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ELEMENTARY PARTICLE PHYSICS

ABOUT THE POSSIBILITY TO MEASURE SOME STANDARD MODEL PARAMETERS AND SEARCH FOR NEW PHYSICS WITH LOW ENERGY NEUTRINOS[*]

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Abstract. There are fundamental questions in particle and astroparticle physics that are still open. New experimental facilities as sources of particles and detection systems are needed to solve them. An incompletely understood sector of particle physics is the low energy neutrino interactions. The scope of this contribution is to investigate the possibility to measure some Standard Model parameters and search for new physics with low energy neutrinos and to suggest the possibility to obtain neutrinos with well determined energies. This physics and some experimental aspects could be applied in the next generation of underground detectors with very large volume, in particular in the LAGUNA project. Arguments of interest for some physics aspects and measurable quantities using neutrinos with low energy are presented. Some possibilities to obtain intense neutrino beams with controlled energy are subsequently discussed.

Key words: weak interaction, neutrino electron scattering, unparticle physics, electron capture decays.

1. INTRODUCTION

The Standard Model (SM) of particle physics covers phenomena in nuclear and particle physics and provides a remarkably accurate description of them. Unfortunately, not all sectors of the SM are well studied and experimental results are obtained with the same accuracy.

The standard electroweak model is based on the gauge group SU(2) × U(1), with gauge bosons W^i_μ, $i = 1, 2, 3$, and B_μ, and the gauge coupling constants g and g'.

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Thus, $\theta_W \equiv \tan^{-1}(g'/g)$ is the weak angle, also called Weinberg angle. The values of $\sin^2\theta_W$, the W boson mass, the values of the masses for the top quark and for Higgs boson are quantities coupled by different equations, so the mass of Higgs, M_H, could be constrained by accurate values for $\sin^2\theta_W$ and M_W.

The value of $\sin^2\theta_W$ is extracted from Z pole observables and neutral current processes and depends on the renormalization prescription. There are a number of popular schemes, see for example the review from PDG [1] leading to values which differ by small factors depending on the masses for top and Higgs.

The value of θ_W varies as a function of the momentum transfer Q, at which this is measured, so it has scale dependence. This variation is an important prediction of the electroweak theory.

Neutrino-electron scattering is a simple, purely weak interaction process that can play an essential role to prove the validity and perform *precision tests of the SM* as well as many of *its extensions*.

If the new physics beyond the Standard Model is considered and the elastic neutrino – electron scattering is investigated, more aspects are of interest:

a) the electromagnetic properties of the neutrino,

b) it is possible to investigate the existence of the unparticle sector as dark matter.

It is also possible to examine processes which depend on the mixing and mass of the neutrinos. If the detector has low threshold, then one can look for oscillations induced by the small mixing angle θ_{13} and the small oscillation length, associated with the large value for Δm^2_{23}.

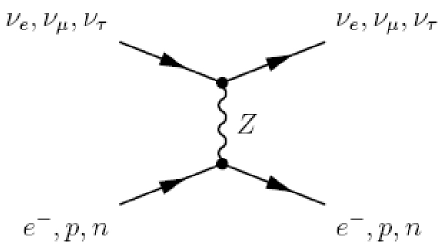
Usually the experiments are realized using electron antineutrino from reactors, neutrino/antineutrino beams from beta or particle decays, accelerated or not, or natural sources.

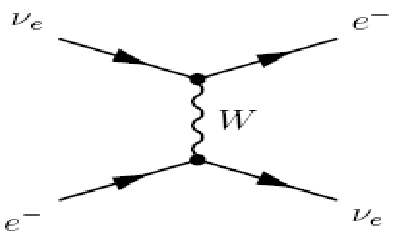
In this paper we investigate the possibility to obtain monoenergetic neutrino beams from electron capture processes in atoms.

The paper is structured into two parts. In the first one, we present arguments of interest for some physics aspects and measurable quantities using neutrinos with low energy, and in the second we discuss possibilities to obtain intense neutrino beams with controlled energy.

