Development of an Astroparticles detector

in frame of the neutrinos characterisation LiquidO

Review

Jean-Luc BABIGEON

30 juin 2022

Table des matières

ABSTRACT

The project deals with Astroparticles detection and measure, particularly neutrinos. The flavour oscillation may be a topic of investigation, but neutrino Physics exploration has to be enlarged to different environments, notably solar one.

As accent is made -thanks to discrimination features of LiquidO- to compactness of new detectors, and it will anticipate civilian and security applications.

Essential work has to be made on performances analysis and technological design. The mock-ups and expected prototypes will be validated in accelerator environment. Participation to detection and discrimination analysis by simulations is also essential for a proper achievement.

0.1 liquidO PROJECT BACKGROUND

0.1.1 Situation of the projet

Still recently, to make particles collide has been the principal technique for elucidating matter mysteries. Some important steps are for example the discovery of weak interaction, the Higgs boson, at CERN ,[1]. Last years, the first important step for an entire on-chip accelerator has been published [28], with high performances 28 e-/pulse at 100kHz, and electron bunch lengths of 700fs.

However, even 100TeV hadron collider or 30TeV $e+e^-$ desired by some physicists [18] can't reach the full scale of Grande Unification (GUT). That one would imply colossal energies, ie approx $10^{15}GeV$ depending on sources, referencing the most energetic cosmic particles, even $10^{19}GeV$ according to Planck scale, probably unreachable by a terrestrial machine inside our century. However Space is by itself a fantastic natural accelerator, via cosmic particles for instance, which in small part impacting the globe, reaches the GUT energy range. So in the next present and the futur, a reliable hypothesis is that Space Physics, and Astroparticles studies will take a proeminent place in the Research and laboratories activities.

Standard terrestrial accelerator techniques are more than ever essential, for several reasons :

1. Numerous physical effects are questionning the Standard Model (SM), at TeV energies, moderate (MeV), and at low energy (keV)
2. Accelerators/colliders are a tool of inestimable precision, regarding other observing tools, and allow repetitive and reproducible experiments
3. Detection from Space inside terrestrial detectors is not without limitations (rares events, uncertainty of astrological datas and models, measurement precision, detector sizes, multiparticle interferences,...)
4. Emission detection from nuclear reactors is prone to discrimination problems and environment BackGround noise (BG)

Detection on hadron beams (protons of ALTO, Ganil,...), with positrons, muons, neutrino Productions On Target (POT), induces multi particles environment, like HEP at (CERN), even filtered. Coming even from GeV, a pure electron collider stays not mono beam, but generates for instance, electron positron pairs.

The principal detector functions in multi particles environment are Capture/detection, Discrimination and Quantitative measurements. Last one include $[p, -iE/c]$, but not exclusively, as seen later ; time shape, differential cross section, recoil energy, spin/helicity discrimination, ... are often part of the detector features

[1] for next decennies, the Accelerator designs will probably be based on laser acceleration -with temporary solutions like THz as THz acceleration is seen as scale economy- and by more sophisticated techniques like laser-plasma acceleration, [52],- and, more perenne solution-by « on-chip » accelerator, [50] exploiting μm wavelengths, nano-circuits, and « low cost » lasers. Acceleration of positrons, even muons by on-chip accelerator are conceptually possible

Concerning neutrinos physics, important part of LiquidO project, mass and installations volume -obeying to keV.ktons.year objective- stay today very high, unlike for accelerators, where technology -as explained above- should evolve toward a better compactness. Hence, for instance, **Measure** -not only observation- of cosmic particles in Space, by satellites, is yet recent. Will it be feasible thanks to μ-detectors ?... Can we imagine concepts like VERITAS, like network of radio antennas, applied to a satellite groups, each one equipped with a μ-LiquidO-like for Astro particles measurements ? ... Since recently, the focus is on compact detectors ; that document deals particularly on innovation braught by LiquidO and on its concrete development.

The aim is to better evaluate the technology rupture raised by liquidO design ; depending on energy ranges, it is planned the definition and design of 1 or several prototypes and their tests/validation on accelerators.

Inside that project, faisability of such study is discussed, for the 3 following ranges : keV/MeV, possibly $[50keV - 30MeV]$, MeV/GeV, possibly $[100MeV - 10GeV]$, and TeV, **but linked to driven neutrino physics** . Given realistic existing colliders, the TeV study will be restricted to a subset of the Very High range (VHE) ie subset of $[100GeV - 100TeV]$, possibly $[100GeV - 10TeV]$, in itself constituting a no man's land for precision measurements, for instance γ cross section déterminations and minority interactions (triplets,...)

0.1.2 Motivations : Which physical environments are the scope to that thesis project ?

0.1.2.1 Neutrinos sources in general, status of discrepancies for ν measurements

Neutrinos sources are found from several decades in solar emission[21], geoneutrinos [37], from astrophysical objects [48], neighbouring to nuclear reactors [3] and produced by accelerator beams[14]. That thesis partly covers neutrino production by accelerators, but should of course contribute to the knowledge of other sources mechanisms. The thinkable accelerators for the support of the study are numerous, and are to be envisaged/proposed in the part 0.5.3. Today, the neutrino BackGround level (BG) in whole energy range starts to be well known, and is cited by many references [8].

In brief, without technical explanation, their measurements have lead to some discrepancies, who could question the actual Particle Physics, and are summerized here[8],[14] :

1. Apart from experimental ν measurement deficit against predicted flux from **reactors** (RAA)[2], an isolated peak at 5MeV (5 Mev excess) is recorded in excess viz theoretical models ; altough precise knowledge of neutronics inside reactor, and precise fuel purity could participate to discrepancies, it remains opened and some new experiments are planned in 2022 at JUNO-TAO, with Gd and SIPM detector, for more accurate determination of disappearence probability of $\hat{\nu}$ flux, and constraints on some mixing angles,

2. The **accelerator** measurements exploits matter effect, the evolution of disappearance problability of ν_μ from the decay beam of μ generated by Protons on Target (POT), and probabilities of transition oscillation $\nu_\mu \rightarrow \nu_X$, above 100MeV. Altough sophisticated likehood fits are done at T2K [14] and NOνVA collaboration, the results are in disagreement for the constraints of CP violation parameters, in different scenarios of mass ordering ; the influence of near effects such contamination of by-products on POT is questionable, compared to the high performances of signal treatments in aval detectors,

3. The survival probability of electronic ν from **solar** experiments in the MeV range, reflects their matter induced oscillations, and presents a difference around 3 MeV with theoretical MSW mechanism. In [8], we observe the principal difference between theory and experience, for ^8B, hep, and CNO reactions. Last point is yet an open question, relative to sun metallicity. The terrestrial experiments -yet growing in accuracy like Borexino- could be helped by space projects, considering the notion of ν-floor, and space detectors is a topic esquissed in the present document,

4. **Supernova** ν-characterization of bursts are by nature complicated, due to low occurence (century) of indiviual events[3] , uncertainties in astrophysical datas (Milky/galaxy speeds, sun/Milky speed, halos,. . .) ; interestingly, with very high emitting ν density, $\nu - \nu$ interactions contribute in non linear part to the mixing[4]. Developments are also linked to Dark Matter (DM) physics, with a domain of interest in the keV range (Xenon1T, excess of recoil electrons).

[2] the gap could be linked to bad knowledge of Inverse Beta Decay (IBD) of isotopes ^{235}U and ^{239}PU

[3] even if rate of global events is some/second

[4] there is no today assumed opinion of accelerator feasability of testing these effects. However some people theorize a possibility via rare decay from lepton-μ, and invoque sterile neutrino influence. The principal help is believed to be inside IceCube

5. Escaping the SuperNovae events and PeV cosmic rays- rare burst events - A very hot topic seems then to be the νSI interaction [20], but I did not distinguish if definitely non linearities stay only inside EHE. Some of these could lie inside MeV range[5], but their study does not extend explicitely [6] to that point.

These -today- open questions are expected to be solved in next years. The present document gives interest and priority to improvements in accelerator techniques -possibly also in solar one in medium term-, so positive expectations in other domains, yet very important and complementary, will not be consequently developped. Another fact not mentioned here due to document space is the close dependance of multidisciplinary experiments.

0.1.2.2 Neutrino sources in interest

To adress the neutrino sources, compare them with the future available liquidO technologies and possibilities, the main scope of study is the neutrino production from accelerators, and a possible motivation to Solar Physics with satellite observatory [47],[22].

Indeed, sun is our closest astrophysical object, a regular and low cost neutrino producer[7]. A future space detector should open the door to satellite networks localised in Lagrange points in the solar system[24]. Even Trojan of Jupiter, for instance, are thinkable compagnons to detector installation, not only the classical L1-L5 today solar-ground points[24]. Of course that project was built on suggestion, selection of some ν sources of the neutrino family viz liquidO features. It is also to the study to determine if an opaque μ-detector may survive to violent environments, without passive shieldings, or with a combination of passive and active shieldings and vetos.

0.1.2.3 industrial and sensible applications

Neutrinos appliances reflect the totally new concept of a non interacting particle, (nearly) non interacting with used technique of now nearly 2 centuries : electromagnetism. However, civilian appliances are free to introspection. Why not consider for instance, the combination of photon and neutrino inside a solar cell, in order to act on the energy yield ? At that time some people seem to share that hope [1].

In fact, if the feasability of neutrino coupling in realistic schemes is confirmed, these new concepts does not apply only to Energy, they open the field of I name « neutrinonic », which could be a synthesis with Spintronic and overcome the present limits of electronic circuits.

[5] linked with Diffuse Supernovae Neutrino BackGround (DSNB)

[6] to read deeper

[7] γ producer also, altough its deliveries are made with a slight delay of 10^5 years

0.1.2.3.1 nuclear safeguarding treaties and military countermeasures

Science sans conscience..."

Rabelais

Since the 1968 signature of Non Proliferation Treaty was followed by the 2017 Treaty on the Prohibition of Nuclear Weapons (TPNW), which came into force soon 2021, prohibit nuclear weapons, and seeks for their total elimination. Waiting for achievement of that ambitious goal, the need for detection, monitoring, and efficient control of stockpiles for avoiding conflicts, nuclear terrorism and nuclear civilian accidents, is more than ever growing. The neutrino detector technology may provide a non intrusive way to monitore the fissile production, manage precisely the wastes and their recycling, do a control of non legacy installation, and perhaps alert on suspect explosions from distant sites, at continent scale.

