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Review article

An overview of the $^{20}Ne+^{76}Ge$ at E_{lab} = 275MeV

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Abstract. The study of the neutrinoless double beta decay ($0\nu\beta\beta$) by heavy-ion double charge exchange (HI-DCE) represents a crucial step toward understanding the fundamental properties of neutrinos and the possible violation of lepton number conservation. Among the candidate isotopes for this rare process, ^{76}Ge plays a central role in current and next-generation experimental searches. In this work, I investigated the nuclear structure aspects relevant to the $0\nu\beta\beta$decay of ^{76}Ge through the analysis of the $^{20}Ne+^{76}Ge$ reaction at E_{lab}=275*MeV*. The reaction dynamics were modeled using the coupled-channels code FRESCO using the *Distorted Wave Born Approximation* (DWBA), which allows for a detailed description of inelastic excitations and single-nucleon transfer processes that are sensitive to nuclear transition densities. Complementary large-scale shell-model calculations were carried out with KSHELL to obtain spectroscopic amplitudes and nuclear matrix elements for the relevant states. The theoretical results were directly compared with experimental differential cross sections from the NUMEN Collaboration, showing good overall agreement in both magnitude and shape. This comparison validates the reliability of the adopted reaction and structure models and provides important constraints on the nuclear structure components that dominate the $0\nu\beta\beta$ nuclear matrix elements.
Keywords: neutrinoless double beta decay *($0\nu\beta\beta$)*, Majorana neutrinos, rare decay, nuclear matrix elements, heavy-ion reactions

Introduction

The search for neutrinoless double beta decay ($0\nu\beta\beta$) represents one of the most significant challenges in modern nuclear and particle physics, as its observation would provide unambiguous evidence of lepton number violation and confirm the Majorana nature of neutrinos. Beyond its fundamental implications for particle physics and cosmology, the $0\nu\beta\beta$decay is a sensitive probe of the

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absolute neutrino mass scale. Several experimental collaborations, such as GERDA [1] and LEGEND [2], have focused on candidate nuclei including 76Ge, owing to its favorable nuclear properties and well-established experimental techniques.

The interpretation of experimental limits or potential future observations relies critically on the theoretical evaluation of the nuclear matrix elements (NME), which connect the measurable decay half-life to the effective neutrino mass. However, the NME cannot be directly measured, and current theoretical predictions differ significantly depending on the adopted nuclear structure model. These discrepancies highlight the necessity of constraining nuclear structure inputs through experimental observables related to the same transition operators involved in the 0νββdecay.

In this context, heavy-ion double charge exchange (HI-DCE) reactions have been proposed as an alternative tool to access nuclear transitions analogous to those driving the 0νββdecay. Such reactions involve similar initial and final states, and share the same spin-isospin operators, providing a possible experimental constraint on the nuclear matrix elements. However, the extraction of meaningful NME-related information from HI-DCE data requires a precise understanding of competing mechanisms, in particular multi-step one-nucleon and two-nucleon transfer processes that may populate the same mass partitions through sequential paths.

A systematic study of heavy-ion–induced one- and two-nucleon transfer reactions using 12C, 18O, and 20Ne beams on different target nuclei is being carried out within the NUMEN collaboration project at the INFN–Laboratori Nazionali del Sud (LNS). The NUMEN program aims to investigate double charge exchange and related reaction mechanisms at energies around 15–25 MeV per nucleon, employing the MAGNEX large-acceptance spectrometer for the detection of reaction products with high resolution and efficiency. These measurements provide crucial benchmarks for theoretical models describing the dynamics of nucleon transfer and charge-exchange processes relevant to the 0νββdecay.

Within this framework, the ^{20}Ne+^{76}Ge system offers an ideal testing ground, as it connects the 76Ge and 76Se nuclei involved in the 0νββ decay through single and multinucleon exchange processes. The study of one-proton stripping and one-neutron pickup reactions at E_{lab} =275MeV allows us to test the predictive power of both the nuclear structure and the reaction models. In this work, the reaction dynamics are analyzed using the coupled-channels code FRESCO [3], which accounts for inelastic excitations and transfer couplings. Spectroscopic amplitudes and nuclear matrix elements were obtained from large-scale shell-model calculations performed with KSHELL [4], ensuring a consistent microscopic description of the nuclear states involved.