2. THEORETICAL FORMALISM: ELASTIC NEUTRINO-ELECTRON SCATTERING IN SM AND BEYOND

The lower order Feynman – Stueckelberg diagrams of the elastic scattering processes that generate the CC and the NC with W/Z exchange are:





In agreement with Vogel and Engel [2], the differential cross-section for the elementary elastic electronic neutrino-electron scattering is:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T} = \frac{G_F^2 m_e}{2\pi}\left[\left(g_V + g_A\right)^2 + \left(g_V - g_A\right)^2\left(1 - \frac{T}{E_\nu}\right)^2 - \left(g_V{}^2 - g_A^2\right)\frac{m_e T}{E_\nu^2}\right], \tag{1}$$

where T is the electron recoil energy, with values in the interval:

$$0 \le T \le T_{\max} = \frac{2E_\nu^2}{2E_\nu + m_e}, \tag{2}$$

depending on the scattering angle:

$$\cos\varphi = \frac{E_\nu + m_e}{E_\nu}\left(\frac{T}{T + 2m_e}\right)^2. \tag{3}$$

The constant has the value $\frac{G_F^2 m_e}{2\pi} = 4.45 \times 10^{-48}\,\frac{\mathrm{cm}^2}{\mathrm{keV}}$.

The correspondence with the Weinberg angle is done by the equations for the coupling constants g_V and g_A: $g_V = 2\sin^2\vartheta_W + \frac{1}{2}$, $g_A = +\frac{1}{2}$, respectively.

If the process is initiated by other neutrinos: muonic or taonic, thus $g_V = 2\sin^2\vartheta_W - \frac{1}{2}$ and $g_A = -\frac{1}{2}$, and for antineutrinos, $g_A \to -g_A$.
A major interest exists for the tests with very high precision of the Weinberg angle at low momentum transfer.

The similar equation for elastic neutrino – electron process, with the consideration of the electromagnetic properties for neutrino is given [2] by the expression:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T}=\frac{G_F^2 m_e}{2\pi}\left[\left(g_V+x+g_A\right)^2+\left(g_V+x-g_A\right)^2\left(1-\frac{T}{E_\nu}\right)^2-\right.$$
$$\left.-\left(\left(g_V+x\right)^2-g_A^2\right)\frac{m_e T}{E_\nu^2}\right]+\frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\frac{1-\frac{T}{E_\nu}}{T}. \tag{4}$$

The significance of new the quantities introduced in the equation for the differential cross-section is:

$x=\frac{\sqrt{2}\pi\alpha\left\langle r^2\right\rangle}{3G_F}=\frac{2M_W^2}{3}\left\langle r^2\right\rangle\sin^2\vartheta_W$ with $\left\langle r_{\nu_l}^2\right\rangle\approx\frac{G_F}{2\sqrt{2}\pi^2}\ln\left(\frac{M_W^2}{m_l^2}\right)$, estimated as $\left\langle r^2\right\rangle\propto 10^{-32}\,\mathrm{cm}^2$.

An extension of the formalism permits to Dirac neutrinos to acquire a magnetic moment:

$\mu_\nu=\frac{3G_F m_e m_\nu}{4\sqrt{2}\pi^2}\equiv 3.2\times10^{-19}\left[\frac{\mathrm{m}_\nu}{1\mathrm{eV}}\right]$, supposed to be different from zero.

In the equation (4) the x term corresponds to neutrino charge radius and the supplementary term in the equation is associated with the magnetic moment.

The existence of the e.m. properties permits to use these results as a probe for new physics, to distinguish between Dirac and Majorana neutrinos, as well to obtain information on charge quantization.

If a neutrino has non-trivial electromagnetic properties, then a direct neutrino coupling to photons could be possible, as neutrino decays and Cherenkov radiation directly produced by neutrinos respectively.