Altough not recent topic, that technology sees a renewal thank's to R&D on compact detectors. There are a few serious open references on that subject, like the review [11]. Neutrinos come from fission and successive β decays of nuclear fuel. Radiation is isotropic, its spectrum bounded by 8MeV approx, with a flat peak at 4 MeV[8].

The detection follows the general rules of ν detection, ie Inverse Beta Decay measurements, ν-e- scattering, and CNνNS. it is possible to linearly link the source and the IBD signal, via detector interaction $\bar{\nu}p \rightarrow e^+n$ in light elements type H, with an energy threshold of 0.78MeV. That threshold may be overcome with CNνNS technique, in heavy elements media detectors. ν-e- scattering, even more indirect, offers a better reconstruction of events, and time sequencing

All discrepancies relative to Reactor Anomalies, even ν oscillations are evocated inside the above cited reference, and pertain also to that domain, rendering essential the proper detector calibrations. Liquid Scintillators Neutrino Detectors (LSND) improved recently their discrimination performances at short distances from reactors, typically 1900m. There are possible applications of in-situ monitoring, with LSND doped with Gadolinium (GD), at distances 25 m. Gd has a better cross section for neutrons, and delivers a strong signal at 8MeV. In comparaison, an other candidate, Li, will product scatters of α and tritium ^3H[9]. Researches are directed to -near field- very compact detectors (a fraction of a ton), it is also -apart any other motivation- because this technical aspect that the present project focuses precisely on these appliances. A recent detector via Nucifer, in Saclay/France, has demonstrated an improvement in suppression of cosmogenic BackGround (BG), and could measure IBD reaction at 7m from OSIRIS reactor[10].

The reconstruction offered by liquidO appears well adapted to discrimination of scattered positron, neutron path, and Compton scattering of e-. Alternative designs use segmented approach, with successive layers (PANDA, SONG1). Operating in an important BG, it is necessary to avoid false coincidences. LSND Scintillating Media were then choosed among 2 families, doped liquid and alternate layers of doped solids. The performances of solid media are shown to be competitive, for instance in DANSS, provided that the scintillator is equipped with Pulse Shape

[8] Wastes are limited lower, to 3MeV, and have naturally lower level

[9] denomination triton inside the ref

[10] notice that OSIRIS has been stopped in 2015, so the measurements were made for residual ν (?)

Discrimination (PSD). PSD permitted a sensible reduction in the grid -5cm- as CHANDLER, 80kg detector. However there is left space to improve scattering length and go to compactness.

The AIEA methods for monitoring are based on conventionnal tools (seals, monitoring of transportation, stock, test of sample…) and additional tests based on γ spectroscopy and Cherenkov, but last one are not always used, and enrichment, natural or predeterminate, is not easy to quantify, contrary to ν techniques, where the fission rates of nuclear fuel components are determinated. However, due to continuous progress of reactors with fast neutrons, low ν energy threshold renders useful the CNνNS technique. The extraction of BG is the main difficulty of ν-techniques, when the location of supervised reactor is far from detector (solid angle of flux interception), stressing the low BG race for advanced equipments. The predominance of natural or man made BG sources (geoneutrinos, other reactors, atmospheric,…) depends on the distance. For instance, reliable monitoring at 1000km would result in a multi-kton installation. Detector directionnality is advantageous to isolate the reactor BG(s) from other installation, and the conclusion drawn, gives a rough limit to fiable compact control at 200km. It could be also appreciated for the control/management of planned geological underground repositories of wastes[11]

0.1.2.3.2 countermeasures That part is not to be developped here.

0.1.3 summary of the part 0.1.2

LiquidO may bring new data on ν-physics and be a complementary of other techniques (dble β decay, LBL and huge kton/yr detectors) by design and smart management of neutrino interactions with fermions.

However it must in first be tested in accelerator beams, in order to beneficiate of reliable calibrations, the proposed uses being in keV/MeV, MeV/GeV, and subset of GeV/TeV ranges.

Compactness is becoming a very important aspect -combined with environmental concerns-. Many appliances from space detection of cosmic particles by satellites ou satellite network, to the implementation of industrial detectors for radio activity monitoring and security are planned.

Beyond the scientific objectives, the open window for industrial appliances could be major inside our century, from Energy ethic race to new signal engineering.

However, one may believe that these motivations could interfere with official programs planned at laboratory, ie for instance collaboration to huge detectors. Let's account for the compatibility of the present project with them, provided one focuses to Short Base Line detectors, which accompagny generally Long Base Line, such E280 for T2K/Hyper-K experiments.

[11] if such unwise underground storage decision is to be taken

0.2 PHYSICS OBJECTIVES, STANDARD MODELE (MS) and NEW PHYSICS (NP)

0.2.1 Remainder on Standard Modele(SM), elements of Beyond Standard Model (BSM) and New Physics (NP)

Particle Physics, at last the SM, is summarized in classical courses, and particularly by [10], [55], where ν flavour oscillation has a contribution. This present document describes an experimental work, but must be driven by formal frame and by recent directions suggested by new theories, last one specifying the proper parameters to verify/measure...

We could start from decades of experiments, observing the growth of quantum rules for atoms and molecules, and go to their nuclear, and further, particle generalization with spin, isospin, color, so a good descriptive and generalist glance, is given among other by [15].... Altough it doesn't follow closely chronology, we may also start directly from mathematics thanks to topological differential topology, because it allows one to better structure/enlight the physical core of SM, and isolate the scientific objectives[12].

An inspirating basis is given by the bright and optimally clear reference [34]. So Nature is today modeled - as today I perceive it... - , as a linear or quasi-linear world invented by humans to face with too complex phenomena, and to build « tangent » spaces to N-dimensions one, every time it is possible. Despite the often arduous and not intuitive notions for me, particularly for rigourous demonstrations, it is my feeling that it should always be a bedtime reading for physics. It is also a determined choice to Aristote conception of locally continuous spacetime, but not underestimating the strength of concurrent atomistic opinions.

Defining an atlas with charts, further, fibrations, the core of differential topology is to introduce tangent applications, and compact manifold, in order to restrict space to local multi linear transforms. Then, for short, equations describing physical phenomena are just a space contraction/distortion by these geometrical transforms. It is somehow a parallel process to the Riemann metric, but encloses exotic and connected spaces, with « holes » and « loops » as those that yet described Maxwell, in his first edition (tome 1) of electromagnetism[38].

Assuming MS landscape, theoretical corpus is based on groups and Lie Algebra, in a Relativistic frame, Quantum Mechanics, where successive extensions allowed to define representations, ie linear spaces where transform operators are associated with operational quantities (scalar, axial, pseudo-vector, tensor, spinnor,...). Then, successive Quantization lead to isospin, flavor, color, charm numbers... and the associated families of particles. Lie representations induce infinitesimal generators, playing around (often) non commutative group operators[13], which describe the « rotation » of elementary particles and explain the terms appearing in di-

[12] There is for me a slight difference in intention, between Beyond Standard Model (BSM) and New Physics (NP), in the sense that BSM expresses less rupture than NP. In BSM, the precise determination of mixing angles, or couplage constants gives a more focused picture of the Nature. For New Physics, the frame in itself of underlying mathematics (a great part of them is at last 1 century old) could be questioned. This may be precised out of that document. Finally, there are probably cases when a very precise experiment opens the door for a totally new theory, and inversely, a sophisticated model may be explained by simple experimental considerations, so the difference could be semantic in the present frame

[13] commutativity is associated with « nothing happens », probably due to Noether theorem, in elementary particles world...

verses state equations (Dirac, Klein Gordon,...) . Elementary particles manifest themselves as superposition of eigen states of operators immersed into the corresponding symmetry group, their eigen values being the quantum numbers cited above.

For a phenomenological description, and because the liquidO orientation is today toward Weak interaction and decays, let's take (one of) the MS Lagrangians[10], which is expected to describe the evolution of particles under EW interaction :

$$\mathscr{L} = \sum_i \bar{\psi}_i(i \mathscr{R} - m_i - \frac{g m_i H}{2M_W})\psi_i \\ - - \frac{g}{2\sqrt{(2)}}\sum_i \bar{\psi}_i(P^\mu(T^+W^+_\mu + T^-W^-_\mu)\psi_i \\ - e\sum -i\bar{\psi}_i\gamma^\mu\psi_i A_\mu \\ - \frac{g}{2cos(\theta_W)}\sum_i \bar{\psi}_i\gamma^\mu(g^i_V - g^i_A\gamma^5)\psi_i Z_\mu \quad (1)$$

Where the notations are explicited in references, but in short, $\mathscr{R}$ is the Feynmann slash, H could be a only a scalar linked to Higgs interaction (with diagonal terms only), m_i is the Dirac mass, ψ_i the fermion fields, M_W is the Higgs boson mass.

The second term is the EW charged current, with the actions of mediated weak (isospin) bosons T and W, via chiral operator P^μ[14]. The third term is electromagnetic interaction via the A potential, and quantized by photons.The last term applies to neutral current with the Z weak boson.

In fact, the precision of coupling constants such g -apart experimental difficulties- raise questions, knowing that this expression is a minimal model. Moreover the Higgs mass is not determined directly, but by knowledge of the W boson mass M_W and the angle θ_W which is also an experimental parameter. We shall live these generalities, not deeply objects of the present project of experimental and design work.

[14] to my understanding, the second term applies also to the leptons and quark states

0.2.2 Specific case of Neutrinos Physics

2 points are emerging :

1. Neutrino Physics may not be taken as sole, isolated from particles zoology : neutrinos are then compagnons of heavy atoms, charged particles, and probably Dark Matter (WIMP, axions, dark photons,...), leptoquarks ?...
2. altough several anomalies were recensed about neutrino production, whatever coming from reactors, atmospheric sources, sun,... the difficulty is now to properly identify and decide which subset of mecanism(s) is worthwhile to invest during a thesis time, given the limited ressources of the Lab/CNRS/collaborations with Science institutes ; of course, it must not be confused with a fashion driven research.

0.2.2.1 Oscillations and friends of

For $\nu - physics$, a review may be found in IUPAP neutrino panel report white paper [8][15]. Let's address that subject in order to extract some useful and possible directions, via the thesis activity.

