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# γ-ray spectroscopy with a $^{8}$He beam

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**Abstract**

The $^{8}$He + $^{208}$Pb reaction was studied in the first experiment with the EXOGAM germanium detector array using beam delivered by the SPIRAL facility. γ-rays from direct and fusion–evaporation reactions were observed with high resolution. γ–γ coincidence data were obtained at a beam intensity level of $10^5$ $^{8}$He particles per second. Specially designed absorbers and beam detectors could further reduce the background radiation by orders of magnitude.


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## 1. Introduction

The advent of accelerated radioactive beams opens a new era in nuclear physics. The use of such beams allows access to new isotopes and increases the production rates of nuclei which are hardly accessible using stable beams. One of the leading facilities specially designed to produce radioactive beams at energies around the Coulomb barrier is SPIRAL [1]. The SPIRAL facility at GANIL provides radioactive beams from $^{6}$He as the lightest to $^{81}$Kr as the heaviest in an energy range from 2–10 MeV A, some ions even up to 20 MeV A. In this paper we report on use of the $^{8}$He radioactive beam for fusion reactions with a $^{208}$Pb target, giving access to high-angular-momentum states in $^{212}$Po. $\gamma$-rays were detected with the EXOGAM germanium-detector array [2,3]. Emphasis is given to the techniques which can be used to further reduce the background radiation when very low-intensity beams are employed.

During recent years, other experiments combining $\gamma$-ray detection with fusion–evaporation reactions have been performed with radioactive beams of $^{19}$Ne ($t_{1/2} = 17$ s) [4], $^{6}$He (807 ms) [5] and $^{145}$Sm$^{m}$ (0.96 μs) [6]. The present work builds on these experiences and now investigates the use of a very exotic, low-intensity beam of $^{8}$He (119 ms).

## 2. Experimental details

Radioactive $^{8}$He was produced through the fragmentation of a 75 MeV A $^{13}$C beam on a thick carbon target. After extraction from this primary target, the $^{8}$He was reaccelerated to 28 MeV in the CIME cyclotron and focused on to a secondary target of $^{208}$Pb. By means of standard beam-transport elements, beam profilers and other beam diagnostics, the $^{8}$He particles were focused to a waist less than 9 mm diameter at the target position. The energy at the centre of the 30 mg/cm$^{2}$ target was 26 MeV. A beam stop, preceded by a 70 mm diameter scintillator detector used to monitor the beam intensity, was placed 3.8 m downstream of the target. With the target in place only 7% of the beam was recorded by the scintillator detector, the rest being scattered; therefore, the radiation background from the beam stopper itself was minimal. We discuss below the scattered-beam effects. During the experiment, the beam intensity varied between $3 \times 10^{4}$ and $3 \times 10^{5}$ particle/s. The effective time with beam on target was about 60 h.

The $\gamma$-rays were detected with an early implementation of the EXOGAM array, consisting of three full-sized EXOGAM clover detectors and one smaller clover detector in the close, so-called "gamma-cube", configuration [3]. The average target–Ge crystal distance was 85 mm, which resulted in a total $\gamma$-ray full-energy-peak efficiency of 3.4% at 661 keV.

The SPIRAL facility is classified as an ISOL project, with $\approx 10^{5}$ reduction of the radioactive-ion beam intensity compared to stable-ion beams. Therefore, great care must be taken to reduce background radiation and radiation from beam particles not producing useful interactions with the target. Depending on the radioactive beam species and its half-life, particles stopped in the target might result in an appreciable source of background. A device capable of holding 22 different targets, which could dispose of and replace a target remotely (under vacuum) is therefore available in conjunction with EXOGAM. The target changing system was used to evaluate $\gamma$-radiation rates with the lead target, an empty target frame, a beam stopper, etc.

## 3. Using a radioactive beam

The reaction products can have similar intensities to the room background radiation when low-intensity beams are employed. This is in contrast to stable-beam experiments, where germanium-detector arrays, such as Euroball [7] and Gammashpere [8] are used to identify weak reaction channels among the dominant products. In the present experiment the background radiation resulted in a singles $\gamma$-ray detection rate of 1440 Hz (on average 90 Hz per germanium crystal). By applying a $10^{5}$ ion/s $^{8}$He beam this rate increased by only 110 Hz, with its largest component being 981 keV $\gamma$-ray events ($\approx 18$ Hz in the full-energy peak) resulting from the $\beta$ decay of the $^{8}$He beam.