The comparison between theoretical predictions and experimental differential cross sections provides a stringent test of the adopted models and interactions. The results of this analysis represent a key step toward improving the reliability of nuclear structure and reaction frameworks used to interpret heavy-ion double charge exchange data and, ultimately, to constrain the nuclear matrix elements that govern the neutrinoless double beta decay (0νββ).

This paper is organized as follows. Section II describes the experimental setup and the MAGNEX large-acceptance spectrometer. Section III presents the methodology of the conducted study, while Section IV shows the results of the elastic channel, the inelastic excitations channel of projectile and target nuclei, the one-proton stripping and one-neutron pickup channels. Finally, Section V summarizes the main conclusions and perspectives of this work.

Experimental setup: MAGNEX spectrometer

The MAGNEX large-acceptance magnetic spectrometer, developed and operated at the INFN–Laboratori Nazionali del Sud (LNS) in Catania (Italy), is a key instrument for the study of nuclear reactions involving heavy ions at intermediate energies. The device is characterized by a solid-angle acceptance of about 50 msr and a momentum acceptance of approximately –14.3% to +10.3%. Its optical system consists of a large-aperture quadrupole and dipole magnet configuration, coupled to a high-resolution focal plane detector (FPD) that enables the identification and tracking of the emitted ions.

A central feature of MAGNEX is its ability to perform precise ray reconstruction of particle trajectories. The reconstruction technique is based on high-order differential algebraic methods implemented through the COSY INFINITY code, allowing for the correction of higher-order aberrations up to the 10th order. This enables an accurate determination of the momentum vector and scattering angles of detected ions, achieving a momentum resolution of about 1/1800 and an angular resolution of ≈0.2°. Furthermore, the spectrometer provides a mass resolution of approximately 1/160, obtained through the simultaneous measurement of energy, momentum, and charge of the ejectiles.

The optical characteristics and large acceptance of MAGNEX make it a powerful and versatile tool for nuclear reaction studies, including single- and multi-nucleon transfer, inelastic excitation, and double charge exchange processes. Its high precision in angle and momentum reconstruction also allows the extraction of absolute cross sections with an accuracy of a few percent, demonstrating its suitability for detailed investigations of reaction mechanisms and nuclear structure observables. Further information could be available in [5].

In the present experiment, a 20Ne beam with an energy of 306 MeV was produced by the super-conducting cyclotron at INFN-LNS and directed onto a carbon target enriched with 76Ge. The 19F (one-proton stripping) and 21Ne (one-neutron pickup) ejectiles were momentum analyzed by the MAGNEX large acceptance magnetic spectrometer.

Methodology

The theoretical interpretation of the angular distributions for the 20Ne+76Ge reaction in the different channels was carried out using the FRESCO code.

The optical model (OM) potential was determined through a parameter search performed with the integrated SFRESCO code, using the experimental angular distribution data provided by the NUMEN collaboration as a reference. The inelastic differential cross section was calculated within the DWBA framework, assuming a pure rotational model to describe the excitation levels. To evaluate the spectroscopic amplitudes required for the channel involving one-nucleon transfer, the KSHELL code was employed in combination with the FRESCO reaction code to calculate the angular distribution of the cross section.

Results

In the following section, the results of the theoretical angular distribution of the cross section are presented for the different reaction channels.

- **Elastic channel**

The elastic channel can be described using a complex optical potential:

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$$U_{OPT}(r) = V(r) + iW(r) \tag{1}$$

V(r) is the real part of the potential, and W(r) is the imaginary part of the potential, described the non-elastic contributions and results as an absorptive effect for the elastic cross section, reducing the flux in the elastic channel. The real part V(r) of the OP is a central Woods-Saxon function in which the radius R, the strength V_0 and the diffuseness are evaluated due to an SFRESCO code.

