The FAMU experiment

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1.1 Basic scientific introduction

The PSI Lamb shift experiment [I1] displayed a disagreement of 7 s between the experimental values of the proton r.m.s. charge radius extracted from e-p scattering and muonic hydrogen spectroscopy. This discrepancy has not yet been explained; it is not even known whether it may be ascribed to the different experimental methods or reflects some fundamental features of the muon. The latter hypothesis may be tested best by comparing the values of an other characteristics of the proton, the Zemach radius $R_p$ [I2], obtainable from measurements of the hyperfine splitting (HFS) in ordinary and muonic hydrogen atoms. By now the HFS has been measured in the ground state of hydrogen [I3] and in the 2S state of $\mu p$ [I4]; the latter provided values of the Zemach radius with an accuracy of several percent that is insufficient for comparison with the former. Resolving the "proton size puzzle" therefore requires new measurements of improved accuracy using alternative methods.

The experimental method we developed for the measurement of the HFS in the ground state of $^{1}_{\mu}p$ that is expected to provide $R_p$ with accuracy of 1% or better and therefore is capable to test the hypothesis of an anomalous muon nucleon interaction and also improve the understanding of the proton magnetic-to-charge form factors ratio at low momentum transfer. The method exploits the fact that the $^{(\mu)p}_{1S}$ atom that absorbs a photon from a IR laser tuned at the resonance wave length 6.7 m of the singlet-to-triplet M1 transition, when collisionally de-excited back to the 1S singlet state, is accelerated by 0.12 meV ($\sim 2/3$ of the hyperfine transition energy). In the method this sequence of processes is detected by the products of reactions whose rate depends on the velocity of $\mu p$ and this way measure the amount of spin-flipped and consequently accelerated $\mu p$ atoms. The original idea to observe the diffusion of the $\mu p$ atoms in a restricted volume by studying the time distribution of the events of $\mu p$ hitting the borders of the target volume and transferring the muon to the nuclei of the target wall material [I5] was later upgraded to observing the muon transfer from the proton to the nuclei of an appropriate heavier gas with pronounced energy dependence of the transfer rate [I6]. In both cases the muon transfer events are identified by the characteristic X rays emitted during the de-excitation of the heavier muonic atom. Monte Carlo simulations gave similar estimates for the expected efficiency of the two methods. The upgraded method of [I6] is applicable in a mixture of hydrogen with a gas for which the rate of muon transfer from (m-p) varies substantially energy in the epithermal range that may be due to specific crossing of levels or resonance-like processes. Such a behavior has been observed in mixture of $H_2$ and $O_2$ [I10] and theoretically predicted for other gases too, but not yet studied with sufficient precision to base the experimental method on it. We therefore plan to perform preliminary measurements of the collision energy dependence of the $\mu$ transfer rate in various gases. The results will help determine the most appropriate gas mixture, temperature and pressure of the gaseous hydrogen target for the HFS measurement that guarantee maximal efficiency of the experimental method and accuracy of the proton Zemach radius $R_p$. 
The realization of these experimental projects has been awaiting for a decade the development of tunable IR laser sources in the 6.7 \( \mu \)m range with sufficient power per pulse needed to invert the spin of a statistically significant amount of \((\mu p)_{15}\) atoms, and became a realistic goal only recently with the first encouraging result of the FAM project team [I7], in combination with the use of a multi-pass cavity of very high reflectivity [I9] allowing for squeezing the laser beam without losing any part of the muon stopping volume. Among the several paths investigated by now we have selected described in what follows which has been shown to enable pulses of energy above 1 mJ. The pulsed muon beam of the RAL-RIKEN muon facility [I8], on its turn, provides up to \(7\times10^4\ mu\) of 60 MeV/c per pulse at 50 Hz repetition rate. We are therefore able to propose a full experimental program for the measurement of the hyperfine splitting in the ground state of the muonic hydrogen atom with a relative accuracy of the order of \(10^{-4}\) and the determination of the proton Zemach radius with accuracy better than 1%. Our motivation now is stronger than in 2009 since:

- The method used by the PSI Lamb shift experiment team in [I4] for the measurement of the hyperfine splitting in \((\mu p)_{15}\) could not provide the accuracy needed to resolve the "proton size puzzle", and our method appears to be the only realistic alternative;
- The latest adjustments of the experimental methods used to determine the r.m.s. radius of the proton have increased the discrepancy from the initially announced 5s to the present 7s;
- The technological progress achieved recently in the development of IR laser sources [I7], of multi-pass cavities of high reflectivity in the IR range of interest [I9] and in producing and guiding pulsed muon beams [I8] help overcome the difficulties related to the low intensity of the laser-stimulated singlet-to-triplet M1 transitions;
- The IR lasers in the 6.7 \( \mu \)m range are expected to have applications in remote sensing of the atmosphere, medicine and other fields.
- Our target: new experimental results on the muon transfer rate, of the relation between the charge and magnetic structure of the proton at low momentum transfer, and an independent test of the QED predictions for the relation.

[I2]: A.C.Zemach, Phys. Rev. 104, 1771 (1956)
[I7]: See annex “Laser”
[I11]: A.Adamczak, Hyp. Interact. 82, 91 (1993)
1.2 General time plan for the coming four years

The FAMU project foresees a progressive approach to the final measurement of the 1S state hyperfine transition on the muonic hydrogen atom. The work on the project includes several activities that will be lead in parallel and converge in the measurement of the hyperfine splitting in the ground state of the muonic hydrogen atom and the determination of the Zemach radius of the proton.

i. Development of the IR laser source
ii. Beam control and monitoring system
iii. Experimental study of the muon transfer rate and gas target design
iv. Temperature stabilization system for the gas target
v. X-ray detection system, read-out electronics and data acquisition system
vi. Simulations
vii. Measurement of the hyperfine splitting in the ground state of the muonic hydrogen atom and the determination of the Zemach radius of the proton.