Inside ideal SM, active $\nu(s)$ should participate to fermionic degenerate multiplets of masses, before any broken symmetry ; in first steps, experimental searches inferred that they are only prone to Electro Weak EW interaction. Later, ^{60}Co desintegration showed that EW can violate the Lorentz invariant Parity, via the fermionic operator $P = \gamma^5$, so the chirality c by the projection operator $C = \frac{1}{2}(1-\gamma^5)$. As most part of discovered Dirac fermions are in left Parity state, so are ν.

Hence, final $\nu(s)$ from accelerators, accompany -even filtered- by-products and are present via weak interaction and probably gravitation[40] ;

ν feature a Left helicity $h = s.p = -$, as it was showed also experimentally. Hence, if they obey to EW, and if they have Dirac character, helicity and Parity being equivalent for a massless particle, imply $m_\nu = 0$, and we should not observe right ν in Nature[16].

However, inside that ideal landscape, experimentations showed that it was possible to determine non null masses of ν, even 3 distincts active ν so the SM was in difficulty. First solutions were suggested by the modelI Seesaw mechanim, describing the savour oscillations of ν between eigenstates of masses.

This model adds a Majorana term in the lagrangian, so we have, with the notations of [14] :

$$\mathscr{L} = -mD\nu\bar{\nu} + \mathscr{L}_M \tag{2}$$

where first term is Dirac mass contribution, and second one is given by :

$$\mathscr{L}_M = -\frac{m_L}{2}(\bar{\nu}_L \nu_{L^c} + \nu_L \bar{\nu}_{L^c}) + \text{id term with R} \tag{3}$$

[15] classifying the open questions left in october 2021

[16] in fact $m_\nu^{Dirac} = 0$**seem to imply**$c \cong h$ and not the reciprocal

where ^{c} is the Majorana conjugaison operator $^c = C\gamma^0*$, C the standard conjugaison operator, L and R are Left and **now Right** postulated ν.

The Majorana contribution violates the leptonic number, and transforms ν to $\bar{\nu}$, which is a sympathetic glance to the Right neutrino, and could solve incompatibility of EW viz SM neutrino models. Now, if that relation is projected on ν spinnors, we come to :

$$|\nu_\alpha >= \sum U^*_{\alpha i}|\nu_i > \tag{4}$$

, where U is the PMNS matrix[17]. With 3 flavours,

$$PMNS = UxM \tag{5}$$

Where

$$M = \hat{i} + e^{i\alpha}\hat{j} + e^{i\beta}\hat{k} \tag{6}$$

encodes 2 angles α and β, who are implied in some CP violations, and

$$U = \mathscr{R}^{\theta_{23}}_{\hat{i}} \mathscr{J} \mathscr{R}^{\theta_{13}}_{\hat{j}} \mathscr{R}^{\theta_{12}}_{\hat{k}} \tag{7}$$

We notice that for the 3 flavors simple modelI Seesaw, the U component may decompose into the product of 3 real rotations matrices and a supplementary one, $\mathscr{J}$ where

$$\mathscr{J} = \begin{pmatrix} 1 + s^2_{13}(e^{-i\delta} - 1) & 0 & -c_{13}s_{13}(1 - e^{-i\delta}) \\ 0 & 1 & 0 \\ c_{13}s_{13}(1 - e^{i\delta}) & 0 & 1 + s^2_{13}(e^{i\delta} - 1) \end{pmatrix} \tag{8}$$

It is also a conspicuous property, that $\mathscr{J}$ behave approximately like a group generator in the limit of $\delta \to 0$. Also, there is -like in the known expression of PMNS- a mixing with the $\hat{j}$ rotation, but the initial reason is probably hidden inside Majorana Lagrangian

Anyway, the search for eigen states for PMNS matrix, enlight the existence of particular solutions of light ν, with observed definite masses. Yet at 2000 era, their experimental values were approached, $\sum_i m_i \leq\sim 24eV$ range[31] on cosmological basis, assuming for instance, Dirac character.

So to emphasize, the precedent model did not decide between pure Dirac masses or Majorana, it is why the searches for unknowns may be for experimentalists, either CP phases only, either $(CP, \alpha\ and\ \beta)$ phases for example, and here for simple Seesaw modelI in the starting basis of 3, and no more, flavours.

The mixing phases, then flavour oscillations take part via ν propagation through matter [14] but more fundamentally in vacuum after a path Δx [9] so I follow last approach[18].

[17] depending on authors, the operator is u or U*

[18] it appears that QM used here could be only the Lorentz relativistic case, not confirm to general relativity, that's perhaps a minor point

Indeed, application of Quantum Mechanics (QM), consists to transform the initial state of $|\nu_i >= \sum_j PMNS * |\nu_j >$ via the quantum propagator $D(p,L,T) = e^{-p\Delta x}$ (p quadri vector), so the state after propagation is $D\nu$, and the probability of measuring flavor j against initial i, is again a projection of the propagated state, (PMNS)x(D)x(PMNS*).

As the propagation phase occurs, so is the -space time- oscillation, via an interference term of $\delta\phi_{jk} = \frac{1}{2p}L(\Delta m^2_{jk} sgn(\Delta m^2_{jk}))$ where $\Delta m^2_{jk} = m^2_j - m^2_k$ is the usual term, p is a mean momentum between the 2 states, and sgn reflects the hierarchy aspect. That simplified form is the result of several hypothesis which may be under more studies, but let's keep it.

Explicit probabilities of evolution

$$P(l \to l') = \sum_j U_{l'j} U *_{lj} U_{lj} U *_{l'j} + 2\sum_{j>k} |U_{l'j} U *_{lj} U_{lk} U *_{l'k}| + cos(\delta\phi_{jk} - ArgW) \tag{9}$$

are deduced in many references, where W is the product of first term of the sum, and U is identified now to PMNS global matrice (Dirac*Majorana). Probabilities for $\hat{\nu}$ may be obtained as well.

The game is to play either with the U values, or with $\delta\phi$ to detect violations of CP symmetries. The second method lies upon Short and Long BaseLine experiments (SBL, LBL), and is adapted to Dirac discriminations masses, while the first one could help to detect Majorana-like violations.

Let's note also [14], the flavour mixing during propagation, starts from hypothesis that neutrinos are produced in flavor mixing states, that mass eigenstates share the same initial moment, and finally that neutrinos are ultra relativistic (GeV). Third hypothesis is requesting a GeV compatible detector, tested with GeV beams. In other side, as suggested by 0.2.1, long baseline is not exempt from ground interaction, more generally with gravity.

These above probability forms are coherent, and may lead to resonnances like MSW one [14] if matter effects are accounted for (ground matter density, but also implications in solar physics); they may also be blurred by experimental imperfections (energy resolution, source size,...) but also by other fundamental reasons, like gravity interactions[40], or quantum entanglement due to velocity differences for instance, so the landscape is of course not described in a few explanations.

The last aspect of that elementary introduction, generated in order to go further to detector physics, resides in hierarchy and specifically in simplification of N-bodies like flavour mechanism. Indeed, to stay strictly in experimental outcomes from reactors and accelerators,

$$n_{flavour} = 3.00\ldots, \text{ with good confidence} \tag{10}$$
$$\Delta m_{21}^2 = o(\Delta m_{31}^2) \tag{11}$$
$$\Delta m_{31}^2 = o(10^{-2} eV^2) \tag{12}$$
$$\tag{13}$$

so the 3-bodies system may be reduced to 2-levels problem between the e_μ flavour and τ one. In that case, we can introduce (Seesaw mechanism), via resolution of the eigen states search, a pivotal solution, as heavy ν and a light one, as light ν, such as $m_{light} \sim \frac{K^2}{M_{heavy}}$, where light ν corresponds to observable today neutrinos, K is linked to a Dirac constant, and M should correspond to hypothetic neutrino[19], which mass is predicted with big uncertainty margins, but greater than $10^{11} GeV$, or even near GUT range ($10^{18} GeV$)[20].

Coming back to [8], In table 2, p14, the phase δCP, α and β are yet subject to researches, together with mass ordering, but the Majorana phases are deliberately excluded from accelerator field-to double β decays priority- with no explicit reason. In fact, these phases are obviously constrained in rare decays experiment, as double β, but a further examination shows that accelerators could bring also a valuable insight. The reasons of trying to exit from double β is from 1st one, to provide an alternative experimental way, and from 2nd one, to escape from very low likehoods/very difficult physics and practical sophistications complained by double β teams.

The core of phenomena is the helicity parameter, and the neutral current studies at targets. It is explicited phenomenologically in [19]. Helicity oscillations are generally indiscernable from Dirac to Majorana-like fermions in standard media, but special electromagnetic media and/or magnetic field could raise indetermination. The last case of that publication invoke a practical case of special medium, with a symmetric character for matter and anti matter. As interaction are of electromagnetic type, between this medium and the μ-magnetic momentum of the ν, it is proposed to search for such specific medium, for instance a crystalline metamaterial, with chiral properties.

[19] in many scenarii, a sterile neutrino is invoked, I don't leave him a great place inside introduction, altough it is considered now as a mainstream topic ; I consider that some freedom must remain yet, before adopting an exclusive theory for an elusive particle, sorry for paronyms

[20] such predictions lead in fact, Theory to envisage a new energy range of BSM

0.2.2.2 Rare decays, π and K decay and friend of

Apart from oscillation phenomena, the ν-physics presents an important component relative to neutrino production, closely linking atmospheric sources to accelerator ν-beams, specifically in their near production zone.

Indeed, the common subject is the formation of intermediate products, π and K and their decay, generating neutrinos. This occurs either from interaction of cosmic rays with atmosphere, or with hadron/target collisions in accelerators. In either cases, as these mesons are part of quark physics, ν may also originate from prompt (heavy flavour) like τ or by weak decays (π,K). The τ production from accelerators, necessitates high energies, but weak decays, pi,K, μ are yet studied and reachable. It is not yet the place to develop the numerous observables coming from boson decay, for instance B_i^n decay proposed by [43], but recent results at LHCb constrain the branching fractions of B^0 and B_s^0, with $p\hat{p}$ collisions in center mass, and with pseudo-rapidity parameter of large diffusion angle[33][21]. There are 2 simple intuitions, about detector consequences : the eventual need for a directional TeV detector- to compare with CMS- and the impact of near zone SBL measurements for future μ-production at ν-storm CERN project.

