Author(s): Jokiniemi, Lotta; Suhonen, Jouni; Ejiri, Hiro

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Lotta Jokiniemi, Jouni Suhonen, and Hiro Ejiri

Nuclear Responses for Double Beta Decay and Muon Capture

Lotta Jokiniemi[1,a)], Jouni Suhonen[1] and Hiro Ejiri[2]

[1] *University of Jyvaskyla, Department of Physics, P.O. Box 35, FI-40014, Finland.*
[2] *Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan.*

[a)] Corresponding author: lotta.m.jokiniemi@jyu.fi

Abstract. The existence of the neutrinoless double beta ($0\nu\beta\beta$) decay is one of the most intriguing open questions in the neutrino physics field. Despite many large-scale experiments have aimed to measure the reaction for decades, it has not yet been observed. Therefore, accurate theoretical calculations on $0\nu\beta\beta$ are crucial. To describe the double beta decay processes reliably one needs a possibility to test the involved virtual transitions against experimental data. In this work we manifest how to utilise the charge-exchange and ordinary muon capture (OMC) data in the study of $0\nu\beta\beta$ decay.

INTRODUCTION

The neutrinoless double beta ($0\nu\beta\beta$) decay of atomic nuclei is a lepton number violating process that has not been observed, despite lots of effort has been directed to detecting it (see References [1, 2, 3]). Since $0\nu\beta\beta$ decay is challenging to study both experimentally and theoretically, we need some complementary tests in order to accurately calculate the involved nuclear matrix elements and to design the large-scale experiments.

$\beta\beta$ decays take place between two even-even nuclei of the isobaric chain trough virtual states of the intermediate odd-odd nucleus. $0\nu\beta\beta$-decay runs trough all possible multipolarities J^π of the intermediate nucleus. These intermediate J^π states of $0\nu\beta\beta$ decay can be studied by utilising the corresponding $\beta^-(\beta^+)$ transitions of the mother(daughter) nucleus, which correspond to the left(right)-branch virtual transitions of the $0\nu\beta\beta$ decay.

Another interesting tool to probe $0\nu\beta\beta$ decay is the ordinary muon capture (OMC). By studying OMC one can probe the right-branch of the virtual transitions of the $0\nu\beta\beta$ decay. The involved large momentum transfer, $q \approx 50-100$ MeV, corresponds to the one of $0\nu\beta\beta$ decay, which makes it a promising tool to probe $0\nu\beta\beta$ decay. Furthermore, due to the large mass of the muon, the OMC can populate final nuclear states that are both highly excited and of high multipolarity J^π, quite like the intermediate virtual states of $0\nu\beta\beta$ decay.

CHARGE-EXCHANGE REACTIONS AS A PROBE

In [4, 5] the energetics and strength distributions of isovector spin-dipole transitions (IVSD), corresponding to the left-branch virtual transitions of the $0\nu\beta\beta$ decay, are studied using pnQRPA theory with large no-core single-particle bases. The particle-hole parameter $g_{\rm ph}$ is fitted to reproduce the data on isovector spin-dipole (IVSD) $J^\pi = 2^-$ giant resonances. Traditionally $g_{\rm ph}$ has been fitted to Gamow-Teller (GT) giant resonances. We refer to the differently fitted parameter values as $g_{\rm ph}(\mathrm{SD}2^-)$ and $g_{\rm ph}(\mathrm{GT})$, respectively.

The nuclear matrix elements (NMEs) of $0\nu\beta\beta$ decay are computed using three different models: In Model 1 $g_{\rm ph}(J^\pi) = g_{\rm ph}(\mathrm{GT})$ for all J^π, in Model 2 $g_{\rm ph}(J^\pi) = g_{\rm ph}(\mathrm{GT})$ for $J^\pi \neq 2^-$ and $g_{\rm ph}(2^-) = g_{\rm ph}(\mathrm{SD}2^-)$, and in Model 3 $g_{\rm ph}(J^\pi) = g_{\rm ph}(\mathrm{SD}2^-)$ for $J^\pi \neq 1^+$ and $g_{\rm ph}(1^+) = g_{\rm ph}(\mathrm{GT})$. We also compare the obtained results with the earlier study of Hyvärinen *et al.* [6], where the $0\nu\beta\beta$ NMEs were computed in much smaller single-particle bases without access to the isovector spin-dipole data. The results are presented in Table 1. As we can see, most of the deviations are due to the extension of the single-particle space of pnQRPA, while the effect of adjusting the particle-hole interaction to data on spin-dipole resonances is relatively smaller.

