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Nuclear structure studies relevant to ^{136}Xe $\beta\beta$ decay

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Abstract. In these proceedings we briefly discuss preliminary results from ^{138}Ba(d,α) and ^{138}Ba(p,t) reactions performed using the Q3D magentic spectrometer at the Maier-Leibnitz-Laboratorium (MLL) tandem accelerator facility in Garching, Germany. Our results aim to provide useful spectroscopic information for the calculation of the ^{136}Xe $\rightarrow^{136}$ Ba double beta decay matrix elements.

1. Introduction

The existence of massive neutrinos open up the possibility of observing neutrinoless double beta ($0\nu\beta\beta$) decays, which are lepton number violating (LNV) processes that would affirm the Majorana nature of neutrinos. Unlike the standard model allowed two-neutrino double beta ($2\nu\beta\beta$) decay process, the (yet-to-be-confirmed) detection of the exotic neutrinoless double beta ($0\nu\beta\beta$) decay mode would require a paradigm shift in our understanding of neutrino properties. The $0\nu\beta\beta$ decay rate for an atomic nucleus can be written as

$$\Gamma^{0\nu} = G^{0\nu}(Q,Z)|\sum_i \eta_i^2 M_i^{0\nu}|^2, \qquad (1)$$

where $G^{0\nu}(Q,Z)$ is a phase space factor, $M_i^{0\nu}$ are the nuclear matrix elements (NMEs) for the decay and η_i are the LNV particle physics parameters that depend on the mechanism driving the process. If the dominant mechanism responsible for the decay is the exchange of light left-handed Majorana neutrinos, the amplitude for the decay reduces to just one term,

$$\eta_\nu M_\nu^{0\nu} = \frac{1}{m_e}\left(\sum_{k=1}^{3} m_k U_{ek}^2\right) M^{0\nu} = \frac{m_{\beta\beta}}{m_e} M^{0\nu}. \tag{2}$$

In the above equation, the U_{ek} are elements of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix, m_e is the electron mass and $m_{\beta\beta}$ represents the effective Majorana mass of the electron neutrino. In such a scenario, a measured $0\nu\beta\beta$ decay half-life would also allow a determination of the absolute neutrino mass scale. However, this requires accurate values of the NMEs, which can only be obtained using nuclear structure dependent theoretical calculations. It is now well established that the matrix elements calculated for various isotopes, using different theoretical techniques disagree with one another at a significant level [1, 2]. Since next generation $0\nu\beta\beta$ decay experiments would delve into more interesting regions of $m_{\beta\beta}$ parameter space[1], it is important at this stage to make every possible effort to reduce the uncertainties in calculated NMEs for various $0\nu\beta\beta$ decay candidates.

This work relates to NME calculations for the decay of ^{136}Xe, which is a promising candidate in several ongoing $0\nu\beta\beta$ decay experiments [3, 4, 5]. We focus on two aspects of the calculations.

(i) Going beyond the closure approximation, which is explained below.

(ii) Testing the Bardeen-Cooper-Schiffer (BCS) approximation for pairing between neutrons in the daughter (^{136}Ba) nucleus.

The NMEs for $0\nu\beta\beta$ decays are calculated as a sum of virtual transitions over states up to high excitations in the intermediate odd-odd nucleus [1, 6]. This makes the calculations computationally expensive and challenging [1], particularly when using the shell model, where one is limited by the dimensionality of the valence space used. To bypass this problem, most calculations have resorted to the closure approximation [1, 7, 8], wherein the energies of the individual states in the intermediate nucleus are replaced by an average energy $\langle E \rangle$. It is now well known that the closure approximation introduces an $\sim 10\%$ uncertainty in the final results [7, 9]. Recent large-scale shell model calculations have tried to address this issue by evaluating NMEs beyond the closure approximation [7, 9, 10], using knowledge of intermediate nuclear states. Compared to the shell model and other calculations (such as the generator coordinate method, projected Hartree-Fock-Bogoliubov method, etc.), the quasiparticle random-phase approximation (QRPA) approach to calculate NMEs seems to be least sensitive to the closure approximation [11]. However, the QRPA calculations assume the ground states in the parent and daughter nuclei to be BCS condensates of proton and neutron pairs. It is known that the BCS approximation for pairing correlations breaks down in nuclei due to changes in deformation or when there is a large gap in the single particle states, such as near a shell closure [12]. Good experimental probes for studying pair-correlations in even-even nuclei are pair-transfer processes such as (p, t) or $(^3\mathrm{He}, n)$ reactions [13, 14, 15]. If all the $L = 0$ pair-transfer strength in these reactions will proceed to the ground states of the nuclei under study, this would validate the BCS approximation.

