SEARCH FOR SPONTANEOUS MUON EMISSION FROM LEAD NUCLEI

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Abstract

We describe a possible search for muonic radioactivity from lead nuclei using the base elements (“bricks” composed by lead and nuclear emulsion sheets) of the long-baseline OPERA neutrino experiment. We present the results of a Monte Carlo simulation concerning the expected event topologies and estimates of the background events. Using few bricks, we could reach a good sensitivity level.

1 Introduction

In the late 80’s, some theoretical work was dedicated to investigate possible exotic types of nuclear radioactivity, consisting in the emission of light particles such as pions or muons from heavy nuclei [1, 2]. Although the theoretical estimates indicated a larger branching ratio for spontaneous (or neutron-induced)
muon emission than for pions\textsuperscript{1}, the experimental searches were mostly dedicated to the pionic radioactivity \cite{3, 4}, since the detection conditions were more favourable with the used experimental set-ups. None of the experiments using heavy radioactive nuclei could prove the existence of the pionic or muonic radioactivities, but some of them may have produced indications in support of these hypotheses \cite{5}. Some experimental indications for pionic radioactivity come from the interpretation of radioactive super giant halos in crystals \cite{6}; such a technique, however, cannot give precise information concerning the nature of the source or allow quantitative estimates of branching ratios, lifetimes, etc. A short review of the theoretical problems and of the experimental results obtained, mostly for the pionic radioactivity, may be found in ref. \cite{7}.

Muons or pions could be emitted by nuclei through the decays \cite{2}:

\begin{equation}
(A, Z) \rightarrow \mu^\pm + \nu_\mu + (A_1, Z_1) + \ldots + (A_n, Z_n),
\end{equation}

\begin{equation}
(A, Z) \rightarrow \pi^\pm + (\pi^0) + (A_1, Z_1) + \ldots + (A_n, Z_n),
\end{equation}

where, for reasons of energy and momentum conservation, the number of fragments \( n \) is \( \geq 2 \). The nuclei \((A_1, Z_1), (A_2, Z_2), \ldots, (A_n, Z_n)\) would yield a sequence of \( \beta^- \) decays leading finally to stable nuclei with a balanced neutron-proton ratio.

In ref. \cite{2} some nuclear charge thresholds for different possible spontaneous particle emission were listed:

(i) \( \mu^\pm \) (prompt muon) for \( Z \geq 72 \)

(ii) \( \pi^\pm \) (prompt pion \( \rightarrow \) delayed muon) for \( Z \geq 76 \)

(iii) \( 2\mu^\pm \) (prompt muon pairs) for \( Z \geq 91 \)

(iv) \( 2\pi^\pm \) (prompt pion pairs \( \rightarrow \) delayed muon pairs) for \( Z \geq 100 \)

Natural lead is mainly composed by three nuclides: \(^{206}\text{Pb}\) (24.1\%), \(^{207}\text{Pb}\) (22.1\%) and \(^{208}\text{Pb}\) (52.4\%). They are stable nuclides, but the channels (i) and (ii) are energetically allowed.

The spontaneous or neutron induced fission of \( \text{Pb} \) has never been observed. Nevertheless, the decay into a lepton-antilepton pair (muon and neutrino) or into a quark-antiquark pair (forming a pion) could enhance the probability that the remaining “hyper-cold” nuclear state be unstable \cite{1}.

A search for a \( \text{Pb} \) muonic decay can be made as a byproduct of the OPERA experiment \cite{8}. Uranium or Thorium could be used in the future; such possible experiments would benefit from the results of an initial search using Lead.

In the hypothesis of the decays (1) and (2), the fission fragments would remain nearly at rest; most of the available energy would be used to produce the \( \mu \) (or \( \pi \)) and the kinetic energies of \( \mu \) and \( \nu_\mu \) (or \( \pi \)).

The total kinetic energy \( Q_\mu \) in a decay

\begin{equation}
\text{Pb} \rightarrow \mu^\pm + \nu_\mu + (A_1, Z_1) + (A_2, Z_2),
\end{equation}

\textsuperscript{1}This observation is not necessarily valid in the case of \( \text{Pb} \), as the predicted branching ratios for the pionic and muonic radioactivities are defined in \cite{1, 2} relatively to the spontaneous fission of the parent nuclei.
assuming close values of $A_1$ and $A_2$ (symmetric fission), is about 30 MeV for negative muons and about 20 MeV for positive muons. Considering that the associated muon neutrino takes away a sizable fraction of this energy, the spectrum of emitted muons could be like in a $\beta$ decay, with an average around $10 \div 15$ MeV.