Besides the constant effort to be carried ahead for the realization of the final power laser system, the foreseen four years time program has two main phases. During 2014-2015 we will perform a measurement of the transfer rate of the muon from the muonic hydrogen (\(\mu - p\)) to heavier atoms present in the gas target. This measurement will be made at different pressures, temperatures and concentrations of the heavier nuclei. A detailed description of this measurement has been elaborated (Annex 1), while a request for beam has been advanced at the RIKEN-RAL Program Advisory Committee (Annex 2, 3), the Committee has assigned 5 days of machine run at RAL in the time window 2014-2015 (annex 4).

The approach to this important measurement will require us to prepare an experimental lay-out which will be tested in two successive steps before being exposed to the muon beam at RIKEN-RAL beam port 4. We will request beam at the LNF BTF in Frascati in the spring 2014, subsequently we will exploit the low energy low intensity MICE muon beam line at RAL late spring 2014. At this point we will expose our instrumentation to the pulsed muon beam to perform the muon transfer rate measurement according to the availability of the RAL accelerator.

Meanwhile the preparation for the final spectroscopic measurement will require the realization of the final optical structure including the tunable high power laser whose scale model has been realized in Trieste. One has to act in such a way that the laser can be ready for integration with the remaining system by 2016, when the second phase of the experiment starts, so that the
final measurement will be realized in 2017 fulfilling the effective need of new results in short time.

The experiment requires different systems; a detailed though schematic list of actions is reported in the following lines.

**first year 2014**

# we ask for only 1-2 days out of the 5 day of beam that we were assigned by RIKEN-RAL;
# we prepare a set up to measure at room temperature the transfer speed for different pressures and compositions. The lay out is simplified but we have to understand the beam conditions and see the signal from the transfer. To do this we will also profit of the beam availability from another experiment (MICE) at RAL. Overmore we will ask for beam time at the BTF at LNF.
# the detection system includes beam monitor + X ray detectors (LaBr + Ge) to cover the largest possible fraction of the solid angle
# the experiment acquisition system has to be prepared
# Detailed simulations of the experiment have to be performed
# Meanwhile we study and prepare the needed lay out for measuring at different temperatures.
# The work on the laser starts with the purchase and the installation of the first power systems
# The work on the optical path and cavity starts with the aim to build a prototype to be inserted in the laser system
# The way to reliably measure the laser line width experienced

**second year 2015**

# we are going to use the second fraction of the RAL beam 3 days, strong from the results of the 2014 runs also at test facilities we will work at lower temperatures.
# the detection system that already includes beam monitor + X ray detectors (LaBr + Ge) will be improved
# the work on the laser goes towards the completion as well as the optical cavity
and optical path
# a new version of the gas target allowing for optical multi-pass cavity and light transparent window will be produced in sight of the final experiment
# final data analysis on transfer rate; Pressure, Temperature and composition of the target for the spin flip experiment is determined by experiment and simulation cross checked.
# data to be presented at RIKEN-RAL PAC together with a new request, supported by the data, of beam for the final experiment

**third year 2016**

# final laser characterization and debugging;
# integration with the target and the optical cavity
# measurement of the effectively available power and line width
# upgrade of the detector system on the basis of the results obtained
# test of the integrated system on the MICE beam line

**fourth year 2017**

# the integrated system is brought to the beam line at RAL
# data taking
# data analysis

### 1.3 The measurement of the muon transfer rate

The experimental program for the measurement of the energy dependence of the rate of muon transfer in a mixture of hydrogen and various heavier gases is scheduled for 2014-2015 at RAL-RIKEN. The proposed experiment combines measurements of the time distribution of the events of muon transfer, similar to the ones performed in the 1990's, with measurements of the overall transfer rate from thermalized atoms μp at different temperatures. According to the Maxwell distribution part of the thermalized atoms have epithermal energies, and the overall transfer rate accounts for their contribution as well. This way the variations of the observed averaged transfer rate with temperature can be directly related through a simple model to the variations of the transfer rate with energy in the epithermal range. We have proposed to study the transfer rate of gases for which there exist experimental evidences for non-flat energy dependence of the transfer rate (oxygen, neon, argon) and of organic gases for which the theoretical estimates show that resonance-like transfer mechanisms may take place.
The muon transfer measurements will use large fraction of the equipment in development for the HFS measurement: μ beam control and monitoring system, temperature stabilization system for the gas target, the X-ray detection system, read-out electronics and data acquisition system, but will not make any use of the IR laser source or multi-pass cavity. This preliminary experiment scheduled for the first 15 months of the project duration, is targeted on:

- Obtaining new data about the muon transfer rate from hydrogen to heavier gas muonic atoms, the will be used to select the optimal measurement method and experimental layout for the HFS experiment;
- Testing some of the components of the equipment and the techniques of beam control.

The original hypothesis of using muon transfer to foils of metal interleaved within the gas target has been set in stand by and eventual back-up due to the evident complication posed by the coupling of multi-pass cavity with this target geometry although some solution viable solution could be envisaged.