In the low energy range at T2K [14], the following minority decays imply n, π,... detection and kinematic,

$$\nu p -> \mu p \pi^+ \tag{14}$$
$$\nu n -> \mu p \pi^0 \tag{15}$$
$$\nu n -> \mu n \pi^+ \tag{16}$$
$$\nu n/p -> \mu n/p \pi xx \tag{17}$$
$$^{22}\nu n -> \mu p \eta^0 \tag{18}$$
$$\nu n -> \mu \Lambda K^+ \tag{19}$$
$$\nu n/p -> \mu n/p \text{mésons} \tag{20}$$
$$\tag{21}$$

The search for NP should enclose the diagnosis of minority and neutral current reactions, in one side to better understand their dynamics, and in other side to better constrain the ν Number (flux). Indeed, the ratio of flavour probabilities is compounded by these unknown by-products, even if Neutral Current (NC) reactions are not supposed to be flavor-changed. Also the π, K, $\Delta(*)$ decays, even filtered (decay at rest) influence the ν population inside the beam. At a mirror concept of source one, the scattering particles inside the detector nuclear and atomic media, are to investigate in term of eventual minority/rare events, by detector design, reconstruction, kinematics (missing mass, transverse momentum,...)

[21] the Quark sector, even external to the present objectives, cannot be entirely ignored, via a next personnal travel around Wilson coefficients

The main reaction being CCQEL, indices muons production :

$$\nu n- > \mu p \tag{22}$$

Full reaction terms satisfy -in principle- conservation relations of leptonic number, isospin, charge and dynamic quantities (p,E). The coexistence of minority and concurrent reactions, worse, non CCQEL, renders difficult the detector discrimination[14]. As described in T2K, the discrimination work, very arduous, could be facilitated by liquidO technology.

Since several decades, there is theoretical and experimental convergences for suspecting non conservation of leptonic number $L(\nu)$. The induced CP violation is today suggested by flavor transition, ie neutrino oscillation, for instance (T2K) from muonic to electronic. Main results are summarized in [10], with more details in [],[],[],[]

The advent of Coherent Neutrino Scattering (CνNS) will also bring some answer to the prediction of baryonic N-bodies evolution inside the nucleus, as it is a spectroscopic-like tool[]. However a careful analysis is to follow because of the multi channels implied inside the nucleus. Also if LiquidO reveals some performances **probably unprecedented to date**, such helicity detection and polarization of neutrinos and photons, it should confer a remarkable advance, and should allow ν-physics answers and as other impacts, astroparticles studies such B-polarization of photons,...

Among the other sources, solar one, as precedently suggested, is an very attractive topic. Indeed, Solar Standard Model (SSM) is to be reviewed by giant scintillators (Borexino, Juno, ...), but the theoretical hypothesis are yet fragile (LZ SSM viz HZ SSM), and will demand many kton.years of acquisitions notably the acurate description of baryogenesis. Moreover, the ν and γ interactions with terrestrial atmosphere are prone to contribute to BG, and the fatal angular attenuation, hence less flow, is not a positive factor for the detector yield. The astrophysical uncertainties are probably less proeminent than for cosmological ν detection, and the energy range input (100keV-10MeV) seem well scaled to liquidO projects. The ^{7}Be at 384 keV and at 862keV have the merit to constitute sharp lines on spectrum. It is a good opportunity to adress that question to Ganil accelerator. The continuous part of pp neutrinos in lower part of spectrum is by itself interesting, as a mean to acceed to triplet reactions, and optimize the energy resolution of the detector, so is continuous spectrum of ^{8}B, altough it will cover the hep one. Lastly, the unknown parameters of mixing like the phase δCP, α and β could be investigated, in coherence with the accelerator data.

0.2.2.3 Links with Dark Matter, DM

The synergy between neutrino physics and DM is well described by [39], and [12]. Particular suggestions are given on detector design, and will be reviewed in common, in the part 0.3

0.2.3 Synthesis of part 0.2

Neutrino physics contains yet many hidden mechanisms. In that part, I tried to extract a subset of what could be a Tantale work, I summarize it :

1. the phase δCP, α and β with deep insight on mass ordering[23], with very ambitious objective to constraint **all 3 parameters** by a serious analysis of accelerator possibilities,
2. $\pi^{\pm}$ and π^0 (and kaons) physics inside accelerator beams, linked with fundamental neutrino life, and prone to enlight the atmospheric neutrino production ; direct mass measurement seems attractive before neutrino capture, because of cross comparaisons with accelerator beams,
3. cross section of heavy elements reactions with neutrinos, linked with baryogenesis and Sun physics, the Coherent Neutrino Scattering (CNS) being then involved,
4. investigation on helicity measure/switching inside detector, via a careful design of specific material

Non linear models of self neutrino interaction is left apart…Les's note that the thesis is based on technological work, and is **servicing** these general themes. It is to the designers to link them with the detector's features, and is the topic of next parts, which tries to show the adequation of multiple flavors of liquidO with these very differents objectives.

[23] quantum decoherence aspects could support short base line detectors, then detector compactness is again mandatory

0.3 NEUTRINOS DETECTORS, STATE OF THE ART/liquidO

A good synthesis of scintillator detector technologies is to be found in [12] and [39].

Altough these refs are WIMP oriented, the corresponding teams faced early with common performances objectives, ie energy resolution, timing and reconstruction, BG, charged and neutral interactions, threshold,.... Inevitably the existing old and recent techniques for ν-detection were adopted[24], at less in scope of « direct detection », the difference being that ν are -often but not always- intrusive particles for their searches. On the other hand, the directionnality concept is initially a specific WIMP detector need, and brings an original insight for future designs of ν one. The physics of diverses interactions is somewhat well described, because of strict necessity for them, to isolate tiny phenomena. Finally, the ν-floor concept is also common to low noise experiments inside multi kton detectors[25].

0.3.1 Scintillators, general

Scintillators exploit luminescence - previously phosphorescence with $\Delta S \neq 0$ - now fluorescence - converting the energy exchange of a charged particle or a photon, to a radiation collected by receivers in optical range[26]. The scintillating medium is a inorganic or an organic substance, in solid, liquid or gazeous form. As soon as a collision happens between an input particle (baryon, ν, μ, γ ...) and the scintillator medium (atoms and nuclei), a great diversity of interactions occurs, among them[27] :

1. emission of β from weak interactions, ($\rightarrow$ re emission of electrons/positrons + $\nu/\hat{\nu}$)[28]
2. radiating γ (if) from neutrons scatterings off nucleons, (depending on neutron energy), $e+e-$ pair creations or successive Compton scatterings of induced γ)
3. pair creation $e+e-$, (if) from input γ,
4. Compton diffusion (if) of γ photons off electrons,
5. (Coherent) scattering off nucleus
6. elastic and inelastic scatterings off individual nucleons, (measurable energy in low range, in ratio of input particle mass/nucleon mass)
7. Deep Inelastic Scattering (DIS) inside nucleons (in relation with quark physics (partons's sea), higher input energy)[29]

[24] halioscopes and haloscopes are not part of that document

[25] the term « detector » is used instead scintillator, despite the object of that document, because several examples of cryostat or spectrometers, contains scintillators, it should be reducing to exclude them

[26] The principal scintillation mecanism is denoted spontaneous emission, in contrast with stimulated one in laser appliances, but the pertinence of that denomination for the detectors, and the conceptual frontier between both of them may be felt unclear. So is the case of fluorescence and phosphorescence, depending of the actual choices, and these have technological consequences, for instance relating to the lifetime of excited states, so the response of the medium

[27] « if » means that the particle is known « as » ; the list is not specifically ordered by growing input energy, partly because of liquidO topic

[28] emission of α, for instance by fragmentation of heavy ion beams is not mentionned here by memorized

[29] At that level, it is supposed always an inelastic behavior

8. [30]...

A first observable of elastic and inelastic scatterings is the recoil momentum of centers (molecules, atoms, nucleons, partons...), which may be measured, in practice more or less directly[], depending on output particles energies and polarization. Kinematically, the recoil momentum will be in ratio of $\frac{p_{recoil}}{p_{input}}$, probably of order $\frac{m_{input}}{M_{recoil}}$, but situation is probably not so simple and better described in [8]. We suppose here that $m_{input} \ll m_{recoil}$ if input is a near massless particle as neutrino. So in ν-physics, like for WIMP, typically GeV supposed inputs should manifest by MeV, even rather keV recorded recoils for instance, helped by kinematic analysis. In other side, there is a threshold, depending on the nature of interaction. For elastic scattering on nucleus [8], one finds 100MeV for ν_{mu} and higher than 3.5 GeV for ν_{τ}.

The ionisation is a central following observable, described for instance by Bethe-Bloch expression[15][]. Although it does not appear into liquidO features, as ionisation is a regularly cited point, it will remains interesting to stay further a little on it.

But there are other fundamental features that ly on Spin discrimination, SI and SD interactions, even physics of Deep Inelastic Scattering (DIS) so scintillators are prone to reveal the corresponding cross sections σ. In terrestrial experiments, these σ are understood in laboratory frame, and involve masses of input and by-products particles/messengers. Let's give one of them, just for information [39], [8].

The Spin Dependent interaction (SD) and associated cross section are described by [39], the link with ν physics in a precise energy range will be to better detail here[31].

If the medium is only made by light atoms, atomic transitions contribute to yield; but the ionisation energy are 13eV, staying in far UV for H, and the lines are not numerous for light materials in general. In the case of heavy ions, there are many lines and the response is complex : for instance, the atomic transitions for the chrome, extend form 6,76eV for 1^{st} line, to 7,9keV for 24^{st} one. However, [42], the forbidden gap is an efficient filter to limit the atomic recorded spectrum. 1 important parameter is the lifetime of excited levels, because it conditions the global response of the detector. Finally, the Density of States (DOS) is the key for evaluation of the medium yield. At ambiant temperatures, thermodynamic models are then necessary to take account of the DOS[32].

Beyond the keV range, and above 1.8MeV, the atomic mechanism are ionisation and pair creation[33].

[30] In that frumpy list, it is not explained why as soon as input energy grows, the scattering length decrease, so we should meet successivly, slight nuclear recoils from electrons scatterings, then coherent nucleus scattering, Compton, ionisation, baryon interaction, and finally deep scattering inside nucleons, all interactions of course, not leaving place suddenly to the next one but coexisting

[31] TODO

[32] laser materials in the eV range are perhaps to consider, in a selection of the scintillating medium for low energies

[33] so the range 100keV-1MeV is somehow heterogen

The electromagnetic radiation is not generally directly observable via opto electronics or PMT's, because it is either localised in hard X rays (in that case, several successive Compton desexcitations into the scintillator raise the wavelength to UV), or by photo electrique transition, where photons disappear and the collision/interaction centers emit molecular, atomic ray, or charged particle (electrons by ionisation)

Some bosons and uncharged particles as neutron will not be signed, at less without magnetic field or nuclear recoil detection, but kinematics allow to restitute their path and their interaction cross section.