In light of the above, any experimental knowledge of excited states in the intermediate nuclei and pairing properties of the ground state wavefunctions would be important to place $0\nu\beta\beta$ decay matrix element calculations on a more secure footing. Below we briefly discuss preliminary results from $^{138}\mathrm{Ba}(d, \alpha)^{136}\mathrm{Cs}$ and $^{138}\mathrm{Ba}(p, t)^{136}\mathrm{Ba}$ reactions that would be relevant for future matrix element calculations of $^{136}\mathrm{Xe} \to {}^{136}\mathrm{Ba}$ $\beta\beta$ decays.

[1] For example, if neutrinos were Majorana particles and have an inverted mass hierarchy, a successful experiment would be imminent if $m_{\beta\beta} \approx 10$ meV.

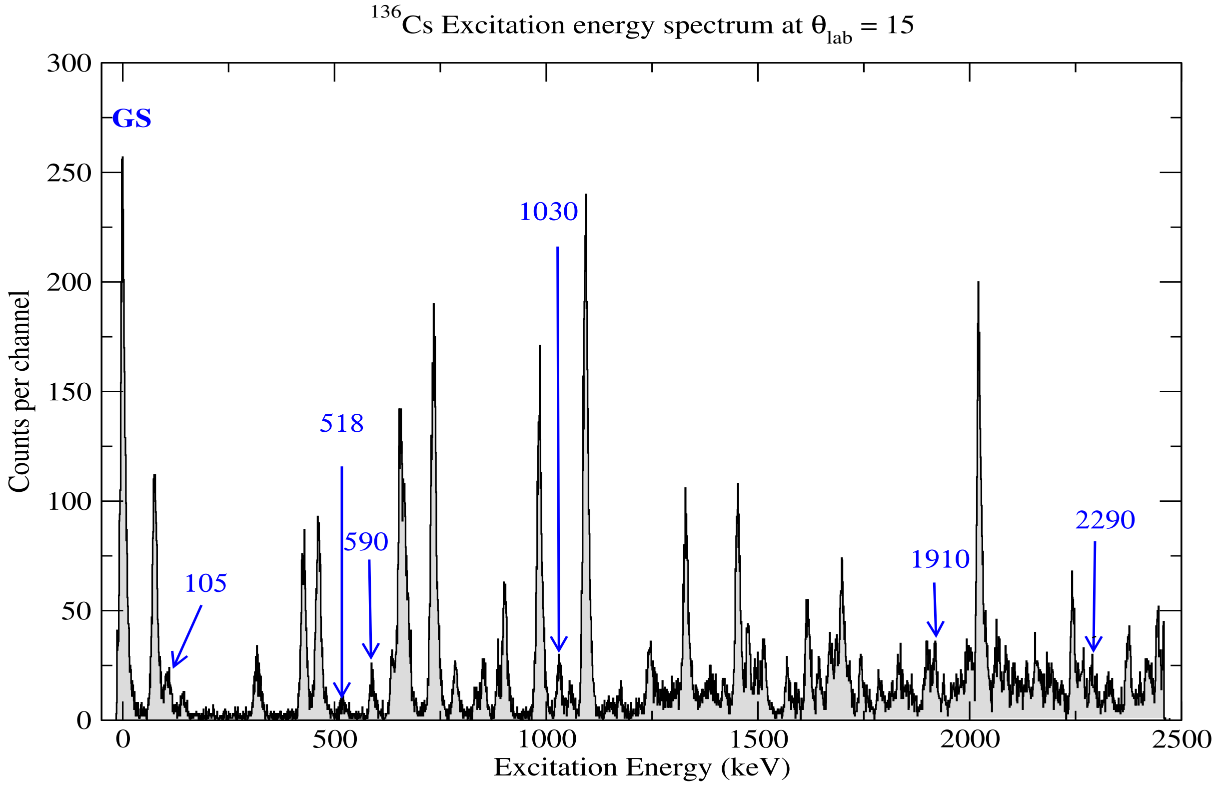

Figure 1. Preliminary excitation energy spectrum for ^{136}Cs from the ^{138}Ba(d,α) reaction. The focal plane spectrum was energy calibrated using well known states in ^{92}Nb from ^{94}Mo(d,α). In this figure we only label those states that have been observed previously. To the best of our knowledge, all the other states have been observed for the first time.