The decay into two fragments would not lead to the best energetic situation since the two resulting nuclei would on the average have large atomic mass and too large neutron numbers. Decays into more than two nuclear fragments would lead to more energetic muons; at the moment there are no estimates available for such decays.

There is only one experiment that published upper limits for exotic decays of Pb [9]. The experiment used 123 g of natural lead, obtaining a 90% C.L. upper limit on the $\pi^0 \to \gamma\gamma$ counting rate of $3.3 \cdot 10^{-27}$ s$^{-1}$, for a total counting time of 109 hours. The same authors searched also for pionic emission from Uranium, and reported a 90% C.L. upper limit for $\Gamma_{\pi}/\Gamma_{SF} \sim 3.1 \cdot 10^{-4}$, where $\Gamma_{SF}$ is the width of the spontaneous decay fission. Using $^{235}$U and $^{252}$Cf they obtained upper limits of $1.4 \cdot 10^{-4}$ and $3.3 \cdot 10^{-10}$, respectively. A search for spontaneous emission of both muons and pions from $^{252}$Cf yielded upper limits for the ratio $\Gamma_{\mu,\pi}/\Gamma_{SF}$ in the range $10^{-6} \div 10^{-8}$ [3].

There are no experimental limits for muonic radioactivity.

In the following we describe a possible search for muonic radioactivity of lead nuclei and we discuss the experimental set-up, the results of a Monte Carlo (MC) simulation giving estimates of the geometric efficiencies, a description of possible backgrounds and the reachable limits.

## 2 Experimental set-up

We propose to perform an experimental search for muonic radioactivity from lead nuclei in the low background conditions offered by the Gran Sasso underground Laboratory (LNGS). The very low cosmic muon flux and the low natural radioactivity of the rock in the experimental halls of the LNGS provide unique conditions, allowing a potential discovery, or at least to establish a very good upper limit for this exotic decay process. A detailed description of the different background sources is given in Sec. 4.

This search could be a by-product of the OPERA experiment [8] presently under construction at LNGS. OPERA is a hybrid long-baseline neutrino experiment, aimed to the direct observation of $\nu_\tau$ appearance from $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in the CERN-Gran Sasso $\nu_\mu$ beam. The detector is made of 2 super-modules, each with a massive lead/nuclear emulsion target, electronic detectors and a magnetic spectrometer. Nuclear emulsions are used as high resolution (0.06 µm) tracking devices for the direct detection of the decay of the $\tau$ leptons produced in the charged current $\nu_\tau$ interactions with the target.

The OPERA base element (“brick”) is composed of 56 lead sheets (1 mm
Figure 1: Illustration of the sequence lead/nuclear emulsion sheets which characterise an OPERA brick.

The OPERA lead bricks (each containing a mass of 8.23 kg of Pb) could allow an experimental search for muon emission from lead, with exposures of several months. Their analyses with the fast automatic optical microscopes [10] would establish the local background contributions and validate the analysis procedures.

A preliminary test using a “small” brick composed of 22 lead sheets and 21 recently refreshed nuclear emulsion sheets was started at the end of March 2005. As the background rejection/reduction (see Sect. 4) is a crucial point for this search, the detectors are surrounded on all sides by a shield, making a closed box structure similar to those used in experiments for dark matter and for neutrinoless double beta decay searches. The shield is composed of an inner layer 5 cm thick of very pure copper followed by 15 cm of very low activity lead. The third and last layer of the shield is a 3 cm thick polyethylene, in order to absorb neutrons. A scheme of the installed shield, with the dimensions for containing 5 OPERA bricks, is presented in Fig. 2. The set-up is located

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²These thicknesses have been found to be adequate with a Monte Carlo simulation considering the effects of $0.5 \div 2.6$ MeV photons, which could produce electrons mimicking the searched events.
in the emulsion storage room, in hall B of the Gran Sasso Laboratory. The radon reduction is obtained with a ventilation system due to fresh air forced circulation.

The mean range of 15 MeV muons in lead is about 1.5 mm, so most of the possibly produced muons could be detected in the two layers of emulsion close to the Pb sheet “source”; depending on the angle of emission and on the location of the decay point, some of them could also be detected by the next emulsion sheets.

It is clear that thinner lead sheets would allow the emitted muons to lose a lower fraction of their energy to escape from the lead and to cross more emulsion layers. They would also yield a higher detection efficiency.