### 2.1 The development of the laser source

The development of the laser source for the spectroscopic transition measurement of the hyperfine splitting of the 1S state of the μp has been the target of a major effort of our group in recent years, in the annex 5 a publication in preparation about the chosen solution and in annex 6 the European proposal submitted in 2012 that we intend to resubmit to the next suitable call. Of course we plan to keep the CSN3 board aware of the eventual other support that would become available.

Here we propose a plan for the building of a laser system based on nonlinear optics for the generation of 6.8μm infrared light. The scheme is based on direct difference frequency generation (DFG) in non-oxide crystals with pump and signal coming from one narrowband fixed wavelength and one tunable solid state lasers emitting at wavelengths below 2μm. Our initial investigations had proved that it is possible to obtain an infrared emission in the 6.8μm spectral region with the parameters needed for the muonic-hydrogen experiment by mixing a Q-switched single frequency Nd:YAG (1064nm) and a narrowband single frequency Cr:Forsterite laser operating at 1260nm, pumped by Nd:YAG laser, in LiInS\textsubscript{2} nonlinear crystal. The distribution of the expenditures is done in a way to give us steady progression throughout the three years of developing the laser system. The idea is at the end of the third year to have a completely integrated and thoroughly studied final version of the laser system allowing system integration at the muon source facility for the hyperfine splitting measurement during the fourth year of the project. The expenditures profile for developing such laser system of the FAM project during the period 2014-2016 foresees:

First year 2014:
i) a single-line Cr:forsterite oscillator operating at 50Hz, 5mJ energy
per pulse with linewidth<5pm, plus pumping laser - (80kE)
ii) Injection Seeder for Linewidth <0.003 cm^{-1} (25kE)
iii) single-line Nd:YAG Laser System (Oscillator/Amplifier) 1-50 Hz,
250mJ per pulse (75kE)
iv) one long crystal (10kE)
v) optical/optomechanical/mechanical components for beam-guiding
and software for beam control (10kE)
vi) electronics for synchronization of the lasers plus hardware (camera)
and software for beam control (15kE).

The total time required to have at our disposal the Cr:forsterite oscillator as well
as the Nd:YAG system (Seeder plus Oscillator/Amplifier) is estimated to be
between 8 and 10 months. As the sums are over 40kE the procedure of collecting
offers and making the orders will be around 4 months plus 3-4 months for the
delivery, installation and training for the Nd:YAG system and around 5-6 month
for R&D, building, delivery, installation and training for the narrow-line
Cr:forsterite laser oscillator (according the time estimation of one of the
possible suppliers).

Time for delivery of one LiInS₂ crystal 20mm long is 6 months, so time for
ordering and delivery - 7 months.

For synchronizing the emissions of the single-mode Cr:forsterite laser oscillator
and the single-mode Nd:YAG system (Seeder and Oscillator) in order to achieve
the phase matching needed for the Difference Frequency Generation two
synchronization units (delay generators) will be needed – order and delivery 3-
4 months. The same time is estimated for the order and delivery of a CCD camera
plus software for observing and controlling the laser beams.

The time for ordering and delivery of optical components (lenses, dichroic
mirrors, wave-plates, polarizers, etc.) 3-4 months. Time for ordering and
delivery of optomechanical components 2-3 months.

After the delivery of the lasers, the electronics for the timing and the optical and
the opto-mechanical components for the beam guiding and coupling the setup
for the DFG scheme will be build. Assembling the available lasers (oscillators) in
a setup for the generation of 6.8μm infrared radiation based on direct DFG
scheme, even having at the beginning moderate output energy values, will give
us the possibility to start a real study of the best working conditions of the
system (also of the two pumping lasers – Nd:YAG and Cr:forsterite) and a
characterization of the 6.8μm emission. Parameters like pulse energy, peak
energy, pulse duration, jitter, beam divergence, and linewidth will be studied.

For the purpose two different setups will be realized with single pass and double
pass of the pumping beams through the LiInS₂ nonlinear crystal (Fig.1 And
Fig.2), the parameters of the output emissions from both setups will be
compared and analyzed, we underline here that the predicted final power
output is of 1.65mJ, for single pass scheme and 2.65mJ for double pass scheme.
The main efforts will be concentrated on measuring the linewidth of the 6.8µm emission and especially studying how it is influenced by the parameters of the different components of the systems (the peak energies of the pulses of the pumping lasers), the energy densities of the pumping beams, the phase matching of the pumping beams, the orientation of the nonlinear crystal, the geometry of the setups, etc.

According to preliminary study of the market and the available offers, the estimated total expenditures for the first year are $215kE (+ IVA)$.

Second year 2015.

i) single/double cascade Cr:forsterite Amplifier 50Hz, 40mJ pulse energy, plus one/two pumping laser/s 

\[ (70kE) \]

ii) one long crystal 

\[ (10kE) \]

iii) optical table, optical/optomechanical/ mechanical components 

\[ (17kE) \]

Time for ordering and delivery of the Cr:forsterite Amplifier (single/double cascade) – 7 months: procedure of collecting offers and making the order for amount over 40kE - 4 months; delivery, installation plus training 3 months. Time for delivery of second LiInS₂ crystal 20mm long is 6 months, so time for ordering and delivery - 7 months. Time for ordering and delivery of optical table and other optical and optomechanical components 2-4 months.

