Searching signature of neutrino-nucleus coherent scattering with Mössbauer Spectroscopy

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Abstract. The Mössbauer spectroscopy is proposed as an alternative experimental technique to be pursued in the detection of Coherent Elastic $\nu$-Nucleus Scattering (CENNS). The neutrino transferred energy in the neutrino-nucleus interaction causes a perturbation at the nuclear level structure of the Mössbauer isotope, leading to a displacement of the isomeric peak of the electromagnetic resonance. We calculate this isomeric shift correction due to the occurrence of CENNS and show that this quantity can be measured with enough precision in a typical Mössbauer spectroscopic experiment. We also shown that a reasonable number of events is expected and allow to extract the correction in the isomeric shift in a typical neutrino reactor flux. This isomeric shift correction is pointed out as a figure of merit for signature of CENNS in our proposal.

1. Introduction

A direct evidence of the Coherent Elastic $\nu$-Nucleus Scattering (CENNS) has been considered an experimentally challenging task to better understand weak neutral current in the context of the Standard Model of Particle Physics (SM) [1, 2, 3, 4]. An evidence of the process has been intensively pursued by many experimental collaborations in the last four decades [5, 6, 2, 3, 7] developing a great effort to the direct detection of this weak process, which has the largest predicted cross section in the energy range below 50 MeV.

Recently, the COHERENT collaboration report the first undoubtedly measurement of the CENNS process[8]. An efficient scintillator detector was used in the experiment carried out at the Oak Ridge National Laboratory. With a Spallation Neutron Source it was produced an extremely intense neutron beam, which was scattered by a mercury target generating a secondary pion beam. Produced pions decays into an intense neutrino flux ($\approx 10^{11}/s$) with energy in the range of 16 to 53 MeV [8]. The pulsed neutrino flux was scattered by 14.6 kg crystal made of CsI doped with Sodium atoms. The experimental setup was properly structured to prevent any contamination from external sources of neutrons and neutrinos, like atmospheric or solar and
galactic neutrinos. This experiment accumulate CENNS events during fifteen months produced in accordance to the SM prediction.

Here we are searching for a signature of the CENNS using Mössbauer nuclear spectroscopy (MS) [10, 9]. The great domain of the technique all over the world makes possible a broad experimental check of our predictions and confirm results obtained by different laboratories.

As it is well known the main characteristic of Mössbauer technique is the recoil less interaction of the electromagnetic radiation with the nucleus in a crystal sample. This aspect is assumed to be preserved in the CENNS process with absorber nucleus used in Mössbauer measurement. The nucleus maintain its fixed position in the local minimum of the crystal potential lattice. The effect of the energy transferred by neutrinos to the nucleus is to induce a perturbation in the inner degree of nuclear structure. We assume that the quantum state of the valence neutron is modified. Consequently, the nuclear volume is changed and the consequent change in the isomeric shift can be observed with the typical accuracy of this spectroscopic technique. To determine our prediction, we assume that only the valence neutron is perturbed at the structure of a characteristic nucleus of Mössbauer machine (a typical one is $^{57}$Fe). With this transition between single particle states of the valence neutron in the CENNS process, we calculate the change in isomeric shift. Pauli blocking prevent transitions at the inner structure of the nuclear core.

In next section of this letter, we summarize the main characteristics of CENNS. Our proposal of use Mössbauer technique to observe CENNS is presented in more details in section III. The isomeric shift correction due to CENNS process is calculated in section IV. In Section V it is estimated the event rates for some Mössbauer isotopes used as absorber. Section VI presents our main conclusions.