3 Monte Carlo simulation

A MC simulation program was implemented to estimate the occurrence of different event topologies. The simulation is based on the GEANT3 [11] package.
applied to the OPERA lead/emulsion set-up. At this point it does not include the complete detector response and does not estimate the real event reconstruction efficiencies.

The simulation reproduces one complete OPERA brick, where muons of different energies (see the first column of Table 1) originate in random positions in the lead sheets. The initial muon directions are isotropically generated. We assumed different definitions for a candidate event, requiring that the muon crosses at least: (i) one single emulsion layer, (ii) two emulsion layers (near the same base), and (iii) three emulsion layers (and thus also a lead plate, which would allow a better identification using the measured energy loss). We also requested the detection of the decay positron or electron in at least (iv) two, (v) three, or (vi) five emulsion layers, together with the muon detection.

Fig. 3 shows the distribution of the number of emulsion layers crossed by a sample of simulated $\mu^-$ (left) and by the electrons resulting from their decay (right), assuming an initial muon energy of 15 MeV and isotropically distributed emission angles.

As there is no theoretical prediction concerning the muon energy spectrum, an overall fraction of events with a defined topology cannot be estimated. The percentages of events listed in Table 1 were computed for samples of MC events with fixed energies. The detection threshold for the $\mu^\pm$, obtained requiring at
Figure 4: Simulated events of spontaneous $\mu^+$ (a) and $\mu^-$ (b) emission from lead inside an OPERA brick, assuming an initial muon kinetic energy of 15 MeV. In (a) the $\mu^+$ starts from the second lead sheet and stops in the third one, where it decays into $e^+\nu_e\overline{\nu}_\mu$. The $\mu^+$ is seen in 2 emulsion sheets, the $e^+$ in 4. In (b) the $\mu^-$ starts from the fourth lead sheet and stops in the second one, where it decays into $e^-\overline{\nu}_e\nu_\mu$. The $\mu^-$ is seen in 4 emulsion sheets, the $e^-$ in $>6$. The change of direction for the $\mu^\pm$ and $e^\pm$ in the interfaces lead-emulsion are due to the MC approximation which, for each material, adds the multiple Coulomb scattering effects and gives a global scattering angle of the outgoing direction relative to the incoming one.

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3.1 Estimates of global detection efficiencies

The geometrical $\epsilon_g$ have to be multiplied by the $\mu^\pm$ and $e^\pm$ reconstruction efficiencies to obtain the total efficiency. We made a first estimate of $\epsilon_{tot}$ for muons based on the measurement procedures and the algorithms used in OPERA [10].
The relation between the energy of charged particles and the density of grains produced in emulsions along their trajectories [12] shows that muons with the predicted energies would give recognisable black tracks without relevant scattering in the emulsion films. For the decay electrons/positrons the tracks would be similar, but with a lower density of grains per unit path-length.

With the OPERA tracking procedure [13], the mean detection efficiency for each “microtrack” in one emulsion film is $\tilde{95}\%$; it is a value averaged on the angular range between tracks normally incident on the plate surface and tracks with incident angles $\tilde{0.8}$ rad with respect to the normal. The instrumental limit of 0.8 rad on the incident direction of each microtrack introduces an event selection of $\sim 30\%$.

The “base track” (obtained from 2 microtracks separated by the plastic base) reconstruction efficiency of $\sim 90\%$ ($95\% \times 95\%$) is comprehensive of the uncertainties due to the emulsion shrinkage and possible surface distortions. The top-bottom linking efficiency ranges from the $\sim 50\%$ for 5 MeV particles to $\sim 99\%$ for particles with energies $\geq$ 20 MeV. It is mainly due to the multiple scattering in the plastic base. The base track linking efficiency is $\sim 6\%$ for the whole range of initial muon energies.

In order to reduce the background, an algorithm defines a “track” requiring at least 4 emulsion films (it means at least 1 lead sheet and 2 plastic bases) crossed by a particle. The detection efficiency $\epsilon_{tot}$ for a muon crossing at least 4 emulsion films is the product of the percentage of events with these topological requirements $\epsilon_{g}$ (col. 6 of Table 1), the 30% given by the angular limit, 4 times the 95% efficiency for the microtracks, 2 times the top-bottom linking efficiency and the linking efficiency between 2 base tracks. As shown in Table 1, the threshold muon energy to have at least 4 emulsion films crossed by the muon is 10 MeV.