In the present work, the following parameters are adopted:

Table 1. Parameters of the Optical Potential

V_0(MeV)	r(fm)	a(fm)	W_0(Mev)	$r_i(fm)$	a_i(fm)
20.257	1.506	0.652	28.627	1.214	0.650

The results of the optical model (OM) calculations performed with this type of potential, together with the experimental data presented in the σ/σ_{RUTH} representation, are shown in Figure 1.

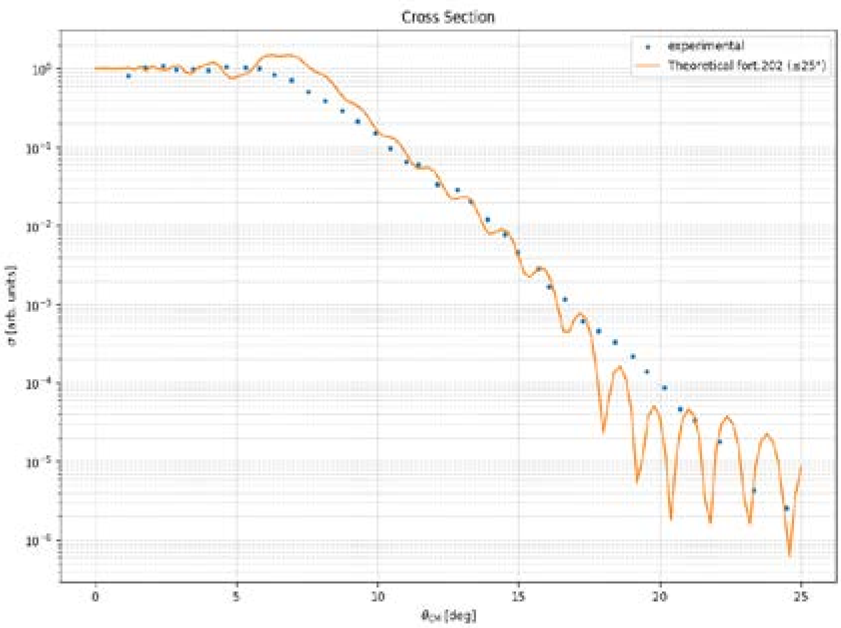

Figure 1. Angular distribution of the elastic differential cross section in terms of ratio with the Rutherford cross section. Blue dots are experimental data

- **Inelastic channel**

The angular distribution of the transition from the ground state of the target $(0^+)$to the excited 2^+ state at 0.563 MeV was evaluated within the DWBA approximation. Assuming a pure rotational model, the transition to the 2^+state was treated as a quadrupole excitation.

Using the KSHELL code, the reduced transition probability of 76Ge was calculated in order to describe the Coulomb deformation of the nucleus, yielding the value B(E2; $0^+ \to 2^+$) = 0.37 e^2b^2.

The nuclear coupling potentials $V_{i2}(r)$were treated in the first-order approximation, following the formulation of G. Satchler [6], given by:

$$V_{i2}(r) = \frac{\delta_{i2}}{4}\frac{dU(r)}{dr} \tag{2}$$

where the deformation lengths $\delta_{i2} = \beta_{i2}R_i$are computed from the deformation parameters $\beta_{i2}$and the nuclear radii R_i of each nucleus i. The results are shown in Figure 2.