2. The Main Characteristic of CENNS

The CENNS was proposed theoretically by Freedman [1] in 1974. A Feynman diagram of this weak process is shown in Fig. 3. The effective Lagrangian to describe the process is given by

$$L = G_F L^\mu J_\mu,$$

(1)

where $G_F$ is the Fermi constant, $L^\mu$ the lepton current, and $J_\mu$ is the hadron current inside the nucleus. Experimental efforts have been developed in the detection of CENNS, some of them represented by large scientific collaborations namely, COHERENT [11, 8], CONNIE [12] and TEXONO [13], among others. As mentioned before, after decades of searching only in the last year the COHERENT Collaboration [8] announced the first irrefutable detection of CENNS.

It is well known that the coherence aspect of CENNS, requires $qR \ll 1$, with $q$ being the transferred momentum and $R$ the nuclear radius. This implies that the wavelength of neutrinos will be comparable to the nuclear radius. Detailed discussions about the phenomena can be found in Refs. [1, 14, 4, 6, 3] and references therein. We stress the fact that the cross section of this process has the largest value ($\sigma \approx 10^{-38}$ cm$^2$) at least four orders of magnitude larger than other neutrino interactions in the same low-energy regime [6].

The Freedman differential cross section for this process is [1, 2, 15]

$$\frac{d\sigma_{\text{CENNS}}}{dT} = \frac{G_F^2}{4\pi} Q^2_w M_A^2 F^2(q^2) \left(1 - \frac{M_A T}{2E^2_\nu}\right),$$

(2)

where $T$ is the transferred energy to the nucleus, $A$ is the target mass, $E_\nu$ is the neutrino energy and $Q^2_w = N - Z(1 - 4\sin^2\theta_w)$ is the weak charge, which depends on the number of neutrons
(N) and protons (Z). Here $\theta_w$ is the Weinberg angle satisfying $\sin^2 \theta_w \approx 1/4$ and the proton contribution is negligible. The last fact made CENNS a very sensitive probe to nuclear neutron density [16]. The form factor $F(q^2) \to 1$ as $q \to 0$ define the coherence condition.

We remind that as a weak process, the interaction involved in the CENNS should be many order of magnitude greater than the gravitational phenomena. Even so, the MS was successfully employed to measure the gravitational red shift of light by Pound and Rebka [17, 18] at the end of the fifties. Thus, we hopefully expect that a properly MS array could be used in the study of electroweak phenomena.

3. The Mössbauer Technique Applied to Detect CENNS

One of the main characteristics of the MS is that the nuclei in the absorber material of the machine are recoil less when interacting with gamma photons becoming from the source decay. This condition is fundamental for the resonant radiation absorption in the MS. We considered that the recoil less feature was preserved for the CENNS because the transferred energy to the nucleus is in the same range of the gamma photon. The transferred momentum by the $Z^0$ exchange is assumed to be transmitted to the valence neutron slightly modifying the neutron distribution in the nuclear surface and promoting a typical isomeric shift correction in the MS experiment. In addition, it is straightforward to show that the recoil less nuclei in the source and absorber is consistent for both processes, the resonant condition of the electromagnetic radiation and for the coherent neutrino scattering by the nuclei. The fraction $f$ of the recoil less nuclei in $Z^0$ exchange between neutrino and nuclei in the CENNS can be analyzed similarly to the case of the gamma radiation interaction. It can be shown that the fraction of recoil less events can be put in the form of Debye-Waller factor [19], which, for the CENNS, takes the form

$$f = \exp \left( -\frac{T^2}{M c^2 \hbar \omega} \right),$$

where $T = E^2 / 2 M c^2$ is the energy transferred by the $Z^0$ to target nucleus of mass $M$. Here $\hbar \omega \approx 10^{-3}$ eV for Fe, Co etc, is the order of magnitude of energy lattice vibrations. In the range of neutrino energies below $\approx 50$ MeV the recoil less $f$ factor is essentially unity. Therefore, we argue that this small energy fraction is accommodated by a perturbed change in valence neutron levels.