In the analysis in order to reduce the background caused by scattering between crystals, each clover was treated as single detector, i.e. the γ-ray energies from the four crystals were added together. A singles γ-ray spectrum is shown in Fig. 1a. This spectrum is dominated by the decay of the beam particles and room background. The $^{8}$He β decays with a half-life of 119 ms to $^{8}$Li [9] and 84% of the decays are followed by a 981 keV γ-ray transition clearly observed in the spectrum. The remaining $^{8}$He decays are by β-delayed neutron emission to $^{7}$Li, with a first excited state that decays by a 478 keV γ-ray transition to the ground state. The 478 keV peak appears broad in the spectrum (Fig. 1a) due to the Doppler shift caused by the neutron emission. The other indicated γ-ray peaks originate from the uranium and thorium decay series, except for the well known 1461 keV transition from the decay of $^{40}$K.

Fig. 1b shows a spectrum in coincidence mode and represents the total projection of a γ–γ matrix.

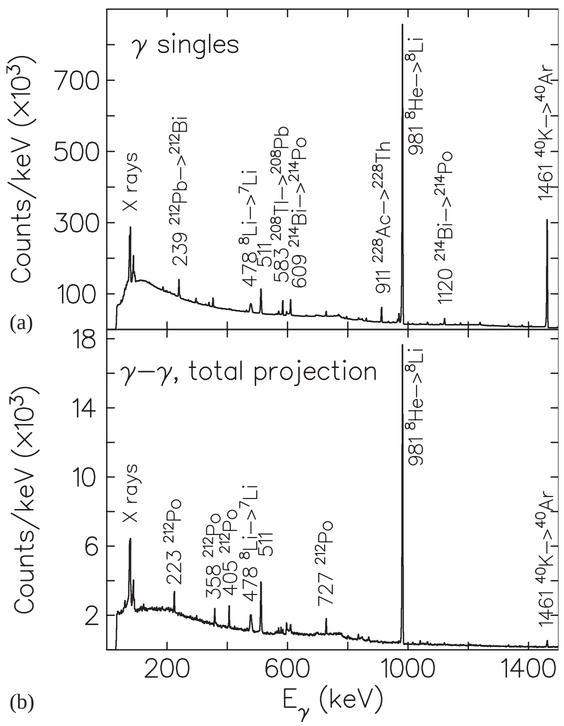


Fig. 1. Singles γ-ray (a) and γ–γ coincidence matrix projection, (b) spectra from the $^{8}$He + $^{208}$Pb reaction (see text for details).

Most of the background from the uranium and thorium families has disappeared and the $^{40}$K transition is barely visible. The 981 keV transition from the $^{8}$He decay is the strongest line in the spectrum. This can be explained by a β–γ or bremsstrahlung-γ coincidence in the germanium detectors, which is possible due to the large, 10.65 MeV, endpoint energy of the β decay. Otherwise, a new set of transitions appears due to the decay of excited states in $^{212}$Po, the most probable product of fusion reactions (following the evaporation of four neutrons).

Due to the high intensity of the background when compared with the reaction γ-rays of interest, it is important to find ways to reduce the background radiation. Here we examine the effect of absorbers, and propose the use of both β-particle detectors and beam-particle detectors.

The $^{8}$He beam can Coulomb scatter from target nuclei and become implanted in the wall of the beampipe. The cross-section of Rutherford scattering (elastic Coulomb scattering) decreases with the scattering angle, but it is huge even at large angles. In our particular experiment it is 13 barn/sr at $\theta = 30^{\circ}$, much higher than for any other nuclear process. As a consequence, the radiation associated with the β decay of the beam arises mainly from forward angles. This can be reduced by using absorbers. The effect of the absorbers was tested by covering the beampipe at forward angles with lead shielding, as illustrated in Fig. 2. As the spectra show, the absorber reduces the intensity of the 981 keV transition and the continuous low-energy background. We estimate that the 981 keV transition was reduced by about 40% using this simple setup. However, significant Rutherford scattering still occurs at 90° (when the scattered beam stops in the target or the adjacent wall of the vacuum chamber).