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TABLE 1. The $0\nu\beta\beta$ nuclear matrix elements for different transitions computed using the different g_{ph} models. The table has been cut in two and appears as left and right halves.

Nuclear transition	Model	$M^{(0\nu)}$
$^{76}\mathrm{Ge} \longrightarrow {}^{76}\mathrm{Se}$	1	6.9 ± 0.3
	2	6.8 ± 0.3
	3	6.6 ± 0.4
	1,small*	6.54
$^{96}\mathrm{Zr} \longrightarrow {}^{96}\mathrm{Mo}$	1	5.3 ± 0.2
	2	5.3 ± 0.2
	3	5.5 ± 0.4
	1,small*	4.47
$^{100}\mathrm{Mo} \longrightarrow {}^{100}\mathrm{Ru}$	1	5.54 ± 0.10
	2	5.55 ± 0.11
	3	5.9 ± 0.4
	1,small*	4.98
$^{116}\mathrm{Cd} \longrightarrow {}^{116}\mathrm{Sn}$	1	5.7 ± 0.2
	2	5.7 ± 0.2
	3	5.39 ± 0.13
	1,small*	4.93
$^{128}\mathrm{Te} \longrightarrow {}^{128}\mathrm{Xe}$	1	5.52 ± 0.15
	2	5.47 ± 0.15
	3	4.9 ± 0.3
	1,small*	5.74
$^{130}\mathrm{Te} \longrightarrow {}^{130}\mathrm{Xe}$	1	4.77 ± 0.12
	2	4.72 ± 0.12
	3	4.1 ± 0.2
	1,small*	5.27
$^{136}\mathrm{Xe} \longrightarrow {}^{136}\mathrm{Ba}$	1	3.72 ± 0.09
	2	3.76 ± 0.10
	3	4.1 ± 0.3
	1,small*	3.50

* The result is obtained from [6], where smaller single-particle bases were used.

ORDINARY MUON CAPTURE AS A PROBE

Ordinary muon capture (OMC) is a weak interaction process quite like electron capture, the main difference being the large mass of the captured muon, which is about 200 times the electron mass. The OMC process we are interested in can be written as

$$\mu^- + {}^{A}_{Z}\mathrm{X}(0^+) \to \nu_\mu + {}_{Z-1}^{A}\mathrm{Y}(J^\pi)\,, \tag{1}$$

where the muon (μ^-) is captured by the 0^+ ground state of the even-even nucleus X of mass number A and atomic number Z leading to the J^π states of its odd-odd isobar Y of atomic number $Z-1$. At the same time a muon neutrino ν_μ is emitted. The energy release is about 100 MeV, of which the largest fraction is donated to the released neutrino, being the lightest object participating in the process. The involved large momentum exchange, $q \approx 50 - 100$ MeV, allows highly forbidden transitions as well as highly excited final states with high multipolarities J^π, which makes it a good probe for $0\nu\beta\beta$ decay.

Muon Capture Formalism

The ordinary muon capture rates are based on Morita-Fujii formalism [7]. The partial muon capture rate to a J^π final state can be written as

$$W = 8\left(\frac{Z_{\mathrm{eff}}}{Z}\right)^4 P(\alpha Z m'_\mu)^3 \frac{2J_f+1}{2J_i+1}\left(1 - \frac{q}{m_\mu + AM}\right) q^2\,, \tag{2}$$

where A denotes the mass number of the initial and final nuclei, J_i (J_f) the angular momentum of the initial (final) nucleus, M the average nucleon rest mass, m_μ the bound muon mass, m'_μ the muon reduced mass in the parent μ-mesonic atom, Z the atomic number of the initial nucleus, α the fine-structure constant and q the Q value of the OMC [7]. For the heavy nuclei the atomic orbit of the muon penetrates the nucleus and the capture rate has to be corrected for the muonic screening. Here we follow the Primakoff procedure [8] where the capture rate has been corrected by the factor $(Z_{\mathrm{eff}}/Z)^4$, where the effective atomic number is obtained from the work of Ford and Wills [9].