Moreover, (scintillator) medium is among others, an electron source, which may also recreate ionisations by Auger effect for instance, but above all XUV, UV radiation ; those radiations are sensed by a receptor network such PMTs, around the -fiducial- volume of the detector.

Organic/plastique scintillators, are available for instance at Saint Gobain [46].

The history of organic scintillators is not recent, even German researches during 2nd war were active. LAB is cited elsewhere in the document.

Inorganic scintillators cited for ν detectors are for instance NaI(Tl), BGO, BaF 2 , CsI(Tl), ZnS, LSO :Ce, GSO :Ce, YAP :Ce,... but a far more extended description is given by [13].

Beyond natural components such $CaWO_4$ (blue), Zn_2SiO_4 (green with traces of Manganèse Mn^{2+}), or ruby (Al_2O_3 red with traces of Cr^{3+}) offering limited possibilities, many man made crystals have been processed, such as Ionic dopants, Lanthanides groups, or Heavy ions.

Ionic dopants belong often to transition family (Ti^{3+},Cr^{n+}, Ag^{+},...) or Lanthanides (Pr^{3+},Nd^{3+}, Gd^{3+}, Tb^{3+},...) and a special mention for Cerium Ce^{3+} where absorption and emission properties are not same, and depends on the host crystal matrix[34] ; a last family is composed by heavy ions, (Ga^{+}, Ge^{2+},...). Most of applications in industry are devoted to visible spectrum, it is why the UV part, despite attractive for scintillators, gathers a few of them ; candidates should be Ag, Gd, Ce, Eu and many heavy ions.

The cristallographic structure of the host crystal -often an oxyde- linked with the determined symmetry of the couple dopant-oxyde, may constitute de facto a network facilitating reconstruction of detection events.

The **Liquid** Scintillator Neutrino Detectors (LSND) are partly described by [53] but may have far different profiles, depending on the energy range and the type of input observed particles.

Transparent scintillating liquids present a low yield, precisely because of their transparency which is found necessary at less in High Energy range and for low Z detectors. Dopings with heavy atoms have been tried since several years in order to increase the (neutron) interaction cross section. The success is validated via a compromise with the transparency. At lower ener-

[34] Same remark apply for Europium, stable element but stability inside matrix for scintillators is to verify

gies, transparency is considered less critical, and photo electric effect is more pregnant, which allows associations of heavy atoms. Moreover, an other approach at high energy (T2K) is to associate an absorbing medium, curbing particles, to a low Z scintillator.

Gaseous detectors are often made of noble gas like Xenon or Argon.

A pragmatic method to present particle detectors is to give 2 examples, typical of recent designs.

0.3.1.1 CREST III, cryogenic crystal detector with scintillating response and veto enveloppe

CREST III [2], localized at San Grasso, implements solid-state cryostat/scintillator detector for measurement of recoil energy of crystal atoms $CaWO-4$, during scattering of a particle. The interaction is Spin Independant (SI) and the recoil energy, much lower than input particle one, manifest under phonon modes, which are collected by adapted transducers.

The crystal of low dimensions (20x20x0.4 cmxcmxcm), generates a global phononic energy response to SI interaction by atomic recoils[35], a radiating (light) response of β and γ scatterings from its scintillating behavior, these 2 signals are collected and synchronised/put in coherence, by a AND gate veto. Supplementary vetos, but for shielding uses against energetic and cosmogenic particles, are made also by scintillating external polyetylene covers and metal sheets. CRESST III is in cryogenic conditions (5mK). Despite the compactness, the scintillator sensibility is very high[36].

The CRESST III band is deliberately for WIMP demand, axed to $< 16keV$ interactions. It is clear that above MeV input energies are not welcome in a fragile crystal. One may note that PMT receivers, contribute to muonic noise, and must be subtracted, at the price of blind temporal windows (-7.6% loss of time). It is possible to calibrate the SI response, taking account of O and W response of atomic components. The energy resolution is outstanding 30 eV/bin. CRESST III is among the best performers in low keV search and exclusion limits, but one may find the coherent neutrino scattering at level $10^{-6}Barn$, 5 order below their best results.

0.3.1.2 Large Underground Xenon (LUX), part of Xenon-like experiments, XENON10

LUX [7] is a typical collaboration for an underground experiment with a double phase Xenon liquid-gaz, around XENON10 collaboration [5]. Inside the liquid phase, the medium behaves as a typical liquid xenon scintillator, the γ interactions generates radiations of different wavelengths, and, after eventual scatterings, UV spectrum, and also photo-electrons; there is also a DC vertical voltage applied in all volume, so every photo-electron is drawn to gaz phase, where it encounters an electroluminescence with gaz molecules, which is also recorded. These 2 events are time separated inside PMT's. The discrimination objective here is axed to WIMP search, so the nuclear recoil events, those who are searched[37], are deduced of substraction from total events (ER-NR discrimination). However, nuclear recoil, -as thresholds are claimed as low as 1keV- as electronic recoil are real subjects for ν-physics, and specifically for potential

[35] here classical thermal longitudinal phonons

[36] A probably interesting reference about response bands of nuclear recoils could be found in ref[12] of the paper, but I did not succeed to extract it

[37] WIMP are supposed not to manifest with U(1) Electromagnetic symmetry group

extensions of liquidO technology. The cryogenic conditions allow DOS to stay inside thermo equilibrium near Fermi, ie the ideal fermion statistics for the scintillator are met (there is not temperature broadening of states). Here also, the range is keV one, but the concept could be reconsidered for MeV range, perhaps even with ambient conditions. An interesting fallout of LUX is the discovery of UV double pulse capability of some PMT's models for low energy photonsdetection. In fact, as interest is focused on SIPM, to know if we can explore such feature in parallel for them demands some studies.

0.3.1.3 Some detector installation/programs

The list of installations should be out of interest[38], in first very large, secondly heterogeneous. It is better adapted to cite characteristic examples, in following table 0.5.4

NOM	APPLICATION	TYPE	
Fermi-LAT	particules cosmiques, γ, e^+, e^-		
MAGIC			
HESS			
JUNO			
VERITAS			
FACT			
Super KAMIOKANDE	neutrinos solaires, atmosphériques, cosmiques	scintillateur Cherenkov	39x42
SNO			

[38] the more I read that list, the more I find it out of interest, I let it safe for the moment, sorry

0.3.2 Description of status of LiquidO technology

LiquidO [16] breaking with transparency, is an opaque scintillator, today made either by organic liquid or pasty medium, with a relatively low absorption length, associated with a shifting wavelength fiber network (WaveLength Shifting Fibers WLSF). The fibers are immersed in the scintillating medium.
These fibers, for example Kuraray B3, present an absorption centered on 350nm and their emission on 450nm. The core is polyethylene, doped by fluorescent centers, and the cladding is in metacrylate [32].

The major phenomena investigated is the inverse-β decay (IBD) reaction $\bar{\nu}p \rightarrow e^+n$, then the attended out-products are a subset, for demonstration, of global potential discrimination.

LiquidO was demonstrated with a low Z version (for input positrons, electrons, μ beam ?) but any MeV heavy variant is possible.

Among the reactions described at 0.3.1, the producted e^+ by IBD annihilates fastly by interaction with an electron cortege of (hydrogenoid) atom of the solution [41] (input energy > 1.8MeV). The resulting 2 γs will lose each one energy, by successive Compton (in)elastic scattering off the atomic cortege electrons of atoms of the solution.

But, depending on actual γ energy, the scattering consequence may also be either ionisation, probably in the first sequence of scatterings, or atomic transitions, at the end of the γ path[39]. That energy exchange have been studied since a long time by Bethe and also Bloch [23][40]. As that point is a central one for today studies on liquidO, despite the detailed -numerical-reconstruction is different to that mean description, one can't avoid to shunt this model. The finally relativistic formula, resulting from quantum development,

$$(-)\frac{dE}{dr} = Kz^2\rho\frac{Z}{A\beta^2}ln(\frac{2m_ec^2\beta^2\gamma^2}{I} - \beta^2) \tag{23}$$

meet several limitations.

The ionisation potential I is the subject of recorded data, where flat approximation $I = (10eV)Z$ applies for $Z \geq 20$. In fact, the chaotic data for low Z media reflects the delicate ionisation treatment in that zone. Also the actual frame is valid for projectile mass $M \geq 1MeV$, ie for a decay-like, for instance with an energy threshold. Inside the frame of [16], the energy range -of a planned keV/MeV liquidO version- is however describable by the Bethe approximations but light input particles as $e-$ behaviour depart significantly from a forward mean path. Indeed, like described in [6], although Bremstrahlung effect does not occur below some 10'z MeVs, the $e-$ path may experiment retro-scattering on target, specially with a doped medium like with Gd fraction. In comparison, the behaviour effect of protons, or even muons is not so much affected by radiation losses at high energies, it must be retain for the GeV/TeV version. Another feature of these mechanisms is the straggling, which conditions the statistics of collisions. Indeed, the average losses are evidently inadequate in a reconstruction landscape. Once more, for Heavy

[39] the first scenario is however supposed rare, accounting its low cross section in low Z media tested

[40] notations from [23] with known variables

input particles, the spreading statistics will be low, the real intricate paths remains the case of $e-$ scattering on heavy doped media.

The atomic transitions are not immediately in UV, because yet too energetic. So they generate firstly photo-electrons, who induce themselves other less energetic transitions, until UV range be reached. So the global optical/UV luminosity or yield of the medium is not directly reflecting the first impact of charged particles (if we just mention $e-$), but all the $e-$s or γs having reached the adequate optical range of receptors by multiple scattering losses, for example the range $< 6eV$. However, the γ anti-coincidence of the first annihilation is a clear signature of e^+ annihilation. Inversely, that anti-coincidence will not occur for an input $e-$ event. It is described by reconstruction plots of [16]

A particular feature described in LiquidO lies in « light confinement ». It is of course not a guided light physics like in photonics but it lies in the proximity of luminophore inside the scintillating medium. Indeed, just imagine that collided or scattered ions are close to dozen of molecular scales, for example some 100nm, it explains the successive and close scattering diffusion of a charged particle, and their Compton or atomic UV/optical transitions in very short segments, giving illusion of confining light[41]. Beyond discrimination seen for e^+ and $e-$, the need is discrimination between $e-$ and γ. According to [16], there is a clear difference, in MeV range, between the spatial extension of each of these 2 paths. It remains some further investigations -other than reconstruction algorithms- to better understand and manage that feature.