2. Experimental details

The experiments were performed at the tandem accelerator facility at Maier-Leibnitz-Laboratorium (MLL) in Garching (Germany). For the measurements we collected triton and alpha particle spectra at laboratory scattering angles of 5°-50° and 5°-45° respectively, using the high resolution Q3D magnetic spectrometer [16]. The focal plane detector [17] of the spectrometer comprised of two proportional counters filled with isobutane gas at $\sim$ 500 mbar (to measure the partial energy loss of the ejectiles) and a 7 mm thick plastic scintillator to completely stop them. The second proportional counter is coupled to a cathode-strip foil that determined the position of the light ejectiles with high resolution. The charged ejectiles were identified from the energy losses in the proportional counters $(\Delta E_1, \Delta E)$ and the total energy deposited in the plastic scintillator (E). Schematic views of the Q3D magnetic spectrometer, focal plane detector and target/beam information are listed in Ref. [8]. Well known states in ^{92}Nb from ^{94}Mo$(d,\alpha)^{92}$Nb reactions on 100 μg/cm^2 thick ^{94}MoO$_3$ target were used to calibrate the ^{138}Ba(d,α) spectrum, while the (p,t) spectra were internally calibrated using well known states in ^{136}Ba.

3. Preliminary results

Fig. 1 shows a calibrated focal plane spectrum with the α peaks corresponding to states in ^{136}Cs. We identify more than 50 new states up to approximately E_x = 2.4 MeV. This is because our reaction offers a different selectivity compared to previous recent work [18] that strongly favored the population of 1^+ states. More explicitly, the (d,α) reaction can be safely approximated as a single-step stripping of a 'deuteron' [19], so that the transfered proton-neutron pair *only* couple to $S = 1$ and $T = 0$ [19]. Furthermore, the large (positive) Q-value for the (d,α) reaction