The term P in Eq. (2) has a complex structure containing all the nuclear matrix elements as well as weak couplings, and some geometric factors and Racah coefficients. The exact form can be found in [7]. P can be expanded in terms of a small quantity $1/M^2$ as $P = P_0 + P_1$, where P_0 is obtained by neglecting all terms containing $1/M^2$ (except for terms containing g_{P}^2, which is large compared with the other coupling constants), and P_1 includes all terms of the order $1/M^2$. The leading order term P_0 is the explicit form that can be found in [7]. The next-to-leading-order term

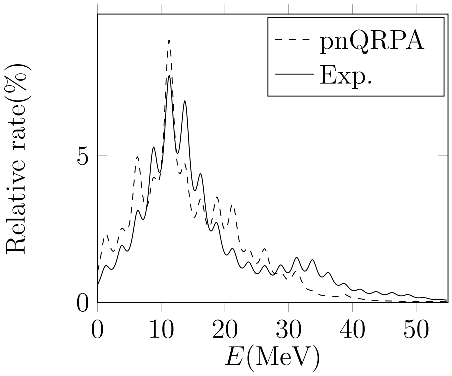
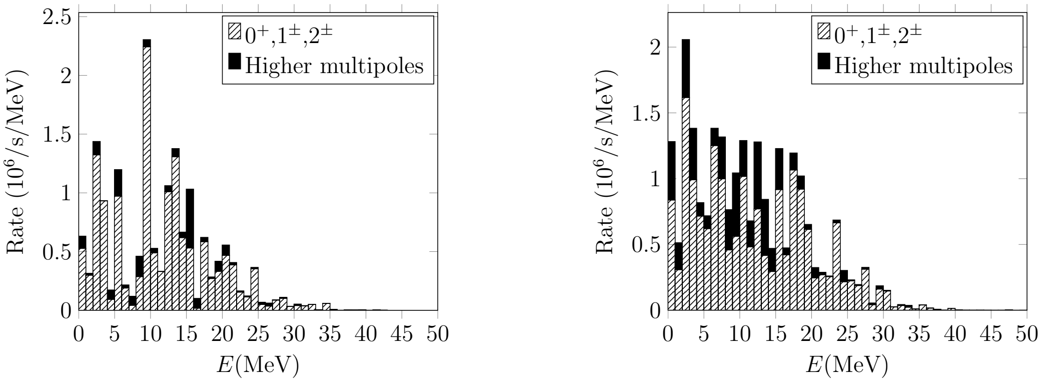


FIGURE 1. Comparison of experimental and theoretical relative muon capture rate distributions in ^{100}Nb.



(a)

(b)

FIGURE 2. OMC rate distribution for transitions (a) $^{76}\text{Se}(0^+_{\text{g.s.}}) + \mu^- \rightarrow\ ^{76}\text{As}(J^\pi) + \nu_\mu$ (b) $^{130}\text{Xe}(0^+_{\text{g.s.}}) + \mu^- \rightarrow\ ^{130}\text{I}(J^\pi) + \nu_\mu$. The transitions to lowest multipole states and higher multipole states are shown separately.

P_1 is sometimes important for weak OMC transitions usually to high-lying states. For that reason we extended the original Morita-Fujii formalism by including the P_1 term in the calculations [10].

Muon Capture Rate Distribution in ^{100}Nb

For the first time, OMC giant resonance was observed in ^{100}Nb [11]. Inspired by the observation, we computed the muon capture rate distribution in ^{100}Nb in pnQRPA formalism with large no-core single-particle basis and compared the obtained spectrum with the experimental one [12]. Both the experimental OMC spectrum and the pnQRPA-computed one show a giant resonance at around 10-12.5 MeV, and tails at higher energies (see Fig. 1).

However, the obtained total capture rate value $W_{\text{tot}} = 17.7 \times 10^6$ 1/s obtained using parameters $g_{\text{A}} = 0.8$ and $g_{\text{P}} = 10$ is a lot larger than the corresponding Primakoff estimate $W_{\text{Prim.}} = 7.7 \times 10^6$ (see Eq. (4.53) of the review article [13]). This suggests a strongly quenched axial vector coupling constant $g_{\text{A}} \approx 0.5$.