At this point (after the delivery of the Cr:forsterite amplifier, the optical table, etc.) all the components needed for building the complete laser system generating 6.8µm light will be available. This will allow us to assemble the final IR laser system and to start studying it. The best working conditions and the parameters for each laser system Oscillator/Amplifier (for both Cr:Forsterite and Nd:YAG) as well as for the complete DFG system – optimal pumping energies, energy densities, optimal beam shaping, time delays, phase matching, etc will be under investigation. Also the parameters of the output infrared emission at 6.8µm - pulse energy, peak energy, pulse duration, jitter, beam divergence, and linewidth will be thoroughly studied and examined. A special attention will be kept on the way how the parameters of the 6.8µm light are influenced by the parameters of the two pumping/mixing beams, the phase matching, the geometry of the setup and etc.

The expenditures for this second year are estimated to $97kE (+ IVA)$.

Third year 2016.

i) two spare long crystals 

\[ (20kE) \]

ii) optical/optomechanical/mechanical components, software, spare components/parts 

\[ (38kE) \]
Totally for the third year will be required 58kE (+ IVA)

Summing up the needed resources for the realization of the FAMU laser are:

- year 1 – 215kE (+ IVA)
- year 2 – 97kE (+ IVA)
- year 3 – 58kE (+ IVA)
- total – 370kE (+ IVA)
Figure 1: Single pass DFG optical scheme for generating 6.8µm: WP - waveplate, Pol - polarizer, M1-M5 - mirrors, T1 and T2 - matching telescopes, BS - beamsplitters, DC - dichroic mirror (reflecting 1.26µm, transmitting 1.06µm, NL - nonlinear crystal

Figure 2: Double pass DFG scheme: WP - waveplate, Pol - polarizer, M1-M6 - mirrors, T1 and T2 - telescopes, BS - beamsplitters, DC1 - dichroic mirror (reflecting 1.26µm, transmitting 1.06µm), DC2 - dichroic mirror (reflecting 1.06 and 1.26 µm, transmitting 6.76µm)
3.1 Gas target

As already outlined, the experimental method uses as signature of the resonance absorption by the $\mu^p$ atom of a photon the change in the time distribution of the events of muon transfer to the nucleus of a heavier gas admixture to the hydrogen target for which the transfer rate is strongly energy-dependent in the epithermal range. The existence of gases with appropriate features has not yet been investigated except for a few experimental demonstrations and theoretical calculations. The final gas target design will depend on the results of the experimental study of the energy dependence of the muon transfer rate to in several conditions of pressure and temperature and several gases of interest, scheduled for 2014-2015 at RAL-RIKEN. These preliminary measurements will lead to the identification of a gas admixture to the $H_2$ target with the required characteristics. The target gas container in this case is an aluminum cylinder of diameter $d_c \sim 10$ cm and height $h_c \sim 20$ cm, its dimensions being selected to minimize the losses of muons in the target walls and guarantee that as much as possible of the muons will be stopped and captured within the target volume at a given gas pressure (20-30 bar).

The precise values of $d_c$ and $h_c$ is being progressively studied by means of numerical simulations but also on the basis of the available options (ANNEX8 gas offer) which are at present under study. In the second phase of the experiment, the target gas container will host a multi-pass cavity with very high reflectivity. The latter will be obtained using the technology and resources applied in the PSI Lamb shift experiment with very similar characteristics. A group composed by the Technical University in Delft and the Milano Politecnico will be dedicated to this activity. The first theoretical estimations indicates that the best conditions for the final measurement of the hyperfine splitting will be having the gas target at low temperature. We are studying different solutions to allow a temperature regulation for the gas target in the range $-200 + 100$ C.

The gas container is surrounded by X-ray detectors. There exact position will be subject to optimization by means of numerical simulations.
3.2 Simulations of the gas target options and priorities

Numerical methods and codes for the quantitative simulation of the ensemble of processes occurring when muons are stopped and captured in hydrogen muonic atoms, incl. the muon transfer to heavier nuclei, have been developed by many authors. The simulations of the measurements in the present proposal are done using the theoretical results and codes of Adamczak et al. [I12] which in the past had been successfully applied to modeling other muonic atom experiments [I13]. Muon beam propagation is modeled with standard codes such as FLUCA, (annex7 Simulations). With these tools we shall determine the final parameters for:

- the optimal momentum of the incident muons,
- the sizes and shape of the gas container,
- the chemical composition,
- temperature and pressure of the gas target,
- the time and duration of the laser pulse,

as well as the shape and optimal position of the X-ray detectors for X-ray energies in the few hundred keV energy range.
4.1 Beam counters system

The beam hodoscopes must primarily provide:

- Beam profile informations, to tune the incoming muon beam inside the target
- Provide a timing information, as respect to RF, for DAQ readout and trigger
- Monitor pulse by pulse the muon beam intensity and allow an estimate of the rate of muon interactions in target

All with a muon beam rate of about 1000 muons in a 100 ns spill, with a 50 Hz repetition rate [1].

This imply the use of two hodoscope stations: one before the target and one after.

The baseline design for both is an array of square Bicron BCF-10 or BCF-12 scintillating fibers along x or y coordinates, readout at the extreme by SiPMs, arranged in a plane of typical dimensions 10 x 10 cm² to match the beam dimensions (estimated sigma of the beam ~1.6 cm). 2 planes (along x,y) are foreseen for the first station (to allow beam profile infos), while only one plane is presently foreseen for the second station. A sketch of the system is shown in figure 1.