The radiation associated with the beam could be reduced even more with specially designed absorbers. The absorbers should shield the detectors from the radiation coming from any part of the beam tube, apart from the direction of the target. However, the singles events due to the electromagnetic radiation from the beam particles scattered at ≈90° still remain. To design the absorbers detailed Monte Carlo simulations are

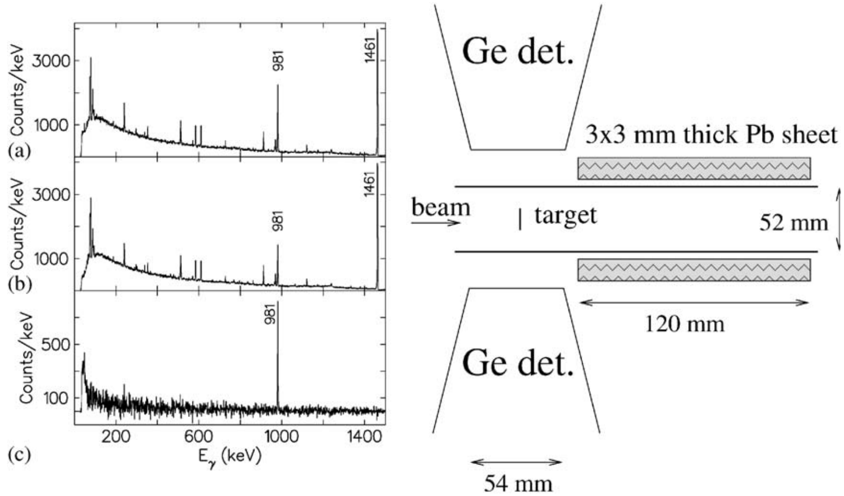


Fig. 2. The effect of using lead shielding on the beam tube. (a) γ-ray spectrum without Pb shielding, (b) with Pb shielding, (c) the difference spectrum of spectra (a) and (b). The (a) and (b) spectra are normalised to the 1461 keV intensity. The beam intensity was $\approx 4 \times 10^4$ ions/s. The setup with the position and thickness of the Pb shielding is also shown.

needed, in order to study both the absorption and scattering due to the added materials.

The β radiation coming from the target can be attenuated [10] by polythene absorbers in front of the detectors, which would reduce the γ-ray coincidence rate associated with the radioactive beam significantly. An alternative to passive absorbers is the use of thin scintillation β detectors [11], operated in veto mode, which would have the advantage of less absorption of low-energy γ-rays.

The typical beam intensity in the present experiment was around $10^5$ ion/s. In stable-beam experiments beam intensities around 1 particle-nanoampere (pnA), which corresponds to $6 \times 10^9$ ion/s, are usual. These rates can be compared to the radiofrequency of the cyclotron accelerator, which in the present experiment was 11 MHz. It is found that in the case of stable (intense) beams there are hundreds of ions within one cyclotron cycle. In this situation, it is a standard procedure to require γ-ray/cyclotron-pulse coincidences in order to select the "prompt" beam-related events. This method was successfully applied also for high-intensity radioactive beams [4]. However, in our case it did not work: the rate of γ-rays from the reaction was too low compared to the background radiation, and no time structure relative to the RF was observed.

Table 1
Comparison of high-intensity (stable) and low-intensity (radioactive) beams.

| | Stable beam | Radioactive beam |
|---|---|---|
| Typical beam intensity | $6 \times 10^9$ ions/s ($\approx 1$ pnA) | $10^5$ ions/s |
| Typical radiofrequency | 11 MHz ($\Delta t \approx 90$ ns) | |
| Ions/cycle | 550 ions/cycle | 1 ion in 110 cycles |

In the case of low-intensity radioactive beams, on average the beam rate is much less than one particle per cyclotron cycle; in our example the rate was just 0.009 ion/cycle (see Table 1). By mounting a beam detector in front of the target, and taking data only when a beam particle arrives, the ratio of events of interest to background events can be improved dramatically. In our example, the background could be reduced by a factor up to $1/0.009 = 110$ (if we consider that the intensity of the γ-rays of interest is much less than the intensity of the background radiation) without reducing the intensity of the prompt reaction γ-rays. A further reduction of the background radiation can be obtained by using an anticoincidence beam detector after the target (Fig. 3). The majority of the beam particles will be Rutherford scattered in the forward direction and recorded by this detector. However, when a fusion-evaporation reaction occurs, no charged particle reaches the anticoincidence detector. (If the species of interest is produced after evaporating protons and/or α particles, the detection threshold would be adjusted to exclude these light ions.) Therefore, by using a beam detector downstream of the target in veto mode, the background radiation can be further reduced. The overall reduction would be orders of magnitude, the exact value depending on several factors: the size of the detector, the distance from the target, reaction kinematics, etc.