Concerning the other output partner, the neutron, the liquidO technology lies on standard Cowan/Reines technique of coincidence. It may be improved by recoil measurements.

When UV range is reached by first low energy input, or last lossy scattering by a charged particle or γ, the question is to render these wavelengths compatible with measurement opto-electronics. Organic liquids such LAB, combinations of cyclic molecules containing linear hydrogenated terminations, interacting with (UV) γ, allow emission of photons with wavelengths around 300nm. In fact, the situation is more complex, given the molecular arrangements and the presence of impurities ; the spectrum of LAB may possess several absorption lines, inside the band 350-450nm [17]

The second transformation is provided by a doping agent, like PPO, which realizes by non radiative transfert a big Stoke displacement (from LAB to PPO) in short, a transfer filter from 300nm wavelengths to 350-400nm approx, whose filter avoids re radiating internally to liquid medium [41]. PPO is typically conditionned in powder, high solvation is -relatively- adequate with LAB, anyway in low volumes. The scintillating medium is then able to emit an nearer-UV radiation, suiting to detectors such PhotoMultiplicators (PMTs). The absorption lenght of a WSLF fiber is optimal toward 375nm, its optimal emission wavelenght toward 450nm. PMTs are fonctioning from 115 to 900nm even to 1700nm depending models, but the most frequent in ν-physics, probably Bialkali, are centered on 450nm, with quantum yields typical of 20%. In the case of LiquidO, the fiber netwotk immersed in the medium, constitutes a spacetime grid of events. If such medium as LAB was transparent, fibers, for example WSLF, could collect radiation, but that one should be diffuse, because all the scintillating medium reacts (the volume is globally enlightened).

[41] as that term is shared by electromagnetic community, sorry

The next liquidO idea, opacity, is to choose a freezing medium (wax). The density of absorbing molecules stays enough low in order to allow a low absorbing lenght, but enough for limiting that absorption lenght to dimension of order those of detecteur. Given the scattering length of 5 mm for a spacing between fibers of 1cm, the network is a real barrier for particles, a few among them escaping to inelastic diffusion with fibers, are propagating without significant absorption.

The collected light by fibers is then measured by a counting electronics based on avalanche diodes (single-photon avalanche diode, SPAD) []. The photon counting is recorded for the scattering by a given fiber, and conditionned by the losses of WLSF fiber, and the efficiency of the counting electronics SPAD.

An opening discussion for liquidO resides in discrimination in $\hat{\nu}$ and ν cases, the last one being the most intricate because of non separability of generated $e-$ from the β BG. Solution of doping with ^{115}In or ^{208}Pb are proposed [16]. Notice that In is a favorite candidate in solid state and semi conductors physics, with a long time expertise in doping. However, like for neutron discrimination, the recoil mesurement techniques should be also proposed as an efficient help. It remains to study their feasability at MeV ranges.

0.3.3 Lessons learned from precedents examples, from the LiquidO ruptures, and problematic

The above detector descriptions, joined with the liquidO status, show that there are 2 families of detectors :

1. multi kton (cherenkov) installations with transparent media, where sensibility and tracking of rare events is primordial,
2. compact detectors where the input flux may (or not) be consistent, with other concerns, such reconstruction, internal data, directionnality, ...

The multi kton detectors parameter is then graduated in kton.year.MeV performances. Its physics and engineering differ from compact one, as predictive statistics take a great place. In compact detectors, the accent is put on precise interactions. Several techniques or geometries are then used : either one encloses a transparent volume by detectors around a solid angle $\Omega \leq 4\pi$, or one exploit a 1D, 2D geometry. In the 3D case, volumes are often huge, and the room is available for detectors. In the cases 1D or 2D, focus is put on compactness, some realizations implement a collecting fiber UV, WLSF-like, on one side for instance [].

Relative to solid -crystal- technology, my « solid-physics tincture » inclines me to feel the necessity to exploit optimally the network geometry[42]. Moreover, the today doping possibilities with ionic centers inside matrix, where compromise is made between yield and destructive internal mechanisms, could contribute to very precise crystalline order, with practical realization

[42] personnal remark : let's imagine -for 1 instant- the plausibility of universe formation description. If the following landscape is reasonnable, ie decoupling neutrino at first second(s), then Baryogenesis very soon, and finally decoupling γ at $\sim 410^5 yrs$, we could envisage that our terrestrial cartesian geometry matches approximately the behaviour of SM radiation, ie a geometric detector reproduces in his intrinsic group structure the proper structure of SM fermionic interactions. In other side of course, one could argue that a neutrino detector should be adapted to a ν intrinsic geometry group, ie for hypothetic flavor symmetry group for instance ; still today, that last design is certainly less trivial...

of supercell concept. Let's clarify that point : suppose, like in [13], an octaedric site, consituted by Cr^{3+} ion, surrounded by 6 O^{2-}. The luminophore-luminophore spacing will be $d_{im} \sim \frac{r_{mesh}}{cr}$ where r_{mesh} is the distance between 2 cr ions in case of a 100% doping, and cr is the effective doping. For a $r_{mesh} = 2\AA$, and $cr = 1\%$, the typical distance between luminophores is 20nm, which is yet in X range for coherent response. Then, the doping has to be very low, with $0,1\%$ for example, the medium response could be 200nm, ie the last range in question for fibers and optimal SIPM. Let's go further, and consider a 2D doping, for instance an epitaxial growth : one layer is doped in its xy plane, surrounded by 2n non doped layer in $\pm z$. We have endowed potentially the medium with a directionnal characteristic if we are able to separate the spectral response in xy plane from orthogonal one.

Moreover, the doping may include several ions types ; depending design strategy, a 3D reconstruction is possible with ion 1 in (xy,z=0+n) plane, and ion 2 in (xy, z=1+n-2) or (z=-1 -(n-2)) planes

However, it is also possible to record the recoil of nucleus at low energy inputs. Above MeV range, we expect an electron recoil. In that case, numerous other effects, like ionisation, hinder the reconstruction. The nucleus recoil could yet be recovered, at price of some additionary tools, like Migdal effect[].

A common difficulty emerging from several installation, is the use of PMT's, as cumbersome, radiating and ionising the scintillator medium, sohisticated and high cost devices. The use of SIPM is a real progress, but their performances in short wavelenghts should be improved, in order to avoid specific WSF-like fibers. It is known that the attenuation of Si has a pronounced high plateau under 400nm, because of GeO_2 component. However, advanced researches at LASP Boulder,USA [51], pulled by Telecommunication sector, extend the limits of classical fibers to hollow fibers, with transmissions up to 125nm. Given the oxygen absorption at 180nm, either the use may exclude that zone, or it may be filled with gaz, N2 or Xenon/argon could be envisaged. Suppose we have lowered the collector wavelengths window, it remains now to lower the wavelenght window of SIPM in such proportions.

Scintillator network designed for medical imaging for instance, present a huge receptor density, and for an adapted scattering length, ie a centimetre spacing between receptors, requires probably a supplementary development, either internal or with supplier. Another concept, for big Cherenkov installations, demanding an important detector surface, should be a **network of imaging networks**

The 2 innovations of LiquidO are to be translated by an approach methodological, topological and physico-chimical.

1. methodology : for a given appliance, HE,ME,VHE, type of searched reactions, to define the scintillating medium,
2. topology : depending on liquid, wax, solid, to define the light collectors configuration linked with the scintillating medium. In the case of collecting fibers, The quality of collecting mechanism is to investigate, for example the cladding contribution,
3. to define the placement of the receptors,
4. to define the electronic treatment and the software

Remarks :

1. Opacity should be deeply investigated because it depends on choosed scintillator medium -not restricted to gadolinium, industry gives interesting suggestions - and considerations of intricate atomic and nuclear phenomena.
2. The big innovation in compactness braught by liquidO and the opto electronic evolutions, drives to a clear preference for the couples **scintillator array/SPAD**.

0.4 PROBLEMATICS

Here are exposed remarks about liquidO status, in order to define progressively one or several research directions.

0.4.1 Energy ranges and observables

LiquidO proposes discrimination characteristics extending away the State of the Art. Inside that part, type and energy domains of liquidO are studied.

0.4.1.1 Tracked particles

In [16], LiquidO records $e^{\pm}$, γ, and less directly n. The p record and later, μ will be included. These are the minimal set, every other candidate is conceivable, depending however on version.

0.4.1.2 Energy ranges

Lower part of LE (100keV-10MeV) from 100keV to 1MeV being mostly populated by photoelectric effect, visibles photons and beyond are out of today study of[16]. In fact, liquidO allows certainly a HE version but discrimination must call for an other criterion than pair creation, below 1MeV.

Above 1 MeV is actual liquidO version ; as indication, practical limit of not huge accelerators is 30 MeV approx, ie ME range. It encloses also the nuclear reactor range (1-10MeV).

In other side, a finite scattering lenght imposed by the grid, does not reflect long distance potentials, as well those of charged input particles, as scintillating centers. A proper experiment could examine that point. That question is yet current inside MeV range, for subatomic physics and N-bodies simulation.

The link with scattering theory [29] cited in Geant4 [25], show that approximations could be constrained, and the energy boundaries extended from 100GeV, considered as HEP when references were published. TeV window stays not precisely studied, despite claimed flat in most cross section data curves.

Apart that update of cross sections, The range 100GeV-10TeV, invoked par some authors[36], [40], ie the start of Very High Energies (VHE, 100GeV-100TeV) allows an investigation, as well for the Lorentz Violation test as for gravitation effect on neutrinonic mixing.

Going further, what is the behaviour of an opaque scintillator to UHE, even EHE fluxes (»100PeV), for rare cosmic events, on a compact device ?

Hence, high energy version of liquidO should be limited to 10TeV.

0.4.2 Synthesis of the part 0.4.1

The preceding comments are intended to propose multiple versions of LiquidO :

1. ver 1 : HE range, 100 keV-1 MeV
2. ver 2 : ME range, 1 MeV-30 MeV
3. ver 3 ; VHE range 100 GeV-10 TeV

0.4.3 Performances and planned objectives

Firstly **How should be a future detector** ?