![Figure 1. Sketch of the beam hodoscope system and exploded view of one detector plane.](image)

The SiPMT detector will be probably be the 3x3 mm² ASD-SiPM3S SMD mount from FBK/IRST, to match the fiber dimensions (2-3 mm). Double cladding and EMA will be foreseen for fibers, to allow optimal light collection. Multiclad Bicron BCF12 (BCF 10) [2] fibers have a peak emission ~435 (432) nm, a trapping efficiency of ~7%, an attenuation length of 2.7 (2.2) m, a decay time of 3.2 (2.7) ns and a light yield of ~8000 ph/MeV.
Advansid 3x3mm² SiPMT (ASD-SiPM3S-P) [3] have a typical gain in the range 1-2.5 x 10^6, a breakdown voltage of ~35 V, peak sensitivity ~480 nm and dark count rate in the range 1-5 x 10^7 counts/s. About 100 channels are foreseen and optimization studies are in course to determine the best fiber layout and readout to minimize the channel number (single side vs double side readout, shifted readout of one side against the other, ...).

As seen in figure 2 the mechanics footprint of 3x3 mm² SiPMT from FBK/IRST slightly exceed the 3mm lateral dimensions of the foreseen fibers. This will imply a dedicated study to optimize the cookie to interface fiber/fibers to a single SiPMT.

SiPMs will be read out by a custom made module developed by INFN Roma Tre inside the TPS project, shown in figure 3. The module (8 ch) will provide the fine regulation of the individual SiPMT HV, signal amplification and shaping, signal discrimination and OR of the 8 input channels for trigger purposes.
The individual output signals will then be fed into a CAEN V792 QADC for measurement of the charge integrated signal, while the OR of 8 channels will be fed into a CAEN V775 TDC for timing purposes.

The project will evolve along the following timescale:

- End 2013-early 2014: test in lab of BCF10 or BCF12 fibers and SiPM readout
- March-April 2014: test at BTF of a detector plane prototype with preliminary front-end electronics to assess mainly the rate capability of the detector
- May-July 2014: tests at RAL at MICE beamline and/or Riken-RAL beamline with muons
- Late 2014: detectors assembling
- 2015: final data-taking at Riken-RAL for the approved R484 project
- 2016-2017: integration with laser/upgrade of the hodoscope detectors

In all steps improvements/upgrades will be dictated by data-taking results and the increasing experience with the RIKEN-RAL muon beam.

References:

2. Saint Gobain Crystals: http://www.detectors.saint-gobain.com
3. Advansid: http://www.advansid.com
4. D. Tagnani et al, presentation at TPS meeting
4.4 The X-ray detection system

The work to study the different solutions for the detection system is on going, we are considering different solutions (see a study in annex_9), about the solution which as of now appears the most promising because of the allowed speed and energy resolution we report here a more complete analysis.

The LaBr₃(Ce) scintillator

The LaBr₃(Ce) is a transparent scintillator material that offers the best energy resolution, fast emission and excellent linearity. It has higher light output than NaI(Tl). Indeed the decay time is the shortest in comparison with other inorganic (non plastic) scintillator materials and the energy resolution is located halfway between scintillators and solid state detectors [1].

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Z eff.</th>
<th>Light yield (ph/MeV)</th>
<th>Decay time (ns)</th>
<th>Refr. index</th>
<th>ΔE/E (PMT)</th>
<th>λ_emiss max (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI(Tl)</td>
<td>3.67</td>
<td>51.0</td>
<td>41,000</td>
<td>230</td>
<td>1.85</td>
<td>9 % @140keV</td>
<td>410</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>4.51</td>
<td>52.0</td>
<td>66,000</td>
<td>630</td>
<td>1.80</td>
<td>14 % @140keV</td>
<td>565</td>
</tr>
<tr>
<td>YAP</td>
<td>5.50</td>
<td>36.0</td>
<td>21,000</td>
<td>27</td>
<td>1.95</td>
<td>20 % @140keV</td>
<td>350</td>
</tr>
<tr>
<td>LaCl₃(Ce)</td>
<td>3.86</td>
<td>49.5</td>
<td>46,000</td>
<td>27 (65%)</td>
<td>1.90</td>
<td>8 % @140keV</td>
<td>350</td>
</tr>
<tr>
<td>LaBr₃(Ce)</td>
<td>5.07</td>
<td>47.4</td>
<td>63,000</td>
<td>16 (97%)</td>
<td>1.90</td>
<td>7 % @140keV</td>
<td>380</td>
</tr>
<tr>
<td>Lu₂₃(Ce)</td>
<td>5.60</td>
<td>60</td>
<td>90,000</td>
<td>30</td>
<td>-</td>
<td>11 % @662keV</td>
<td>472</td>
</tr>
<tr>
<td>BGO</td>
<td>7.1</td>
<td>83</td>
<td>9,000</td>
<td>300</td>
<td>2.15</td>
<td>10 % @511keV</td>
<td>480</td>
</tr>
<tr>
<td>LSO</td>
<td>7.4</td>
<td>66</td>
<td>30,000</td>
<td>40</td>
<td>1.82</td>
<td>10 % @511keV</td>
<td>420</td>
</tr>
<tr>
<td>LYSO</td>
<td>7.1</td>
<td>65</td>
<td>25,000</td>
<td>42</td>
<td>1.82</td>
<td>11 % @511keV</td>
<td>420</td>
</tr>
</tbody>
</table>

*Measurements was performed by the authors with H8500 Hamamatsu metal channel dynode position-sensitive (8x8 anode array) photomultiplier (PSPMT) with QE = 27% @ 380 nm (typical).