4. Isomeric Shift Correction due to the CENNS Interaction

We consider that the energy transferred to the valence neutron is considered as a first-order perturbation term in the valence neutron state of a shell model non-perturbed base. We assume that the perturbed neutron wave functions acquire a small projection in the next state.
of the unperturbed system. This model is similar to that proposed in the reference [8] in which weak force produces low energy electron states mixtures. This picture allows us to consider the problem as a two-level system, with neutron state fluctuating between the two unperturbed state levels. In the present case we will focus on $^{57}$Fe because it is the most common in the literature, but many other nuclei can be studied with this technique, e.g., La, Te, Cd and Sm [10]. The unperturbed $^{57}$Fe valence neutron is at a state of definite angular momentum, given by the common distribution of the neutron and proton content [20] in nuclear shell model – its wave function is regular at the origin (typically a Bessel function). Thus the perturbed valence neutron states, after the $Z^0$ interaction are

$$\Phi^+ = \frac{-\lambda j_{3/2}(kr)}{\sqrt{1 + \lambda^2}} + \frac{j_{5/2}(kr)}{\sqrt{1 + \lambda^2}},$$  

$$\Phi^- = \frac{j_{3/2}(kr)}{\sqrt{1 + \lambda^2}} + \frac{\lambda j_{5/2}(kr)}{\sqrt{1 + \lambda^2}}.$$  

The $\lambda$ parameter in the above equations appears in the perturbed treatment and is associated to the ratio between the square of the transferred energy and the energy difference of the non-perturbed energy states [21] of the valence neutron. Explicitly we have,

$$\lambda = \lambda(E_\nu) = \frac{3E^2_\nu}{8M^2c^2(E_{5/2} - E_{3/2}).}$$  

The term $(E_{5/2} - E_{3/2})$ is the difference between the energy of the non-perturbed states of the valence neutron. In $^{57}$Fe case, this is responsible for the emission of 14.4 KeV photon which is emitted and absorbed resonantly without nuclear recoil.

In the context of the shell model for Woods-Saxon potential with spin orbit term [22, 20, 23, 24], the two states of valence neutron for the $^{57}$Fe can be described by spherical Bessel functions, $j_{3/2}(kr)$ and $j_{5/2}(kr)$. We have used for the wave number of the valence neutrons $k \approx 0.5$ fm$^{-1}$, which is, as usually, approximately the inverse of twice neutron radius.

The isomeric shift can be calculated [10] as being

$$\delta I^*_s = \frac{4\pi Z e^2 R^2_{gs}}{5} \left( \frac{R_{exc} - R_{gs}}{R_{gs}} \right) [\psi^2_{l=0} - \psi^2_{l=0}s],$$  

where $Z$ is the number of protons in the nucleus, $R_{gs}$ is the mean radius of the charge distribution at the ground state of nucleus and $R_{exc}$ for the $Z^0$ excited nuclear radius, respectively, the $\psi^2$'s are the $s$ electrons wave functions, evaluated at the origin [19, 10] for the absorber and the source of gamma radiation. In the literature, the difference between nuclear radius of the excited nucleus and the ground state is $(R_{exc} - R_{gs})$, which in conventional gamma resonance is reported to be $\approx 10^{-3}R_{gs}$ [19, 10]. Our estimate for $(R_{exc} - R_{gs})$, calculated using the perturbed neutron wave functions $\Phi^+/-$ above is $\approx 10^{-4}R_{gs}$. With this result and Eq. 7, we can obtain the correction at isomeric shift induced by the weak process $(Z^0$ exchange) in CENNS. As we can see only one order of magnitude smaller than the typical characteristic $\gamma$ measurements. This value for $\delta I^*_s$ is perfectly solved with the MS technique accuracy, namely $10^{-10}$ eV [17, 18, 10]. Consequently, we point out that if we take subtraction of a MS measurement without the neutrino flux and other result of identical measure with the reactor neutrino beam, we would reveal the contribution of the CENNS interactions.
5. Event Rates for Mössbauer Isotopes