### Table 1: Percentage of events as a function of the minimum number of emulsion films crossed by both \(\mu (N_{\mu})\) and \(e (N_{e})\), for different \(\mu\) initial energies (col. 1).
The column in bold refers to the conditions requested by the OPERA tracking system to define a track \((N_{\mu} = N_{e} = 4)\).

| \(N_{\mu}\) | 2 | 2 | 2 | 2 | 4 | 4 | 4 | 6 | 6 | 6 | 6 |
|------------|---|---|---|---|---|---|---|---|---|---|---|
| 5 MeV     | 12| 10| 9 | 7 | - | - | - | - | - | - | - |
| 7 MeV     | 25| 23| 21| 14| - | - | - | - | - | - | - |
| 10 MeV    | 51| 46| 41| 31| 0.6| 0.5 | 0.4| 0.3| - | - | - |
| 15 MeV    | 74| 66| 58| 44| 31| 28 | 23| 17 | 1 | 1 | 0.9| 0.7|
| 20 MeV    | 84| 72| 63| 49| 56| 50 | 40| 30 | 29| 26| 21| 15|
| 25 MeV    | 89| 75| 66| 50| 70| 60 | 49| 36 | 48| 42| 34| 25|
| 30 MeV    | 92| 75| 67| 52| 78| 66 | 54| 36 | 60| 51| 42| 28|

The column in bold refers to the conditions requested by the OPERA tracking system to define a track \((N_{\mu} = N_{e} = 4)\).
For the electrons, the probability of crossing at least 4 emulsion films $\epsilon^{\text{g}}_\text{e}$ is about 68% for the whole range of initial muon energies. This percentage was obtained from the simulated events requiring a minimum number of 4 emulsion films crossed by the electron and no constraints on the muon trajectory. The convolution with the topological requirements of the angular directions within 0.8 rad (30% selection), the 95% efficiency reconstruction of the 4 microtracks, the top-bottom linking efficiency and the linking efficiency between base tracks yields the total electron detection efficiency.

We intend to optimise the tracking procedure for this search using new scanning conditions. It may be possible to require only 2 emulsion films crossed by a muon to reconstruct its track. This optimisation should be possible, because of the easily recognisable black tracks produced by slow muons. Once a muon is found, we should be able to check visually the presence of the decay electron.

Table 2: Geometric efficiencies ($\epsilon^\text{g}$) and total muon detection efficiencies ($\epsilon^{\text{OPERA}}_{\text{tot}}$) as a function of the initial muon energy computed on the basis of the OPERA tracking procedure for $N_\mu = 2$ (col. 2-3) and for $N_\mu = 4$ (col. 4-5). The values $\epsilon^{*}_{\text{tot}}$ (col. 6) are obtained relaxing the angular and position tolerances in the base track reconstruction (see text). All values are in %.

| $E_\mu$ (MeV) | $N_\mu = 2$ | $N_\mu = 4$ | $N_\mu = 4$ |
|-------------|-------------|-------------|-------------|
|              | $\epsilon^\text{g}$ | $\epsilon^{\text{OPERA}}_{\text{tot}}$ | $\epsilon^\text{g}$ | $\epsilon^{\text{OPERA}}_{\text{tot}}$ | $\epsilon^{*}_{\text{tot}}$ |
| 5            | 12          | 1.5         | -           | -           | -           |
| 7            | 25          | 4.3         | -           | -           | -           |
| 10           | 51          | 12          | 0.6         | 0.006       | 0.1         |
| 15           | 74          | 19          | 31          | 0.4         | 5.6         |
| 20           | 84          | 22          | 56          | 0.8         | 11          |
| 25           | 89          | 24          | 70          | 1           | 14          |
| 30           | 92          | 25          | 78          | 1.1         | 16          |

Table 2 shows the % efficiencies $\epsilon^\text{g}$ and $\epsilon^{\text{OPERA}}_{\text{tot}}$ computed requiring at least 2 emulsion films crossed by the muon (col. 2-3) and 4 emulsion films crossed by the muon (col. 4-5). The values refer to the present OPERA tracking [13]. The linking efficiencies may be improved relaxing the angular and position tolerances between consecutive base tracks. This should be possible because of the low background conditions. Requesting an angular tolerance of 100 mrad and a position tolerance of 100 $\mu$m, we obtained the values given in col. 6 of Table 2.

In OPERA the different emulsion sheets of each brick are aligned mechanically and then exposed to cosmic ray muons to have a relative alignment of $\sim$ 1 $\mu$m [14]. In the present case, due to the low background conditions, we expect that the mechanical alignment precision should be adequate for the purpose; since the emulsion layers are placed horizontally, a check of the alignment
could come from the few high energy cosmic ray muons which should cross the emulsions [15].