Another aspect of new physics could be in principle extracted from very precise measurements of elastic neutrino-electron process. All particles exist in states that may be characterized by a certain energy, momentum, and mass. In the SM the "scale invariance" manifests only for massless particles. For all others, the same particle type cannot exist in another state with all properties scaled up or down by a common factor. Recently, Georgi [3] proposed a new theory related to the existence of an undiscovered sector of the current physics model which is “scale-invariant”, *i.e.*, one in which objects don’t change when their dimensional qualities are multiplied by a rescaling parameter. This idea does not make sense in particle theory because most particles have a definite nonzero mass. This excludes particles which mediate infinite range forces and can, therefore, have zero mass such as photons and gravitons. The idea comes from conjecturing that there may be "stuff" that does not necessarily have zero mass but is still scale-invariant, with the same physics regardless of a change of energy (or equivalently length). This stuff is unlike particles, and is described as unparticle physics (field).

Such unparticle stuff has not yet been observed, and this suggests that if it exists, it must couple with normal matter weakly at observable energies. Unparticles would have properties in common with neutrinos, which have almost zero mass and are therefore nearly scale invariant. Neutrinos barely interact with matter and their effects are observable as "missing" energy and momentum after an interaction. A similar technique could be used to search for evidence of unparticles. According to scale invariance, a distribution containing unparticles would become apparent because it would resemble a distribution for a fractional number of massless particles.

As we specified, the unparticle sector can appear at low energies in the form of new massless fields coupled very weakly to the SM particles. Their contribution to the cross section could come from a scalar or from a vector interaction:

$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}T}=\frac{\mathrm{d}\sigma}{\mathrm{d}T}+\frac{\mathrm{d}\sigma_U}{\mathrm{d}T}. \tag{5}$$

For the scalar interaction:

$$\frac{\mathrm{d}\sigma_{U_S}}{\mathrm{d}T}=C_1\cdot\frac{1}{\pi E_\nu^2}\left(m_eT\right)^{(2d-3)}\left(T+2m_e\right) \tag{6}$$

and the vector contribution is:

$$\frac{\mathrm{d}\sigma_{U_V}}{\mathrm{d}T}=C_2\cdot\frac{1}{E_\nu^2}\left(m_e\right)^{(2d-3)}\left(T\right)^{(2d-4)}\left[1+\left(1-\frac{T}{E_\nu}\right)^2-\frac{m_eT}{E_\nu^2}\right], \tag{7}$$

with $C_1=\dfrac{2^{(2d-6)}\left[g_{0e}^{\alpha\beta}(d)\right]^2}{\pi\Lambda^{(4d-4)}}$ and $C_2=\dfrac{2^{(2d-5)}\left[g_{1e}^{\alpha\beta}(d)\right]^2}{\pi\Lambda^{(4d-4)}}$.

The parameters of the model are therefore λ_{if} (the coupling constant), d and Λ. Usually, the energy scale where the theory is invariant is Λ=1 TeV. For the vector contribution an interference term must be considered. Details of the theory and discussions about the contributions to cross-sections could be found in references [4, 5, 6].

Montanino and co-workers [7] previously discussed the possibility to probe the neutrino magnetic moment and unparticle interactions using Borexino detector.

In Fig. 1, the different contributions to the cross section are calculated or estimated. The contributions in the frame of the SM are calculated as absolute values for incident neutrinos of 1.036 MeV energy. For all the other, arbitrary values are used because of the existence of model parameters. Due to the experimental threshold energy for recoil electrons, the vector contribution of unparticle to interactions is more probably to be observed, if it exists.