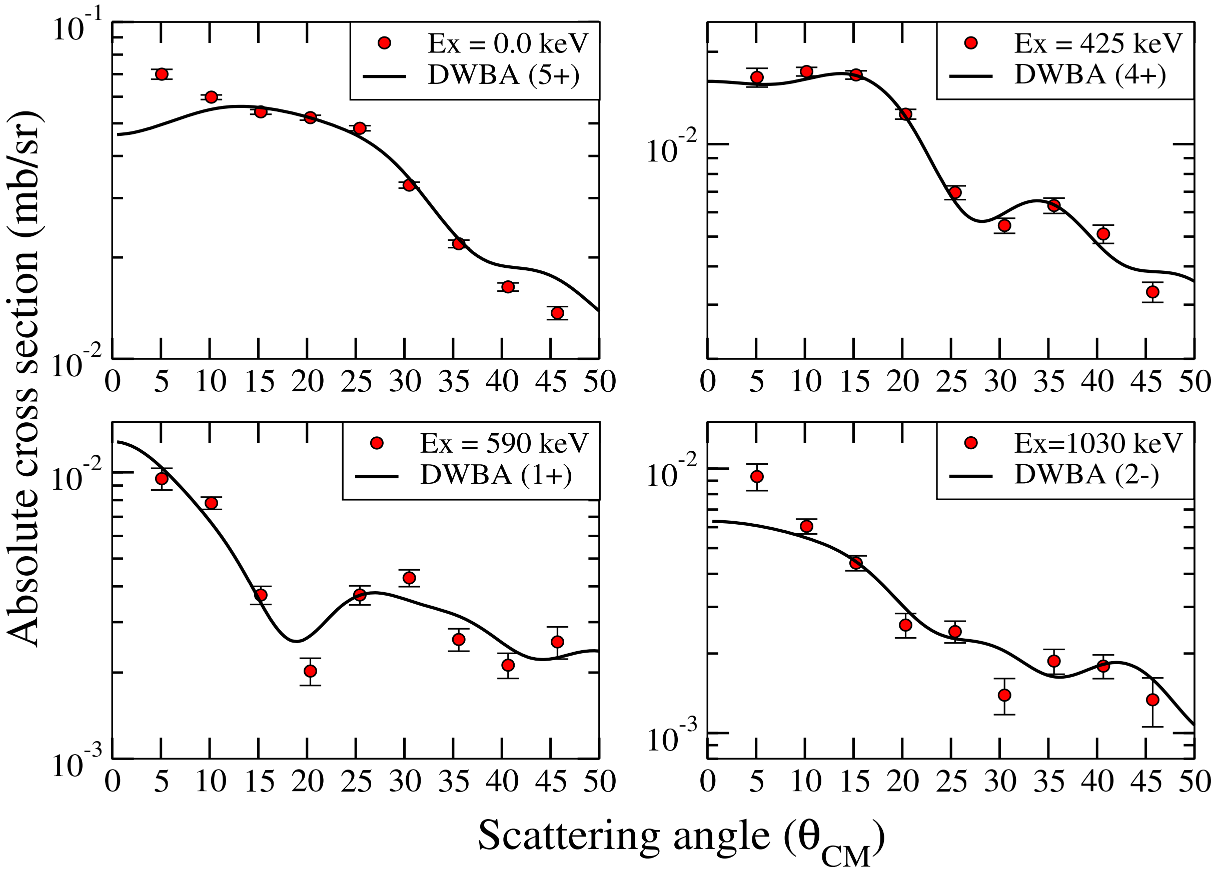

Figure 2. Comparison of DWBA calculations with measured ^{138}Ba$(d,\alpha)^{136}$Cs angular distributions.

allows for larger L values to be transfered, favoring transitions to states with (reasonably) higher angular momentum [20].

The measured angular distributions from ^{138}Ba(d,α) were compared to predictions from Distorted Wave Born Approximation (DWBA) calculations [21]. The global optical model potential (OMP) parameters best suited for the DWBA analysis were deduced from ^{138}Ba(d,d) elastic scattering data for the incoming channel [22] and from McFadden and Satchler [23] for the outgoing $(\alpha +^{136}$ Cs) channel.

Since both natural and unnatural parity states are populated by the (d,α) reaction, the total angular momentum of the final states satisfy the conditions $J = L$ and $J = L \pm 1$. Using these and the chosen OMP parameters, we obtained the DWBA predictions for the angular distributions, which were normalized to the data using a least squares minimization routine, so that

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm expt} = \alpha \left(\frac{d\sigma}{d\Omega}\right)_{\rm DWBA:J=L} \tag{3}$$

for natural parity states and

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm expt} = \beta \left(\frac{d\sigma}{d\Omega}\right)_{\rm DWBA:J=L+1} + \gamma \left(\frac{d\sigma}{d\Omega}\right)_{\rm DWBA:J=L-1} \tag{4}$$

for the unnatural parity states, where α, β and γ are relative normalizations.