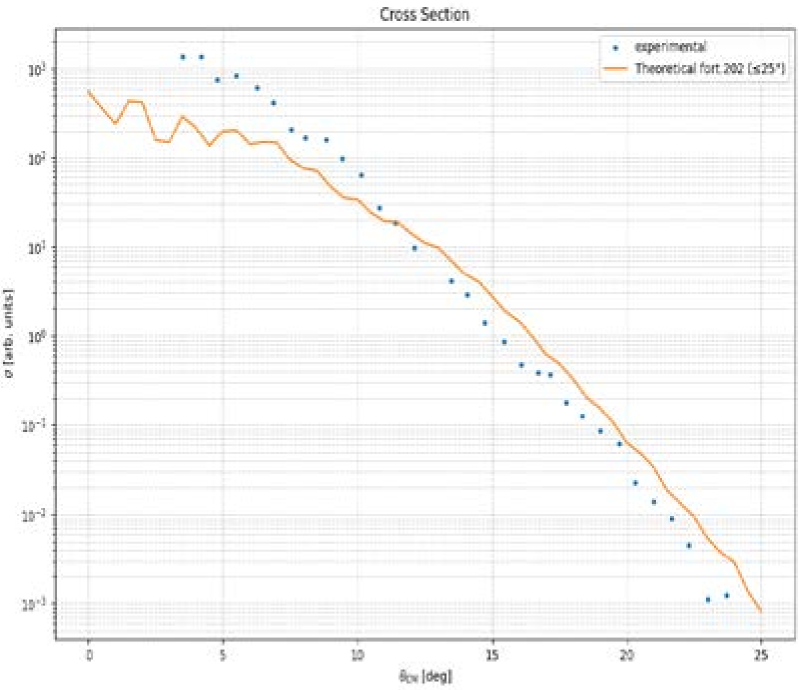

Figure 2. Angular distribution of the inelastic differential cross section in terms of the ratio with the Rutherford cross section. Blue dots are experimental data

- **Neutron pick-up**

Particular attention was devoted to nucleon-transfer processes. In particular, the neutron pick-up mechanism in the reaction ^{76}Ge(^{20}Ne, ^{21}Ne)^{75}Ge*was investigated. The theoretical angular distribution of the cross section (shown in Fig. 3) was evaluated by assuming the ^{20}Nenucleus in the state with angular momentum $5/2^+$at an excitation energy of 0.351 MeV. For the residual nucleus ^{75}Ge, the first five excited states were considered.

The spectroscopic amplitudes required as input for the FRESCO code were calculated using KSHELL, employing the **w** interaction for the projectile nucleus and jun45 for the target nucleus. Moreover, in order to reduce the number of degrees of freedom and limit computational effort, a *particle–hole truncation* was introduced, which significantly decreased the overall time consumption of the simulation.

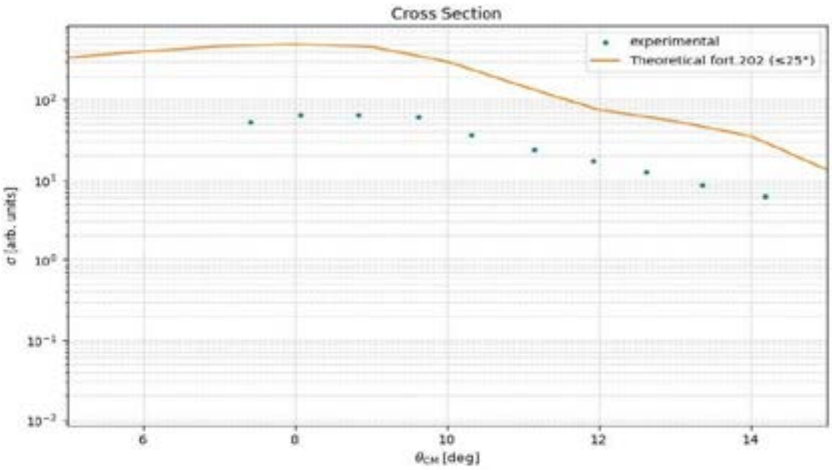

Figure 3. Angular distribution of the 1N-Pick up differential cross section in terms of ratio with the Rutherford cross section. Blue dots are experimental data

- **Proton stripping**

As a final analysis, the theoretical angular distribution of the cross section associated with the proton stripping process in the reaction $^{76}Ge(^{20}Ne,\ ^{19}F)^{77}As$ was evaluated, and the corresponding prediction is presented in Figure 4. As in the previous cases, the calculation was performed within the DWBA framework, which provides the most suitable theoretical description for single–nucleon transfer mechanisms at intermediate energies.

For the emitted nucleus 19F, the state with spin and parity $5/2^{+}$at an excitation energy of 0.197 MeV was considered, consistent with the nuclear configurations expected for a stripping process. Regarding the residual nucleus ^{77}As, the nuclear structure input was constructed by including the first five excited states of the target ^{76}Ge, in order to obtain a more comprehensive description of the accessible population channels in the reaction.