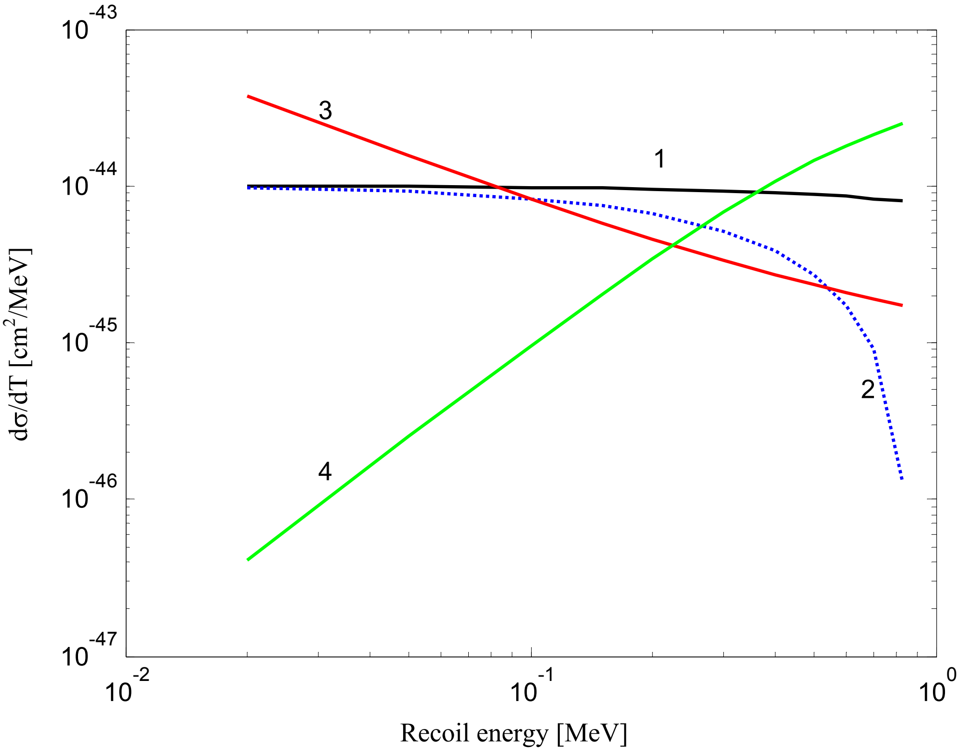


Fig. 1 – Differential cross-section in elastic neutrino-electron scattering as a function of recoil energy. Neutrino energy is considered as 1.04 MeV. The black curve (1) is the neutrino process, in SM hypothesis, compared with antineutrino scattering (blue -2) – as absolute values. The unparticle contributions in red - 3 (scalar) and vector (green -4) are suggested (arbitrary scale).

A different phenomenon that must be considered is the neutrino oscillations. In the experiments using neutrinos with low energy, smaller oscillations lengths are obtained, in accord with equations (8) and (8’). In the LAGUNA project [8], the great dimensions of the detector systems will permit to explore this new range of lengths.

$$\lambda[\mathrm{m}] = \left(\frac{\pi}{1.27}\right)\left(\frac{E_\nu[\mathrm{MeV}]}{\Delta m^2[\mathrm{eV}^2]}\right) \cong \frac{2.5E_\nu}{\Delta m^2}, \tag{8}$$

$$\lambda[\mathrm{m}] \approx E_\nu[\mathrm{keV}]. \tag{8'}$$

Thus, the accurate determination the neutrino oscillation parameters appears as an opportunity, in particular the unknown θ_{13} mixing angle, responsible on the CP violation in this leptonic sector. A detailed analysis was done by Vergados and Novikov [9].

3. SOURCES OF MONOENERGETIC NEUTRINO BEAMS

For a precision measurement, it is obviously better to have an experiment using neutrinos with controllable and precisely known energy.

To achieve this, we consider making use of a nucleus that absorbs an electron and emits a neutrino (electron capture process):

$$(Z, A) + e^- \rightarrow (Z - 1, A) + \nu_e\ , \tag{9}$$

where Z is the electric charge of the mother nucleus and A is its mass number. In this case neutrinos have a line spectrum and their energy is precisely known. In the last years this possibility has received a great interest [10, 11].

Possible isotopes that decay dominantly as electron capture are presented in Table 1.

Decay schemes are extracted from reference [12].