More physical properties of LaBr₃(Ce) are summarized in tables and figures below.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>5.08 g/cm³</td>
</tr>
<tr>
<td>Melting point</td>
<td>1116 K</td>
</tr>
<tr>
<td>Thermal expansion Coefficient along C-axis</td>
<td>8 x 10⁻⁶/°C</td>
</tr>
<tr>
<td>Cleavage plane</td>
<td>&lt;100&gt;</td>
</tr>
<tr>
<td>Hygroscopic</td>
<td>yes</td>
</tr>
<tr>
<td>Characteristic</td>
<td>Value</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Wavelength of emission max</td>
<td>380 nm</td>
</tr>
<tr>
<td>Refractive index @ emission max.</td>
<td>~1.9</td>
</tr>
<tr>
<td>Primary decay time</td>
<td>0.016 µs</td>
</tr>
<tr>
<td>Light yield</td>
<td>63 photons/keV\gamma</td>
</tr>
<tr>
<td>Photoelectron yield</td>
<td>165 % of NaI(Tl) for γ-rays</td>
</tr>
</tbody>
</table>

Saint Gobain LaBr₃(Ce) scintillator (commercial name BrilLanCe 380) response to ¹³⁷Cs (red line). Spectrum obtained with a PMT [2].
In blue the comparison with a NaI(Tl) scintillator.
Resolutions and light yield are indicated.

Energy resolution obtained with a single crystal of LaBr₃:0.5% Ce³⁺ for x/γ rays from ¹³⁷Cs, ²⁴¹Am, and ²⁴¹Am/Mo source. Spectra obtained with a Hamamatsu R1791 PMT [3].
Scintillation emission spectrum of the LaBr$_3$(Ce) (BrilLanCe 380) crystal and Quantum Efficiency of a bialkali ETI9266 PMT with (B) Borosilicate, (W) UV glass, and (Q) Quartz face plates (Q.E. data courtesy of Electron Tubes, Inc.) [2].

Gamma and X-ray absorption efficiency for various thicknesses of LaBr$_3$(Ce) [2].
Timing with LaBr₃(Ce) (BrillanCe 380) Integrated Detector as a function of the crystals’ dimensions [2].

Timing resolution spectrum measured for a LaBr₃:Ce (5.0% Ce) crystal in coincidence with a BaF crystal [4].
Self radioactivity

Lanthanum halide scintillators have the drawback of their own internal radioactivity. This is due to naturally-occurring radioisotopes $^{138}\text{La}$ and $^{227}\text{Ac}$ [5].

$^{138}\text{La}$, which comprises 0.09% of naturally-occurring lanthanum, has a $1.05\times10^{11}$ yrs. half-life and produces two gamma rays: a 788.7-keV gamma ray from beta decay (34%) to stable $^{138}\text{Ce}$, and a 1435.8-keV gamma ray from electron capture (66%) to stable $^{138}\text{Ba}$.

There are also strong Ba K x-rays from 31-38 keV [6].

$^{227}\text{Ac}$ has a 21.77 yr half-life and is naturally-occurring as part of the $^{235}\text{U}$ decay series. Chemically, actinium is very similar to lanthanum, and is directly below it on the periodic table. $^{227}\text{Ac}$’s decay chain to stable $^{207}\text{Pb}$ includes five alpha decays. Initial commercially-available lanthanum halide crystals had a contamination level of $1.3\times10^{-13}$ $^{227}\text{Ac}$ atoms per La atom. This has since been reduced by over two orders of magnitude [7] but, still affects background spectra.

Using a nitrogen cooled HPGe detector in a well of lead, a long-time spectrometric measurement was performed on two LaBr$_3$(Ce) detectors with dimensions of 50.8 x 50.8 x 6 mm$^3$. Scintillators was encapsulated in Al with a 3 mm thick quartz window. In hereunder figure, one spectrum is presented. Measuring time 12h. Specific activity results of 2.0 Bq/g or 0.39 Bq/cc with an estimated error of about 5%. This very low activity cannot account for electrons and $\alpha$ particles that are not detected because remains in the crystal bulk but generate scintillation light.

![Energy spectrum](image)
Contribution of $\beta$ particles is shown in the left figure [2].

| 0.226 cps/cc | 0-255 keV beta continuum |
| 0.065 cps/cc | 790 keV – 1000 keV gamma + beta |
| 0.068 cps/cc | 1468 gamma peaks |
| 0.034 cps/cc | Alphas above 1600 keV |

Contributions of $\alpha$ particles is located over 1750 keV.

This component of the background strongly depends on the manufacturer and from research in progress. Saint Gobain declares the background values reported to the left [2]. Laboratory measurement we have performed with H8500 PSPMT provide a background of 2.6 cps/cc including all the noise sources.

**LaBr$_3$(Ce) scintillator coupled with Si detectors**

An important advancement should be obtained coupling a LaBr$_3$(Ce) scintillator with a Silicon Drift Detector (SDD). The SDD is a photodetector characterized by a very low noise thanks to the low value of output capacitance independent from the active area. With respect to a PMT, the SDD offers a higher quantum efficiency which reduces the spread associated to the statistic of photoelectrons generation. Also with respect to an APD, the SDD offers a lower photoelectrons statistic contribution which, in the APD, is worsened by the excess noise factor with respect to pure Poisson statistics. Moreover the SDD has a stable behavior, less sensitive to temperature and bias drift.

In the past years, good energy resolutions were measured using a SDD coupled to a CsI(Tl) crystal. However, the long shaping time, to be used with this scintillator to prevent ballistic deficit, was too far to exploit the best noise performances achievable with a SDD obtained at shaping times in the order of 1
On the contrary, this optimum shaping time is fully compatible with the short decay time of the LaBr$_3$(Ce) crystal.

In literature, Fiorini et al. [8] describe in detail a spectrometric detector based on LaBr$_3$(Ce) scintillator coupled with a 30 mm$^2$ SDD. Results are very good as shown in the hereunder figure.

