions, also in regions with abrupt changes in the level density. The reliability of the method makes it a promising tool in the study of hot nuclei where the search for phase transitions is of outmost interest.

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Fig. 8. First generation NaI γ-ray spectra (left) and unfolded spectra (right) deduced from the ^{171}Yb(^{3}He, αγ)^{170}Yb reaction with $E(^3\text{He}) = 45$ MeV. The excitation energy window has a width of ~ 1 MeV.

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