The criteria used in this selection were:

– the energies for emitted neutrinos: more than 150 keV up to few MeV;

– very simple decay scheme and higher intensities of radiation;

– lifetime more tens of minutes, up to years.

Technical aspects of their production were not considered. The binding energy of the electron is not included in the final calculations.

In the rest frame of the mother nucleus, monoenergetic neutrinos are emitted isotropically. If we accelerate the mother nuclei appropriately, with the Lorenz boost factor γ, the range of neutrino energies will be between zero and $E_\nu \le 2\gamma Q$, where Q is the energy difference between the mother and the daughter nuclei. In the centre of the beam, the maximum in energy will be attained, and if the neutrino is detected or interacts at a distance R from the centre of the beam, in an experiment with the baseline length L, the energy will be $E_\nu(R) \cong 2\gamma Q \Big/ \left(1 + \frac{\gamma^2 R^2}{L^2}\right)$.

In a solid angle in the rest frame, the neutrinos are distributed uniformly. A uniform distribution in energy exists too. If the detector is able to measure the energy and the point of interaction, from these measurements the energy of neutrinos could be determined very precisely [10].

To stimulate the electron capture, different options were proposed: use of an electron accelerated beam with the same Lorentz factor as the ion beam, or a laser beam, and then we can control the neutrino energy and make use of the EC to produce monoenergetic neutrinos with an enhancement factor.

Table 1

Some isotopes that decay dominantly as electron capture

Isotope	$T_{1/2}$	Intensity (%)	Q (keV)	E_ν (keV)	$T_e^{\max}$ (keV)
^{125}I	59.4 d	100	185.8	150	55.5
^{55}Fe	2.7 y	100	232	226	106
^{137}La	6 x 104 y	100	600	600	421
^{145}Sm	340 d	100	620	620 (91%), 559 (8.6%)	439 384
^{111}In	2.804 d	100	866	621 (100%)	440
^{51}Cr	28 d	100	753	433 (9.94%) 753 (90.06%)	272 562
^{146}Pm	5.53 y	66	1472	282 (22%) 428 (0.7%) 1018 (44%)	148 268 814
^{113}Sn ^{113}Sn$_m$	115.1 d 21.4 min	100	1036 1036	644 (97.8%) 389 (2.2%) 1036 (100%)	461 235 831
^{132}Cs	6.48 d	98	2130	1462 (95.4%)	1244
^{141}Nd	2.49 h	100	1814	1814 (95.7%)	1590
^{130}Cs	29.1 min	98.4	3022	2484 (44.6%) 3022 (49.9%)	2252 2786

Short half-life nuclides have the advantage that they can be rapidly produced in reactors, whereas long-lived ones need long-term irradiation in order to accumulate necessary decay intensity. For example, if we consider the Chromium isotope, 2.5 g will produce an intensity of neutrinos in the order of 10^{16} s^{-1} and the same quantity of ^{141}Nd will produce 10^{18} s^{-1} neutrinos.

If the measurements are realised using giant detectors and isotopic sources, in a very simple experimental configuration, *e.g.* with the source immersed in the centre of the detector, the weak angle and neutrino oscillations could be obtained simultaneously.

The physical potential of this problem was also investigated by Agarwalla and Huber [13] and could represent a field of interest for LAGUNA and DUSEL Programmes [8, 14]. Other methods of detection for very rare interaction processes could be considered [15, 16].

For these experiments the background is essential and thus deep underground locations are the most adequate. The characteristics of some world laboratories were presented by Spooner [17] and these results were completed in Refs. [18, 19, 20, 21].

4. SUMMARY

The possibility to use neutrino-electron elastic scattering to prove the validity and perform *precision tests of the SM* as well as some of *its extensions* (electromagnetic properties of neutrino and the existence of unparticle sector as dark matter) was suggested.

It is possible to investigate simultaneously the very short baseline neutrino oscillations sector, and small mixing angle θ_{13}, in all experiments using monoenergetic low energy neutrinos which are released in the atomic electron capture by nuclei.

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