The following features according [4],[43] must be analysed for a technico economical compromise. The table hereafter is driven by physics arguments, not design oriented, but encloses receptors [27]

Features	State of the Art	Objectives	Unit
Detector photon yield			ph/MeV
Extinction length			
Isotope fraction			
Identification/discrimination			
Polarization detection			
Helicity detection			
Absorption length			
Emission intensity (ref NaI(Tl)			
Emission time (electronic performances)			
Energy resolution			
Linearity and thresholds in energy			
Recording of neutral current reactions			
External magnetic fields sensibility			
Spatial resolution/localization			
Reflexions on walls (fiducial volume ?)			
Treatment software			
Acquisition speed			
BackGround suppression			
Radiation strength and contamination			
vibrations ?			
Temperature influence on medium			
Recycling			
Global volume/weight			
Cost/industrialization			
Séparation between Cherenkov and light confinement ?			
***	***	***	

[43] who is limited to Liquid Water based Scintillatorsr, WbLS, then it is not exhaustive for solids scintillators

There are in fact multiple tables, each one devoted to keV/MeV, MeV/GeV and Gev/TeV.

0.4.4 Salients point of liquidO and suggested evolutions

Liquid scintillators like Borexino [9], exploit transparence of a huge volume, its isolation from external radio-actif BG, and the 3D tracking of events by PMTs networks.

At T2K, one plays with an large absorption by high Z materials (iron), and alternate superposition of solid scintillator (graphite).

With LiquidO, one directly starts from a scintillator who realizes a first λ conversion helped by WLSF fibers, and one accesses to photon counting via SPDE (Single photon Detection efficiency) of SPADs. An advantage [16] is the ability to mechanically maintain fibers by the wax.

Hence liquidO innovations are compactness and its discrimination performance compared to complex statistics treatments of T2K experiment [14]. The SPAD technology should overcome PMT one and goes naturally toward compactness.

LiquidO was evaluated in the context of double-β, and leaves out photo-electric effect, invoking the interest of low photo-fractions for better discriminations, but it may be discussed, for low energy versions,

But from event to SPAD signal, (γ, e^+, μ,...), multiples losses are possible, with the consequences of lower yield and BG rejection.

The respective roles of scintillating medium and collecting fibers are a central subject for that detector study [45]

Is there a better transfer for the couple scintillator/receptors ?

Let's imagine several scenarios, *without limiting us strictly to existing technology performances* :

1. WLSF fibers are replaced by fibers with direct transfer (without λ shifting) and the SPAD are modified[44] for an optimal gain in the XUV range (100-300nm), but the scintillating medium is inchanged,

2. Scintillating medium (liquid or amorphous) is replaced by a crystal (ordered medium or a medium presenting symmetries), we keep fibers,

3. Scintillating medium (liquid or amorphous) is replaced by a crystal (ordered network or a medium presenting symmetries) and we create light guides inside,

Third solution is inspired by nanophotonics. The crystal may be doped or not, some luminophore centers are thinkable asZnS(Ag) [30].

Discussion about knowledge updates on waxes is available within RAHA [44], where parafin-like waxes are compared to micro-crystal one. Local atomic order induces a higher bounding energy, and a better temperature strenght, but presents other drawbacks.

[44] by R&D, hence an action which importance is to evaluate

Another avenue is cryogenics or very high pressures, where hydrogenoids acquire a solid structure. Beyond material choice, depending on group structure of scintillating material, how are they acting on propagation, directionnality and nuclear reactions ? Is it possible to « taylorize » those reactions, even amplify a given phenomena θ_{13} with a proper structure of the medium ?

Another parameter is the importance of the forbidden gap for atomic transitions recording, inside a quasi-crystal medium [42].

It is clear that one can't with a compact detector, obtain an equivalent object of 50ktons one, with a sole crystal. Hence, the volume reduction gained by opacity and the effective surface offered by a miniature detectorr miniature are key evaluations, inside the frame of an accelerator (or a satellite. . .).

Apart detector tpology, other questions come relatively to the discrimination :

How to improve discrimination by intrinsic performances of the detector ?

The kinematics of -charged or not- particles, neutrinos, neutrons,. . . raises the need of dynamics description (p,E) of in and out products. Among solutions are, together or not, a magnetic field, and a dedicated software[45].

How to manage spatial resolution ?

Beyond simulations of [16] (fig 1-c) which illustrate the impact on fibers grid -but also the scintillating reaction-, how to reduce pixel areas, since the noticed event is point like ?

Is the ν travel source of a useful coherent radiation, Cherenkov or Askaryan (if the medium is dielectrically dense) ?

In that case, coherent radiation, could emerge from BG, and should be a useful signal for liquidO.

Moreover, in addition to timing technique[16] z-coordinates extraction, the xy spatial structure of collectors is suitable for a treatment by (spatial) Fourier transform, Wavelets or Radon transforms [35],[39]

So 2 directions :

1. physically, to vary the pitch and the grid configuration (constant, variable . . .), and to quantify the opacity concept,
2. for data treatment, to use 2D Fourier, even most adequate transform.

First proposition is easily understandable. But what is the gain provided by a conjugated variable ?

The « cuts », defining the fiducial volume[46] are reachable by Hough transform [14], which, in T2K experiment, integrates also a reconstruction function. In other side, wavelet transform is also suitable to the contour detection[26]. Whatever selectionned method, the speed and quality of treatement are primordial.

How to record polarization of γ photons ?

How to record particles helicity ?

A suggestion was made above, to investigate metamaterials with specific symmetries.

How to manage induced radio-activity by BackGround BG and by tracked events ?

[45] it must take account of electronic blanking so multiplexing SPAD is an idea

[46] is fiducial volume in adequation with compact detector ?

BackGround (BG) is here inside all detectors, and is well described in Borexino experiment[9]. Even with careful material selection one meets some unexpected situations, for instance WLSF fibers are sources of radiations. Concerning receptors, the SPAD are clearly less noisy than PMT's, but the activation of scintillating medium must be constrained.

Even with opaque detector, natural sources in air, water, hygroscopic environment exist. The following chain for instance :

$$^{238}U - - >^{218} Rn - - >^{206} Pb \tag{24}$$

who is present in non purified air and water, is prone to live significant traces inside scintillator medium. Radio active contamination is conditioned by the material choice, the environment, the assembling care, and maintenance/reliability ; it is to be eliminated, even helped by a reset mechanism.

A last but important concern is the possible occurence of Wigner effect, ie unwanted distortion of solid detector structure in case of neutrons flux. Of course liquid media have a certain advantage. However, Waxes and amorphous materials may be subject to Wigner effect. A reset procedure is to study, for instance with thermal cycles for solid crystals. The neutron cross section inside medium is a key parameter to the understanding of eventual degradations.

0.5 METHODS, RESOURCES

0.5.1 Methods

Despite innovation of LiquidO, its destination and use are today oriented to medium energy range, double decay-like experiments, and ionisation/γ detections, even for demonstration need it was probably not possible to generalize too much the purpose.

Let's go from a project of a miniature detector, not a cousin of JUNO, INGRID, . . . Its size is transportable, (satellite, medical, industry, SBL for accelerators, includedat CERN for NUstorm. . .).

To put a firm basis on opacity and associated compactness, means a validating work by complementary prototypes and simulations, following the first demonstrations [16]. These experiments must be cross linked with software (cf 0.5.2)

Firstly, The 3 styles of prototypes suited to 3 energy ranges, with certainly very different features, should be defined. That method has to be precised by a development plan

These actions are falling into a consortium frame, so they must be prior object of a mutual acceptation. Moreover, the present thesis must profit from multidisciplinary group expertise, so it must be validated soon.

0.5.2 Simulation tools

The leader simulation tool is Geant4 for particles physics. Main models are limited to energies 100GeV approx [25]. Numerous among them, for cross sections come from experimental, even empirical data, helped by somehow considerable historic.

However, Montecarlo simulation, is not exhaustively representative for a concrete design/realization ; some additional constraints add :

1. radioactivity (and BG),
2. mechanical strength,
3. thermal resistance,
4. electromagnetic responses of medium and light collectors,
5. signal processing

Fluka is adapted for radioactivity studies, and if necessary, IJCLab may help.
Mechanical evaluation is the scope of Catia modules[47] ; It is also possible to find ressources at IJCLab, and also for thermal resistance.

[47] notice that open sources such Blender may be a performant alternative to Catia

Electromagnetic responses deal with low frequency reflections on walls and upon the fibers. Tools like OpenEMS, FDTD, or by finite elements (Julia) or else in multi-physics (freeFEM) should help and complement nuclear/atomic simulations and enlight the detector fonctioning.

Electronic development is a serious need, specially if one searchs for SPAD optimization.

For signal processing, which encloses an acquisition part, existing tools are welcome, so a first tour about State of the Art is to be made.

The spatial and timing grids in LiquidO call for multidisciplinary disciplins like antenna networks, imaging processing, SPAD counting,...

Data exploitation will be specific, but can't be fully efficient if acquisition has not been optimized. Existing file formats for instance for Telescopes and astrophysic domain is recommended for future compatibility.

0.5.3 Ressources, tests platforms

Scintillating response, even the global transfer function at XuV range is reachable with IJCLab/LaseriX tools. Platform for validating the transfer function to gammas (X, durs,...) is also to find.

An other necessary step concerns triggers. For hardware, which implies a fast technology (FPGA), to define, then associated software architecture. RF service of Dpt accelerateurs and electronic service of IJCLab have the possibilities for -RF testing still 6 GHz, with also fast oscilloscopes- and an expertise relative to PMT's ; mutual collaboration is to enhance : PrF, counting, Electromagnetic Compatibility, triggers...

Accelerateurs will be the final validation tools : They are selected either by their energy range, or by the type of particle beam. The performances of their beams (PrF, charge, emittance,...) are to analyze before planning tests.

keV injectors are available at 10KeV at Maryland University. Note that some recent accelerator onchip could deliver keV electron pulses [28]. for MeV, LCP/Orsay has a photo injector ; GeV is attractive at synchrotron Soleil. Last, VHE is possible at CERN. These tools allow charged particle injections for 1st calibrations. For direct neutrino injections, standing for 2026 muons project $\nu - storm$ of CERN, the today range is from 500MeV (JPARC) to 500GeV (TeV II).