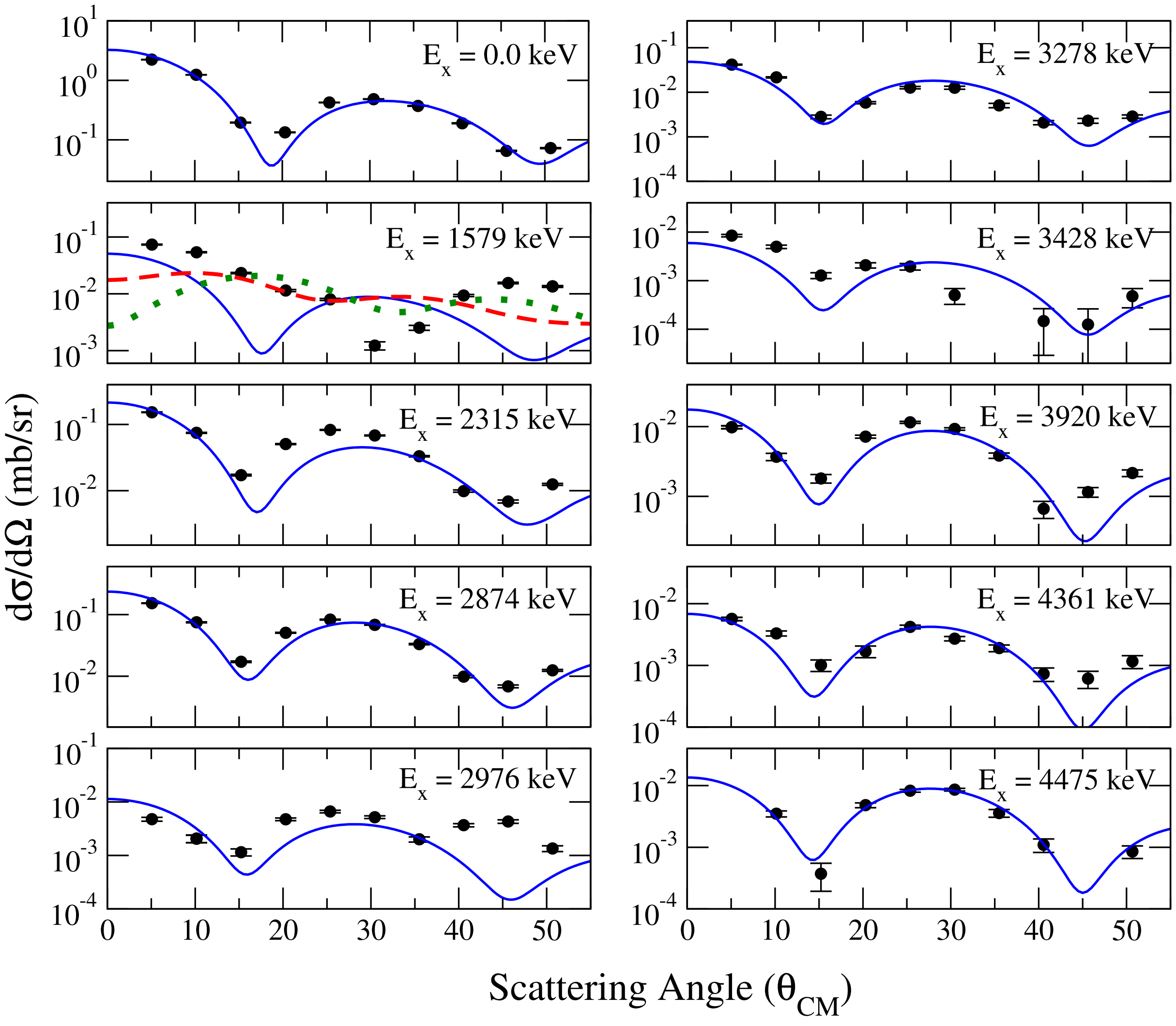

Figure 3. 0^+ states populated via the ^{138}Ba$(p,t)^{136}$Ba reaction. The measured cross-sections are compared to normalized DWBA curves. The dashed red line for the $Ex = 1579$ state is the DWBA curve for an $L = 1$ transfer, while the dotted green line represents a $L = 2$ transfer. The solid blue line in all the plots is for $L = 0$.

As examples, we show normalized DWBA angular distributions for a few states in ^{136}Cs in Fig. 2. The ground state of ^{136}Cs is known to be $J^\pi = 5^+$. Furthermore, the 590 keV state was determined to have $J^\pi = 1^+$ from a previous measurement [18], while the 1030 keV state is known to be 2^- [24]. As shown in the figure, the extraction of the spins and parities of these states using our analysis is in reasonable agreement with previous determinations. Fig. 2 also shows that we determine $J^\pi = 4^+$ for a previously unknown state at $E_x = 425$ keV. A final analysis for all other observed states shown in Fig. 1 is currently in progress.

Similar to the (d,α) analysis, we identified 0^+ states in ^{136}Ba from the (p,t) reaction by comparing the measured angular distributions with DWBA predictions. For these data we used the proton and triton global OMP sets from Ref. [25] and Ref. [26] respectively. Fig. 3 shows our measured angular distributions for the three excited 0^+ states (at $E_x = 1579$, 2315 and 2784 keV) that were previously known from the literature [27], as well as six additional 0^+ states newly identified from this experiment. However, it must be noted that our data do not confirm the previous assignment of $J^\pi = 0^+$ for the 1579 keV state. As the figure shows, the DWBA predictions for $L = 0$, $L = 1$ and $L = 2$ transfer largely disagree with the data. We are presently looking into potential systematic effects that might be causing this discrepancy.

In order to study neutron pairing properties in ^{136}Ba, we calculate the (p, t) transfer strength to excited 0^+ states relative to the ground state using the equation,

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Rel}} = \left(\frac{\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{Lab}}_{0^+_{\mathrm{ex}}}}{\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{DWBA}}_{0^+_{\mathrm{ex}}}}\right)\left(\frac{\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{Lab}}_{0^+_{\mathrm{gs}}}}{\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{DWBA}}_{0^+_{\mathrm{gs}}}}\right)^{-1}. \tag{5}$$

A significant cross section to the excited 0^+ states at small angles (for $L = 0$) would indicate a deviation from the BCS-like behaviour for neutron pair-correlations in ^{136}Ba. Preliminary results from our data show that approximately 10% of the ground state strength is fragmented to the 0^+_2 and 0^+_3 states at 2.3 and 2.8 MeV respectively.

4. Conclusions

In conclusion, we have performed a high resolution spectroscopy of states in the odd-odd ^{136}Cs nucleus using the ^{138}Ba(d, α) reaction. We have also performed a test of neutron pairing correlations in ^{136}Ba using the ^{138}Ba(p, t) reaction. We observe a significant fragmentation of the $L = 0$ strength to excited 0^+ states. It is anticipated that these data will be useful in constraining future NME calculations for ^{136}Xe $0\nu\beta\beta$ decays.

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