KSHELL spectroscopic amplitudes**,** required to characterize the structural contribution of the various transfer channels and to provide input for the FRESCO code, were computed using KSHELL**,** employing the appropriate interaction models for the nuclei involved.

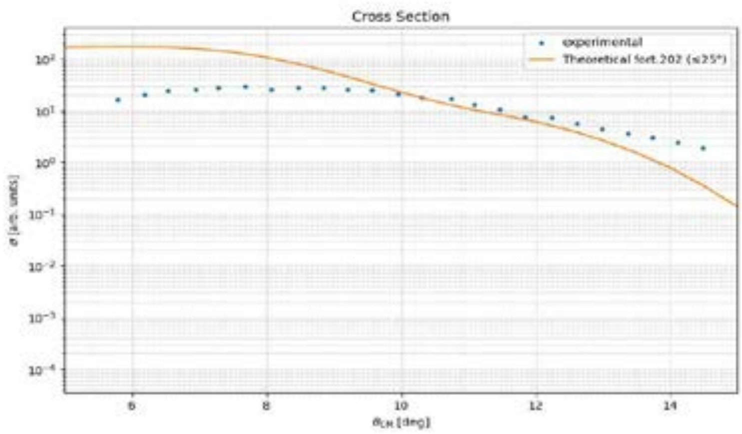

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Figure 4. Angular distribution of the 1P-Stripping differential cross section in terms of ratio with the Rutherford cross section. Blue dots are experimental data

Discussion

In this work, I put under investigation the system ^{20}Ne+^{76}Ge at a beam energy of $E_{lab} = 306$MeV for different reaction mechanisms. This reaction system is of particular interest within the framework of the NUMEN project, which aims to constrain the nuclear matrix elements relevant to neutrino-less double beta decay ($0\nu\beta\beta$) through the study of the corresponding heavy-ion–induced double charge exchange reaction. Achieving this objective requires a thorough understanding and accurate quantification of all multistep transfer processes connecting the same initial and final mass partitions. The results reported here contribute to this broader effort by providing essential experimental benchmarks and theoretical insights needed to improve the reaction modelling and, ultimately, the reliability of the extracted nuclear matrix elements.

In the *elastic channel*, good agreement with experimental data is observed for small angles, while at larger angles an oscillation of the theoretical angular distribution of the cross section emerges. This behavior could be attributed to convergence problems in the *FRESCO* code, probably related to the shape of the potential used. A possible solution could consist of a more accurate fit of the experimental data.

In the *inelastic channel*, the angular distribution of the cross section correctly reproduces the experimental data, but a more realistic description could be obtained by adopting a model-independent approach for excitation, as an alternative to the pure rotor model.

Finally, for the *one-nucleon transfer channels*, an increase in the degrees of freedom in the interaction model would allow more accurate spectroscopic amplitude values, thus improving the overall agreement with the experimental data.

In conclusion, due to the quantum nature of the reaction mechanism, it is not possible to experimentally isolate the cross sections associated with individual nuclear states. Instead, the measured observables represent the coherent outcome of all contributing processes. For this reason, a robust theoretical framework for nucleon-transfer reactions becomes essential, as it enables the prediction of cross sections for intermediate steps that cannot be accessed experimentally. Such theoretical guidance is crucial for completing the reaction picture and for supporting the interpretation of the measured data, ultimately allowing for a more accurate reconstruction of the reaction dynamics involved in the studied system.

Conclusion

In general, there was good agreement between the theoretical angular distributions of the cross section in the different reaction channels and the experimental data, except in the neutron pick-up channel. These results confirm the reliability of the model adopted and allow indirect access to information on nuclear matrix elements, which cannot be determined directly. Looking ahead, a significant development of this research could consist of extending the calculation times and modelling complexity of the simulations with KSHELL, to employ interactions with a greater number of degrees of freedom and obtain more accurate and complete spectroscopic amplitudes.