0.5.4 Some possible accelerators for LiquidO validation

NAME	APPLICATION	TYPE	SIZE	PARTICLES	ENERGIES	DATES	P
JPARC	muons	scintillator		ν	2022	T2K/Japon	
SPS	beams π,K and heavy		>100GeV	ν	permanent	CERN	
NUSTORM	muon		ν	2026	CERN		
FERMILAB	neutrinos beam		ν		US		

The japonese JPARC beneficiates from neutrino specific skill, and it has a serious historic with T2K. The energy range is extended to MeV and is available because installations dedicated to medical.

FERMILAB, with Booster Neutrino Beam (BNB) represents also an interesting possibility, and LarTPC (Liquid Argon Time Projection Chamber) such μBoone are the basis of developments analogue to LiquidO.

SPS is more easily reachable, permanent, at Europe level, and source of numerous possible scenarios in the range >100GeV. Coexistence of several detectors and calorimeters is a must for the test comfort of LiquidO.

Lastly, Nustorm project [54], which achievement is planned for 2026, is the opportunity to demonstrate LiquidO, as well as a miniature detector concept for example 20tons sized, or a pseudo far detector at 2km, of 1.3ktons or else the update in opaque version of a far detector of 120/130 ktons [49].

0.6 CONCLUSION

LiquidO detector, constituting already very promising direction, needs 2 actions and analysis in order to become a performant answer to existing and future projects in Particle Physics, :

1. the extension of studies of fundamental phenomena which will be enlighted,
2. the implementation of an available and suitable technology.

Fundamental researches dealing with NP, even SM, are extensive, among them :

1. flavour ν oscillation, and μ,π physics from targets beams,
2. a better knowledge and processing of nuclear potentials,
3. solar physics, first step to cosmic inboard studies (satellites),
4. industry applications.

For these topics, design of 3 different detectors in energy ranges HE, ME and start of VHE is proposed. Scintillating media must be carefully selected, depending of energy range and type of observables and reactions...

other detection expertises, like $C\nu NS$, recoil measurements, directionnal performance, parton physics, ... are not to be excluded, it is the lesson of neighbouring techniques, including WIMP searches, and their adaptation to opacity -or not- is an interesting subject.

scintillators will use the 2 concepts of opacity and space time sampling. Spatial geometry of liquidO fibers is for the moment different from those of standard LarTPC. Hence it drives a new methodology of detection/discrimination which must be ascertained beyond today simulations.

Lastly, the compactness race for an hoped use in Space or Industry (satellites network, planet landed detectors,...) and the important and fast progress of electronics (SPAD, scintillating grids, software treatments), should drive us to a deeper knowledge of rare events, inside the frame of NP.

Bibliographie

[1]

[2] A.H. Abdelhameed and al. First results from the cresst-iii low-mass dark matter program. March 2019.

[3] D. Adey and The Daya Bay Collaboration. Measurement of the electron antineutrino oscillation with 1958 days of operation at daya bay. *PHYSICAL REVIEW LETTERS 121, 241805 (2018)*, December 2018.

[4] J. R. Alonso and Al. Advanced scintillator detector concept (asdc) : A concept paper on the physics potential of water-based liquid scintillator, 2014.

[5] J. Angle and Al. A search for light dark matter in xenon10 data. June 2011.

[6] NC Apim. Perte d'énergie des électrons et positrons, 2010.

[7] D.S. Askerib and Al. Extending light wimp searches to single scintillation photons in lux. January 2020.

[8] Sajjad Athar and Al. Iupap neutrino panel white paper, October 2021.

[9] J. Benziger and al. The nylon scintillator containment vessels for the borexino solar neutrino experiment. *Elsevier*, August 2018.

[10] J. Beringer and al. Particle physics booklet, extracted from the review of particle physics, phys. rev. d86, 010001. Technical report, CERN, 2012.

[11] Adam Bernstein and al. Colloquium : Neutrino detectors as tools for nuclear security. March 2020.

[12] Julien Billard and al. Direct detection of dark matter – appec committee report, April 2021.

[13] Georges Boulon, November 1999.

[14] Christophe Bronner. *Etudes du changement de saveur des neutrinos muons dans le mécanisme d'oscillation quantique avec l'expérience T2K au Japon*. PhD thesis, Universite Pierre et Marie Curie, PARIS VI, June 2011.

[15] Damir Buskulic. Introduction à la physique des particules, module phys805, master 1 re année, notes de cours.

[16] Anatael Cabrera and al. Neutrino physics with an opaque detector. *COMMUNICATIONS PHYSICS | (2021) 4 :273*, December 2021.

[17] J.H. Cao and al. Light absorption properties of the high quality linear alkylbenzene for the juno experiment. *Nuclear Instruments and Methods in Physics Research Section A : Accelerators, Spectrometers, Detectors and Associated Equipment Volume 927, 21 May 2019, Pages 230-235*, May 2019.

[18] B. Cros, P Mugli, and al. Alegro input for the 2020 update of the european strategy for particle physics : comprehensive overview. Technical report, Alegro collaboration, ANA, CERN, 2018.

[19] Alexandra Dobrynina and Al. Helicity oscillations of dirac and majorana neutrinos. *Physical Review D*, 93(12), Jun 2016.

[20] Ivan Esteban and Al. Astrophysical neutrino self-interactions in the high-statistics era. *17th International Conference on Topics in Astroparticle and Underground Physics, Journal of Physics : Conference Series 2156 (2022) 012103*, 2022.

[21] Danielle Fargion. Neutrino solar flare detection for a saving alert system of satellites and astronauts. *PHYSICAL REVIEW LETTERS 121, 241805 (2018)*, December 2018.

[22] Jonathan Folkerts. Neutrino detector design, attenuation studies, and testing for the ν-sol project, May 2017.

[23] Joe Fowler, September 2009.

[24] Gilbert Gastebois.

[25] * Geant4. Physics reference manual, release 11.0, rev6.0, December 2021.

[26] Christian Glaser and al. Nuradioreco : a reconstruction framework for radio neutrino detectors. *The European Physical Journal C*, May 2019.

[27] Hamamatsu photonics. *PHOTOMULTIPLIER TUBES Basics and Applications third edition 3a*, 2007.

[28] Tomohiko Hirano, Karel E. Urbanek, Andrew C. Ceballos, Dylan S. Black, Yu Miao, R. Joel England, Robert L. Byer, and Kenneth J. Leedle. A compact electron source for the dielectric laser accelerator. *Applied Physics Letters*, 116(16) :161106, 2020.

[29] J.H. Hubbell and al. Pair, triplet, and total atomic cross sections (and mass attenuation coefficients) for 1 mev100 gev photons in elements z=1 to 100. *J. Phys. Chem. Ref. Data, Vol. 9, No.4*, 1980.

[30] Donald Hutchinson, Roger Richards, L. Maxey, Ronald Cooper, and David Holcomb. Optical readout for imaging neutron scintillation detectors. *Proceedings of SPIE - The International Society for Optical Engineering*, 09 2002.

[31] D. Karlen. Number of neutrino types and sum of neutrino masses, 2002.

[32] Kuraray. *Plastic Scintillating Fibers*.

[33] Evgenii Kurbatov. Lhcb results on rare leptonic decays of b-mesons. 2019.

[34] Francois Laudenbach. *Topologie differentielle*. 1996.

[35] Junqiang Li and al. A rebinning technique for 3d reconstruction of compton camera data. *2001 IEEE Nuclear Science Symposium Conference Record (Cat. No.01CH37310)*, November 2001.

[36] Tony Tsen-Yuan Lin. *Measurement of the Bethe-Heitler Cross Section in the TeV Regime and Search for Lorentz Invariance Violation with VERITAS*. PhD thesis, McGill University Montreal, Quebec, March 2020.

[37] L Ludhova and Al. Studying the earth with geoneutrinos. *Advances in High Energy Physics Volume 2013, Article ID 425693*, July 2013.

[38] James Clerk Maxwell. *A treatise on electricity and magnetism, volume 1, 1954 unaltered third edition*. Dover publications, Inc, 180 Varick St, N.Y. 14, N.Y., 1891.

[39] Ciaran A.J. O'Hare. *Detecting WIMPs, neutrinos and axions in the next generation of dark matter experiment*. PhD thesis, University of Nottingham, April 2017.

[40] Madhurima Pandey, Debasish Majumdar, Amit Dutta Banik, and Ashadul Halder. The violation of equivalence principle and four neutrino oscillations for long baseline neutrinos. *Modern Physics Letters A*, 36(35), Nov 2021.

[41] Patrick Pfahler. Basic mixing and purification of liquid scintillators, angranote 006-2008 (draft). Technical report, Technische Universität München (TUM) Institute for astroparticle physics (E15) Germany, June 2008.

[42] Ludivine Pidol. *Scintillateurs denses et rapides pour la détection de rayonnement gamma Monocristaux à base de silicates de lutécium dopés Ce* $3+$. PhD thesis, Université Pierre et Marie Curie, PARIS VI, September 2004.

[43] Albert Puig. Rare decays of flavoured mesons at the lhc. September 2016.

[44] inc Raha. Raha.

[45] Rory Rosselot and al. Tile detector with wavelength shifting fiber readout. Technical report, BNL, February 2018.

[46] Saint gobain. *Plastic Scintillating materials BC-400, BC-404, BC-408, BC-412, BC-416*.

[47] N. Solomey and Al. Astrophysics and technical study of a solar neutrino spacecraft, 2018.

[48] Basile Solvay and al. Battle au sein de la matière ; comment le muon teste-t-il la force faible du proton ? Technical report, Lycée Marie Reynoard, Académie de Grenoble, 2013.

[49] Jian Tang and al. Prospects and requirements of opaque detectors in accelerator neutrino experiments. *Phys. Rev. D 102, 013006 (2020)*, July 2020.

[50] Stanford Univ. Achip collaboration.

[51] Dmitry Vorobiev and Al. Measurement of far-ultraviolet transmission in hollow-core optical fibers. 2021.

[52] Ke Wang. *Design study of a Laser Plasma Wakefield Accelerator with an externally injected 10-MeV electron beam coming from a photoinjector*. PhD thesis, Université Paris-Saclay, July 2019.

[53] Minfang Yeh. Scintillator detectors for neutrino physics, June 2015.

[54] P.A. Zyla and al. nustorm at cern feasibility study. Technical report, CERN, October 2020.

[55] P.A. Zyla and al. Review of particle physics,prog. theor. exp. phys. 2020, 083c01 (2020). Technical report, CERN, 2020.