Thin carbon foils can be used as beam detectors. These are based on the detection of electrons knocked out by the beam particles. Similar devices are used in Rutherford scattering experiments and time-of-flight measurements through recoil separators. They can have close to 100% efficiency [12] (depending on the $Z$ and energy of the ion and the foil thickness), have a time resolution better than 0.5 ns [12,13], and use carbon foils with a thickness of 1–5 $\mu m/cm^2$ [14].

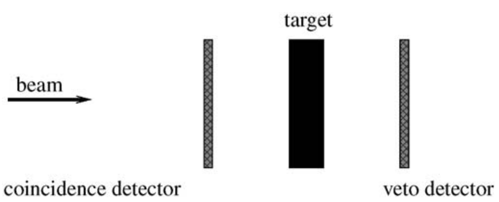


Fig. 3. The setup suggested to reduce background when using low-intensity beams.

## 4. Results

The strongest fusion-evaporation channel at 26 MeV beam energy is the $^{208}Pb(^{8}He, 4n)^{212}Po$ reaction, with an estimated cross-section of ≈500 mb. The level structure of $^{212}Po$ has been studied previously by Poletti et al. [15] using the $^{208}Pb(^{9}Be, \alpha n)$ reaction. A gated spectrum of the two-fold coincidence events from the present work is shown in Fig. 4a. Excited states up to spin $(11^-)$ at an excitation energy of 2411 keV are clearly identified. We note that the present radioactive-beam results fall short of the stable-beam data with respect to spectral details. However, the stable-beam results obtained with much higher beam intensity only add a few more spin units and 500 keV of excitation energy compared to the present data.

In addition to fusion-evaporation reactions, there is evidence for neutron-pickup reactions in the data. A gated γ-ray spectrum for $^{209}Pb$ is shown in Fig. 4b. The population of the low-spin single-particle states (see level scheme in Fig. 4)

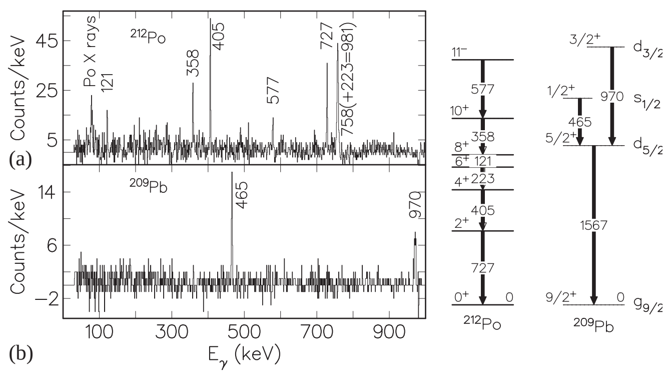

Fig. 4. Gated γ-ray spectra for: (a) $^{212}Po$ (gated at 223 keV) and (b) $^{209}Pb$ (gated at 1567 keV). $^{212}Po$ and $^{209}Pb$ were produced in fusion-evaporation and neutron-pickup reactions, respectively. In the 223 keV γ-ray gated spectrum, in addition to the transitions belonging to $^{212}Po$, a 758 keV peak is also visible as a result of Compton scattering between detectors of the strong 981 keV γ-ray. The partial level schemes are also shown [9,15], together with the proton single-particle configurations for $^{209}Pb$.

suggests that $^{209}Pb$ was populated in the neutron (from $^{8}He$) + $^{208}Pb$ pickup reaction, and not fusion-evaporation. Although the statistics of the present experiment are low, it seems that the reactions leading to $^{212}Po$ and $^{209}Pb$ have comparable cross-sections (with a factor of about two in favour of $^{212}Po$).

## 5. Conclusions

The first results using the EXOGAM Ge-detector array with a radioactive beam have been presented. The beam intensity of order $10^5$ ion/s and the γ-ray detection efficiency of 3.4% at 661 keV were high enough to identify the products of fusion-evaporation and direct reactions. Specially designed absorbers and β detectors could greatly reduce the background from the β decay of the radioactive beam. By using these, and beam detectors both before and after the target, the background (both related to the beam and room background) could be reduced by orders of magnitude. Furthermore, the full EXOGAM array is designed to give a γ-ray detection efficiency of up to 28% at 661 keV, so that dramatically improved data can be anticipated.

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