In this section we estimate the expected event rate $n$, for some nuclei of interest in Mössbauer Spectroscopy. This number could be given by the expression 8.

$$n = N_t \int_{E_{min}}^{E_{max}} dE_\nu \Phi(E_\nu) \frac{d\sigma(E_\nu)}{dE_\nu}, \quad (8)$$

Where $N_t$ is the number of target nuclei, which we assume of order $10^{23}$, $E_\nu$ is the energy of neutrinos at incident flux, $\Phi$ is the reactor flux of neutrinos, $\sigma$ is the cross section of CENNS. $E_{max/min}$ is the maximum/minimum energy at the spectrum of neutrinos. In the case of Mössbauer nuclei, the energy exchange of Z and the target nucleus is integrally absorbed by the neutron field, and the overall nucleus has no momentum inside the crystal lattice. Then the cross section is maximal and given by:

$$\sigma_{cen} = \frac{G_F^2 E_\nu^2 N^2}{4\pi}, \quad (9)$$

In this expression $G_F$ is the Fermi constant and $N$ is the neutron number, $E_\nu$ is the energy of neutrinos. The proton contents contribution is ignored due its tiny weak charge. The energy distribution of the neutrino flux from the reactor neutrinos is not well established in complete details[25]. However some estimations can be used in order to have a practical definition of the rate and number of events in an experimental test.

The reactor neutrino flux is not well theoretically understood in its full extent. As we see at the figure 2 below, it presents a bump of anti neutrinos at 4.5 Mev, which is not yet well explained. We know that it holds a very high quantity of neutrinos/cm$^2$s, of order $10^{13}$. It ranges between 0 to $E_{max} = 10$ Mev.

![Figure 2. Reactor Anti-neutrino flux from Daya Bay(top). There is an Anti-neutrino excess around 4.5 Mev(middle). Comparison of predicted and measured prompt energy spectra(bottom). This figure was taken from [26].](image)

In our estimation we use the normalized function $\Phi(E_\nu) = 22.6 \times 10^{-3}(E_\nu - \frac{1}{6} \times 10^{-6} E_\nu^2)$ as the mostly simple curve that fits approximately the spectrum for the reactor showed at figure 2. With these assumptions, the event rates $n$ for some Mössbauer isotopes are displayed in the graph below and more specifically for three MS isotopes at table 1.
Figure 3. Events calculated from expression 8. We are considering $\approx 10^{23}$ nucleus subjected to an integrated reactor anti neutrino flux of order $10^{13}/cm^2 s$

Table 1. Event rates for nuclides of interest

| Nucleus | N  | Cross Section($10^{-35} cm^2$) | Event rate |
|---------|----|-------------------------------|------------|
| Fe      | 30 | 3.8                           | $\approx 10^2/day$ |
| Rh      | 58 | 14                            | $\approx 10^3/day$ |
| Bk      | 150| 9600                          | $\approx 10^5/day$ |

The isotopes Bk and Rh present higher event rates than the Fe, however there are some difficulties in CENNS observation in the use of them. The separation of the valence levels energy, are some hundreds of keV, making the parameter $\lambda$ in Eqs.(4 – 5) almost null. Additionally the measure of the spectra of these elements is hard to calculate, due to their tiny relative abundance. This appoints the conventional Iron isotope as a favorable choice of the CENNS experiment using the Mössbauer Technique.

6. Conclusions

This work develops model calculation to determine some estimate of the rate and number of events to give support for the use of MS spectroscopy as a suitable technique to see the CENNS process.

The isomeric shift correction obtained when the machine is exposed to a neutrino flux of reactors is the signature of contribution at the MS experiment. Our estimate is a correction of the order $\sim 10^{-7}$ eV for a system using $^{57}$Fe isotope, this value is greater than the typical energy resolution of this technique, $\sim 10^{-10}$ eV. We then guess, that future MS experiments could be suitable to integrate the neutrino experimental plants.

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