Muon Capture Rate Distributions on the Daughter Nuclei of $\beta\beta$ Decay Triplets

The ordinary muon captures on the daughter nuclei, ^{76}Se, ^{82}Kr, ^{96}Mo, ^{100}Ru, ^{116}Sn, ^{128}Xe, ^{130}Xe and ^{136}Ba, of the key double beta decay triplets leading to the excited states of the corresponding intermediate nuclei, were computed in the pnQRPA framework using large no-core single particle bases as in the case of ^{100}Mo. The corresponding OMC

TABLE 2. The "most probable" experimental OMC strength distribution below 1.1 MeV in ^{76}As [14] compared with the corresponding pnQRPA-computed distribution [10]. 'g.s.' means transitions to the ground state that could not be measured.

	OMC rate (1/s)			OMC rate (1/s)	
J^π	Exp.	pnQRPA	J^π	Exp.	pnQRPA
0^+	5120	414	3^+	60 160	55 355
1^+	218 240	236 595	3^-	53 120	34 836
1^-	31 360	28 991	4^+	-	2797
2^+	120 960	114 016	4^-	30 080	23 897
2^-	145 920 + g.s.	177 802			

strength functions have been analysed in terms of multipole decompositions (see Fig. 2 for examples).

The low-energy part ($E < 1.1$ MeV) of the computed spectrum for the transitions $^{76}\mathrm{Se}(0^+_{\mathrm{g.s.}})+\mu^- \rightarrow {}^{76}\mathrm{As}(J^\pi)+\nu_\mu$ can be compared with measured rates deduced from the recent results of Zinatulina *et al.* [14]. The capture rates to each J^π multipole below 1.1 MeV are summed, and the obtained experimental and pnQRPA-computed values are presented in Table 2 (for details, see Ref. [10]). In the pnQRPA calculations we used the parameter values $g_{\mathrm{A}} = 0.8$ and $g_{\mathrm{P}} = 7.0$. The obtained capture rates are generally surprisingly close to each other, but pnQRPA seems to underestimate the capture rates for transitions to 0^+ states.

CONCLUSIONS

Neutrinoless double beta decay has not yet been measured despite a lot of effort has been directed to observing it. Thus, the $0\nu\beta\beta$ calculations need some complementary tests in order to reliably describe the intermediate states, and finally to probe the half-lives of $0\nu\beta\beta$ decays.

Both charge-exchange reactions and ordinary muon capture serve as useful detours to study the intermediate states of $0\nu\beta\beta$ decay, and we have studied how to utilise those reactions in the study of $0\nu\beta\beta$ decay.

By extending the experiments and calculations on OMC to other $0\nu\beta\beta$-decaying nuclei we could shed light on the effective values of the axial-vector (g_{A}) and induced pseudoscalar (g_{P}) couplings, and the NMEs related to $0\nu\beta\beta$ decay and astro-(anti)neutrino interactions.

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REFERENCES

[1] H. Ejiri, Phys. Rep. **338**, 265 (2000).
[2] J. Vergados, H. Ejiri and F. Šimkovic, Int. J. Mod. Phys. E **25**, 1630007 (2016).
[3] H. Ejiri, J. Suhonen and K. Zuber, Phys. Rep. **797**, 1 (2019).
[4] L. Jokiniemi and J. Suhonen, Phys. Rev. C **96**, 034308 (2017).
[5] L. Jokiniemi, H. Ejiri, D. Frekers and J. Suhonen, Phys. Rev. C **98**, 024608 (2018).
[6] J. Hyvärinen and J. Suhonen, Phys. Rev. C **91**, 024613 (2015).
[7] M. Morita and A. Fujii, Phys. Rev. **118**, 606 (1960).
[8] H. Primakoff, Rev. Mod. Phys. **31**, 802 (1959).
[9] K.W. Ford and J.G. Wills, Nucl. Phys. **35**, 295 (1968).
[10] L. Jokiniemi and J. Suhonen, Phys. Rev. C (2019), *submitted.*
[11] I. H. Hashim, H. Ejiri, T. Shima, K. Takahisa, A. Sato, Y. Kuno, K. Ninomiya, N. Kawamura and Y. Miyake, Phys. Rev. C **97**, 014617 (2018).
[12] L. Jokiniemi, J. Suhonen, H. Ejiri and I. H. Hashim, Phys. Lett. B **794**, 143 (2019).
[13] D. F. Measday, Phys. Rep. **354**, 243 (2001).
[14] D. Zinatulina, V. Brudanin, V. Egorov, C. Petitjean, M. Shirchenko, J. Suhonen and I. Yutlandov, Phys. Rev. C **99**, 024327 (2019).