Energy spectra of a $^{55}$Fe source, measured at room temperature (left) with 0.25 $\mu$s shaping time and at -10 °C (right) with 1 $\mu$s shaping time. The longer shaping time used at -10 °C is used thanks to the reduced leakage current that, for the SDD, falls below 10 e$^-$ rms.

Other authors [8] are studying the timing performance of SiPMs in combination with LaBr$_3$(Ce) for medical applications (in PET). Results are very interesting regarding the resolving time: the average coincidence resolving time (CRT) equals (101 ± 2) ps FWHM. The spectrometric capabilities are summarized with the following spectrum.

Pulse height spectra of two similar detectors, measured using a $^{22}$Na source. The observed widths of the 511 keV peaks are ∼ 3.7% FWHM and ∼ 3.2% FWHM for detector 1 and detector 2, respectively.
Seeing that results, the applications of LaBr₃(Ce) on large area position sensitive SDD is very promising but further studies must be made.

A new interesting idea regards the use of Silicon Carbide photodetector (SiC). Its properties are:

- wide bandgap $E_G = 3.2$ eV $\Rightarrow$ Room & high temperature operations
- High critical Field $E_C = 2$ MV/cm $\Rightarrow$ High voltage devices
- High thermal conductivity = 4.9 W/cm K $\Rightarrow$ High power devices
- High saturation velocity $v_S = 200$ $\mu$m/ns $\Rightarrow$ High frequency/speed devices
- Very high X-ray intensity operations without damage

SiC used directly as $\gamma$-ray detector shows good enough spectroscopic properties but is very fast.

In summary: SiC efficiency is low but it can operate with very high intensities and is fast! No known researches on these application are known, all the work is open.
**LaBr₃(Ce) scintillator coupled with Position-Sensitive Photomultiplier (PSPMT)**

Using the H8500 (bialkali) PSPMT (8x8 anode array) and a LaBr₃(Ce) continuous crystal we realized an imaging detector and we have experimentally measured a medium intrinsic spatial resolution of $(1.05 \pm 0.04)$ mm (see figure below).

For this measurement, a LaBr₃(Ce) slab with active dimensions of $49 \times 49 \times 5$ mm$^3$ (assembled in an Al case with a 3 mm thick quartz window) was coupled with an H8500 PSPMT. The H8500 Hamamatsu metal channel dynode PSPMT have 8x8 anode array disposed on an active surface of 49 x 49 mm; its QE is 27% @ 380 nm (typical).

Recently Hamamatsu introduced the *ultra bialkali (UB)* H8500 PSPMT, they have higher quantum efficiency: QE = 42%. Testing the LaBr₃(Ce) slab with one of these UB PSPMT better energy resolution and better intrinsic spatial resolution was obtained [2]:

### Intrinsic Spatial Resolution

<table>
<thead>
<tr>
<th>keV</th>
<th>H8500 BA</th>
<th>H8500 UBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>2.20 mm</td>
<td>2.00 mm</td>
</tr>
<tr>
<td>81</td>
<td>1.35 mm</td>
<td>1.25 mm</td>
</tr>
<tr>
<td>140</td>
<td>1.00 mm</td>
<td>0.95 mm</td>
</tr>
<tr>
<td>160</td>
<td>0.95 mm</td>
<td>0.90 mm</td>
</tr>
<tr>
<td>356</td>
<td>0.70 mm</td>
<td>0.65 mm</td>
</tr>
<tr>
<td>Improvement</td>
<td>10%</td>
<td></td>
</tr>
</tbody>
</table>

### Energy Resolution

<table>
<thead>
<tr>
<th>keV</th>
<th>H8500 BA</th>
<th>H8500 UBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>11.6%</td>
<td>10.5%</td>
</tr>
<tr>
<td>122</td>
<td>9.1%</td>
<td>8.4%</td>
</tr>
<tr>
<td>511</td>
<td>4.5%</td>
<td>4.0%</td>
</tr>
<tr>
<td>662</td>
<td>3.9%</td>
<td>3.6%</td>
</tr>
</tbody>
</table>

Spatial resolution depends on the γ-ray energy and crystal thickness and a theoretical evaluation can be made and compared with experimental measurements [10]:

<table>
<thead>
<tr>
<th>Crystal size (mm)</th>
<th>Crystal thick (mm)</th>
<th>Optical window (mm)</th>
<th>Energy resolution FWHM* (%)</th>
<th>Expected spatial resolution (mm)</th>
<th>Measured spatial resolution (mm)</th>
<th>Efficiency* (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 x 50</td>
<td>4</td>
<td>3</td>
<td>7.5</td>
<td>0.85</td>
<td>1.4</td>
<td>70</td>
</tr>
<tr>
<td>50 x 50</td>
<td>5</td>
<td>Integral assemb.</td>
<td>7.5</td>
<td>0.70</td>
<td>1.0</td>
<td>80</td>
</tr>
<tr>
<td>50 x 50</td>
<td>10</td>
<td>3</td>
<td>12</td>
<td>1.90</td>
<td>1.9</td>
<td>95</td>
</tr>
</tbody>
</table>

*Values at 140 KeV, crystals coupled to Hamamatsu H8500 PSPMT.
The last PSPMT produced by Hamamatsu, has 16 x 16 anode disposed on the effective area of 49 x 49 mm² (50 x 50 mm² real area). The photocathode is made of bialkali and the dynode structure is of metal channel type. Due to compact structure of this PSPMT, the transit time is 6 ns with a rise time of 0.8 ns and a transit time spread is 0.4 ns FWHM (see Attachment 1).