As the expected half-lives $t_{1/2}$ are much larger than any reasonable exposure time $T$, the expected sensitivities are estimated from

$$\frac{\delta N}{N_0} = \frac{\ln 2}{t_{1/2}} T \epsilon_{tot}$$  \hspace{1cm} (4)

where $\delta N = 2.3$ is the number of events corresponding to a 90% C.L. limit assuming no candidates, $N_0$ is the initial number of nuclei, and $\epsilon_{tot}$ is the experimental efficiency.

Assuming the use of one OPERA brick for one year exposure and a global detection efficiency of $\sim 10\%$, we could reach a sensitivity of about $7 \cdot 10^{23}$ yr (90% C.L.).

4 Background estimates

The background originates from several different sources.

1) The environmental radon background is reduced by the ventilation and may be monitored using nuclear track detectors, such as CR39 or Makrofol, that are insensitive to muons.

2) The background produced by the ambient neutron flux ($\sim 0.42 \cdot 10^{-6}$ neutrons/s/cm$^2$, with energy greater than 1 MeV [16]) should be studied; its effect can be reduced by a proper shielding and appropriate “event definitions”.

3) The background produced by the radioactive $^{210}$Pb isotopes present in the lead. The $\alpha$ and $\beta$ radioactivity of the lead used in OPERA [8] is $< 0.02$ Bq/g. A single lead plate has an activity $< 3$ Bq, and only a fraction of the particles emitted from the outer surfaces of the material escapes from the lead sheets. The $\alpha$ background could be eliminated by thin plastic foils inserted between the lead plates and the emulsion sheets.

4) The background produced by radioactive nuclides present in the emulsion, for example $^{212}$Po nuclei. The emitted $\alpha$ particles have an energy of 8.785 MeV and a range in emulsion of 74 $\mu$m. This background should be reducible by dE/dx measurements on the tracks and from range considerations.

5) The background due to cosmic rays.

(i) Cosmic ray (CR) muons reaching from above the LNGS underground labs (3700 kg/cm$^2$ average rock cover) are $\sim 1$ mm/h/m$^2$ [15]; the number of CR muons expected to cross one brick during one year is about 90, sufficient to improve alignments of the different emulsion layers. They have an average energy of 240 GeV [15]. Tracks produced by CR muons in emulsion may be easily identified on the basis of their high energy and relatively small energy loss. Low energy CR muons can be removed requesting that the tracks start in a lead plate.
(ii) Pions produced by muons interacting in the lead plates. Slow pions decay into muons and simulate a spontaneous muon emission. This process was investigated by MC techniques in MACRO, since it was a background for the measurement of the upgoing muon flux [17]; the probability to produce a pion by a CR muon through photonuclear interactions in a layer of 150 g/cm$^2$ was estimated to be $< 2 \cdot 10^{-5}$, and the fraction of low energy backward scattered pions is $< 2 \cdot 10^{-4}$. Since in an OPERA brick the yearly rate of charged pions produced inside the plates is $< 6 \cdot 10^{-4}$, this background may be neglected.

(iii) The flux of muons resulting from atmospheric $\nu_\mu$ interactions around the detector is known from measurements done by MACRO [18]; they yield a negligible background.

(iv) In the Gran Sasso underground laboratories the CR neutron flux is about $\sim 10$ neutrons per square centimetre in one year [16, 19]. Only a fraction of these neutrons interact in the detector and the events produced by them should be recognisable in emulsions.

6) The future CERN-Gran Sasso neutrino beam may yield a background contribution; the energies of muons induced by the $\nu$ beam will be much higher than the energies of emitted muons from lead. Moreover, the beam will be continuously monitored. Also this background should be easily recognised and removed. The beam will not be present before the middle of 2006.

5 Conclusions and perspectives

We described a test search for spontaneous emission of muons from Pb nuclei, using some OPERA lead/emulsion bricks. The proposed test is suggested by some theoretical works performed in the last years; it would be complementary to other experiments looking for such exotic radioactivities from heavier nuclei and could reach a good sensitivity level. For a visual fine-grained technique (the emulsion technique) the identification is easier and the background lower. The test will yield the first information relative to the background in the OPERA bricks.

We are in the process of making a complete simulation of the detector including its response and the track reconstruction efficiencies. As already stated, thinner lead sheets would improve the scanning and the track reconstruction efficiencies.

We have shown that stringent limits for spontaneous muon radioactivity may be reached. We would obtain $t_{1/2} \geq 7 \cdot 10^{23}$ years.

In the future, one could repeat the experiment using elements heavier than lead.
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