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The contribution of the authors

Pappalardo L.F. – is responsible for all the phases of the research, including the writing of the FRESCO code, the interpretation of the results, and the writing of the manuscript.

Soukeras V. – supervised the study, verified the accuracy of the results and the implementation of the FRESCO code, and critically reviewed the manuscript.

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E_lab = 275MeV энергиядағы 20Ne+76Ge реакцияға шолу

Аңдатпа. Ауыр иондардың екі заряд алмасуы (HI-DCE) әдісі арқылы бейтарап нейтриносыз қос бета ыдырауын (0νββ) зерттеу нейтринолардың негізгі қасиеттерін түсінуге және лептон санының сақталу заңының бұзылу мүмкіндігін анықтауға бағытталған маңызды қадам болып табылады. Бұл сирек процесс үшін кандидат изотоптардың ішінде 76Ge қазіргі және келесі буындағы эксперименттік ізденістерде орталық рөл атқарады. Осы жұмыста мен 76Ge ядросының 0νββ ыдырауына қатысты ядролық құрылым аспектілерін E_lab=275 МэВ энергиясындағы 20Ne+76Ge реакциясын талдау арқылы зерттедім. Реакция динамикасы Distorted Wave Born Approximation (DWBA) әдісін қолданатын FRESCO куплетілген каналдар коды арқылы модельденді, бұл ядролық өту тығыздықтарына сезімтал серпімсіз қоздырылулар мен бір нуклонды тасымалдау процестерін егжей-тегжейлі сипаттауға мүмкіндік береді. Қосымша ауқымды қабықша-модель есептеулері KSHELL бағдарламасымен жүргізіліп, тиісті күйлер үшін спектроскопиялық амплитудалар мен ядролық матрица элементтері алынды. Теориялық нәтижелер NUMEN ынтымақтастығының эксперименттік дифференциалдық қималарымен тікелей салыстырылып, мәнді де пішіні жағынан да жақсы сәйкестік көрсетті. Бұл салыстыру қолданылған реакция мен құрылым модельдерінің сенімділігін растап, 0νββ ядролық матрица элементтерін басым ететін ядролық құрылым компоненттеріне маңызды шектеулер қояды.

Түйін сөздер: бейтарап нейтрино қатысатын қос бета ыдырау (0νββ), майорана нейтринолары, сирек ыдырау, ядролық матрица элементтері, ауыр иондық реакциялар

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Обзор реакции 20Ne+76Ge при энергии E_lab = 275MeV

Аннотация. Исследование безнейтринного двойного бета-распада (0νββ) с помощью двойного обмена зарядами тяжелых ионов (HI-DCE) представляет собой важный шаг к пониманию фундаментальных свойств нейтрино и возможного нарушения сохранения лептонного числа. среди изотопов, подходящих для этого редкого процесса, 76Ge играет центральную роль в экспериментальных поисках текущего и следующего поколения. В данной работе я исследовал аспекты ядерной структуры, имеющие отношение к распаду (0νββ) 76Ge, посредством анализа реакции 20Ne+76Ge при E_lab=275 МэВ. Динамика реакции была смоделирована с помощью кода fresco с использованием приближения Distorted Wave Born Approximation (DWBA), которое позволяет детально описать неупругие возбуждения и процессы переноса одного нуклона, чувствительные к плотностям ядерных переходов. Дополнительные крупномасштабные расчеты по модели оболочки были выполнены с помощью KSHELL для получения спектроскопических амплитуд и ядерных матричных элементов для соответствующих состояний. Теоретические результаты были непосредственно сопоставлены с экспериментальными дифференциальными сечениями, полученными в рамках коллаборации NUMEN, что показало хорошее общее согласие как по величине, так и по форме. Это сопоставление подтверждает надежность принятых моделей реакции и структуры и дает важные ограничения на компоненты ядерной структуры, которые доминируют в элементах ядерной матрицы 0νββ.

Ключевые слова: безнейтринный двойной бета-распад (0νββ), нейтрино Майораны, редкий распад, элементы ядерной матрицы, реакции тяжелых ионов

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