Coupling the LaBr₃(Ce) scintillator with this kind of PSPMT we can obtain the energy resolution already shown [2], a spatial resolution depending on the photon energy, the crystal dimensions and the high anode density. Moreover the time resolution expected is less than 1 ns (with the 6 ns offset due to PSPMT transit time).

For different applications (in space and medical physics) we have developed a detector based on LaBr₃(Ce) scintillator coupled with H9599 PSPMT [11, 12]. For the front-end stage a commercial ASIC type VA32_HDR11 products from IDEAS was used. Referring to Attachment 2, the ASIC is composed of 32 channels each of which consists of preamplifier charge (CSA), shaper and sample and hold. The CSA has a large dynamic range, suitable for the readout of the signals already strongly amplified by PSPMT. To read the 256 anode of PSPMT, 8 ASICs are needed. A PCB was designed to host 2 of this ASICs (one for side) and to be connected, by means of a connector board, on the rear side of PSPMT in vertical position. Four PCBs provides all the ASICs required and the ensemble is very compact and does not exceed the size of the H9500 (50 x 50 mm²). The Attachment 3 shows the circuit drawing of the connector and ASICs boards.

For trigger purposes we studied the signal from 12th dinode of the H9500 PSPMT coupled with LaBr₃(Ce). This signal is not simply positive as found in the literature but has a complex shape in which there is a quick (about 2ns FWHM) positive pulse whose duration does not depend on the type of scintillator used but is probably due to an effect of charge induction due to movement of the electrons in the particular geometry of the electrodes of the PSPMT. Hereunder the waveform is shown.

The amplitude of the positive pulse is roughly linked to the photon energy (the experimental data show a deviation of the 25-30% from linear trend). A negative pulse follows the positive peak; this negative pulse is the “true” signal: its duration is consistent with the type of scintillator used and its integral is in good proportionality with the energy deposited by a photon. Finally, there will be a positive “long” overshoot, the duration of which can however be controlled with a proper impedance adjustment. This latter pulse does not provide information but is crucial for the determination of the dead time because of its long duration. The thorough study of this behavior with different types of scintillators – NaI(Tl), CsI(Tl), LaBr₃(Ce) with his negative pulse of about 80 ns and LYSO which has a pulse of about 50 ns – persuaded us to use the fast positive pulse as the source of the trigger for timing and the negative pulse, after an appropriate shaping, as the signal for spectrometric purposes.
The trigger thus conceived is also shown in Attachment 3. One differential ECL-compatible comparator ADCMP536 ensures a timing better than 1 ns, also tanks to high light yield of LaBr₃(Ce) and fast rise time of positive peak from 12 dynode of the H9500 PSPMT. We think possible better time resolution (probably of the order of 100-200 ps) but 1 ns is the goal we posed for this work.

The subsequent negative pulse pass through a shaping amplifier and a window comparator computer controlled (see Attachment 3 for circuits drawings and logic timing diagrams). An 8 channel differential buffers stage complete the detection system. The power supplies circuits, for low and high voltages, are not reported for simplicity.

**Evaluation of realization costs**

Estimation of net cost for the realization of a detection system as above described:

1) For LaBr₃(Ce) crystals (Saint Gobain, see preliminary offer in Attachment 4):

   Cost isn't proportional to dimensions because the cutting, housing and preparation (vacuum encapsulation with light diffusive powder) are predominant.

   Dimensions: diam. 38.1 mm x 15.0 mm, B380 crystal, 0.5 mm aluminum housing, 5 mm thick light guide,
   - for 1 piece  4360 EUROS
   - for 10 pieces 3455 EUROS

   Dimensions: 25 mm dia and 25 mm high, B380 crystal, Drawing 1-4-5978,
   - for 1 piece  3930 EUROS
   - for 2+4 pieces 3120 EUROS
   - for 10 pieces  2830 EUROS

   Dimensions: 38 mm dia and 38 mm high, B380 crystal, Drawing 1-4-5981,
   - for 1 piece  5755 EUROS
   - for 2+4 pieces 5180 EUROS
   - for 10 pieces  4620 EUROS
2) For Hamamatsu H9500 PSPMT (offer available):
   Quantity 4, H9500,
   Unity price  6340 EUROS

3) For VA32_HDR11 ASIC. About these ASICs there is to say that are now obsolete and probably no longer in production, it will therefore examine a new type of component.
   Unity price  250 to 400 EUROS (estimate)

4) Production of PCBs with gold-palladium coating when needed for bondig,
   Estimate cost  5000 EUROS

5) Electronic components:
   Estimate cost  3000 EUROS

6) Bonding manufacture, consumables, box realization,
   Estimate cost  7000 EUROS

We are still evaluating the possible alternative solutions, among them, in order to contain the costs at least in the first phase, we could use smaller crystals and traditional PM and electronic chain, let us suppose to build a set of 10 detectors optimized for high speed given the characteristics of the pulsed muon beam:

10 units - fotomultipliers about 2000 euro each: tot 20 K eu

10 units – fast front end electronics ( 50 MHz) to suit LaBr3: 1 K eu

10 units – PM High Voltage supply: 2 K eu

10 unità - elettronics fast shaping + MCA, (Amptek) 3000 euro each:
   tot 30K eu
   the same home made would cost about 1/2
   laboratory needs + pcb 3K eu

PMT 20000
front-end 1000
HV 1500
Fast read-out 30000
PCB 3000
TOTALE  55500 euro (+IVA)
References


