

Spectroscopy of low lying states in ^{136}Cs

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Abstract. The low-lying excited states in ^{136}Cs relevant to the double beta decay of ^{136}Xe were studied via a $^{138}\text{Ba}(d, \alpha)^{136}\text{Cs}$ transfer reaction with a high resolution magnetic spectrometer. Preliminary results from the experiment are presented.

1. Introduction

Within the standard model of particle physics [1] neutrinos are assumed to be massless. However, the observation of neutrino oscillations [2, 3] shows that the neutrinos have non-zero mass. One important goal in current physics research is to determine this mass. The experimental observation of neutrinoless double beta ($0\nu\beta\beta$) decay could provide relevant information in this regard. The $0\nu\beta\beta$ decay is possible only if the neutrino coincides with its own anti-particle (and therefore is a Majorana fermion) and it occurs when a $Z=\text{even}$, $N=\text{even}$ parent nucleus is more bound than its daughter, so that the single beta decay is energetically forbidden. In this case, a two neutrino double beta ($2\nu\beta\beta$) decay to the ‘granddaughter’ nucleus would still be energetically possible. The $2\nu\beta\beta$ decay is a second-order standard-model-allowed transition that occurs with the emission of two electrons and two neutrinos. On the other hand, if the neutrino were a Majorana fermion, a double beta decay could also occur with the emission of two electrons but no neutrinos. This is the $0\nu\beta\beta$ decay, a standard-model-forbidden decay mode that has not been observed so far. Once experimentally measured, the $0\nu\beta\beta$ decay rate directly relates to the so called “Majorana mass” $\langle m_\nu \rangle$ through Fermi’s golden rule,

$$\Gamma^{0\nu} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \frac{\langle m_\nu \rangle^2}{m_e^2}. \quad (1)$$

In the above equation, $M^{0\nu}$ is the nuclear matrix element (NME) for the decay, $G^{0\nu}(Q, Z)$ is the phase space factor and m_e is the electron mass. The dominant uncertainty in translating a



limit on the $0\nu\beta\beta$ decay amplitude into the corresponding neutrino Majorana mass arises from theoretical limitations in calculating the nuclear matrix elements, which depend on the structure of the nuclei involved in the decay. When calculated using different methods, depending on the choice of NME calculation, the upper limit obtained on the Majorana mass is found to vary significantly [4]. For instance, a determination of the lower limit on the $0\nu\beta\beta$ decay half-life of ^{136}Xe translates into a Majorana neutrino mass smaller than 0.2-0.4 eV [5].

2. NME calculations for ^{136}Xe $\beta\beta$ decays

The NMEs for double beta decays are usually calculated (using perturbation theory) as a sum over a range of intermediate states $|k\rangle$ with energy E_k . In particular, in the case of $2\nu\beta\beta$ decay, the matrix elements $M^{2\nu}$ are calculated as a sum of virtual Gamow-Teller excitations through 1^+ states in the intermediate nucleus,

$$M^{2\nu} = \sum_{k,l,m} \frac{\langle 0_f^+ | \sigma_l \tau_l^+ | k \rangle \langle k | \sigma_m \tau_m^+ | 0_i^+ \rangle}{E_k - (M_i - M_f)/2}, \quad (2)$$

where $M_i - M_f$ is the total energy released in the decay.

On the other hand, in the case of $0\nu\beta\beta$ decay the NME connects all the multipoles of the intermediate nucleus. In such decays the virtual neutrinos transfer a large momentum ($\sim 100 - 200$ MeV), allowing for nuclear excitations in the intermediate nuclei upto very high energies. This makes the matrix element calculations computationally expensive and challenging. The problem is bypassed in most calculations by using the completeness relation, where the energies of the intermediate states is replaced by an average energy, $\langle E \rangle$. This assumption, called the closure approximation, is extensively used for the NME calculations. It is now well known that the closure approximation introduces an uncertainty of $\sim 10\%$ in the computation [6, 7]. Therefore, recent shell model calculations have used the knowledge of low-lying intermediate states in a truncated model space in order to have more precise calculations of the $0\nu\beta\beta$ matrix elements [8]. Thus, any knowledge of the low-lying states in the intermediate nuclei is important to place double beta decay matrix elements on a more secure footing.

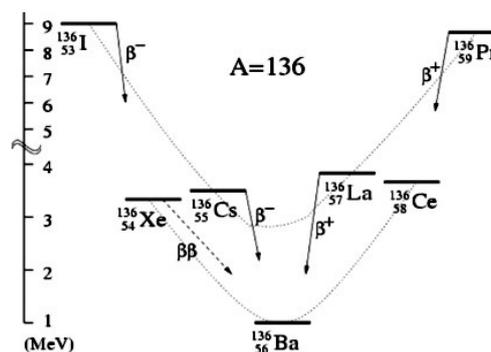


Figure 1. Mass parabola for $A=136$ showing the double beta decay candidates. Figure taken from Ref. [4].

The decay of ^{136}Xe to ^{136}Ba is a promising candidate for the observation of the $0\nu\beta\beta$ decay in both ongoing and proposed experiments, such as, EXO [9], Kamland-ZEN [10] and XMASS [11]. Until recently, experimental information regarding the states in the intermediate ^{136}Cs nucleus (Fig. 1) was limited to the ground state and to an isomeric 8^- state. In 2011, the experimental

information on the excited 1^+ states in ^{136}Cs and the corresponding Gamow-Teller strengths (the $B(GT)$ values) relevant for the NME calculation of the ^{136}Xe $\beta\beta$ decay were obtained using the Grand Raiden spectrometer in RCNP (Japan) via the $^{136}\text{Xe}(^3\text{He}, t)$ reaction [12]. The tritons were measured on the focal plane of the spectrometer, with an energy resolution of ~ 40 keV to obtain the total Gamow-Teller strength. Since the level density in ^{136}Cs is expected to be relatively high, we report a new measurement of the excited states in ^{136}Cs with a higher resolution (~ 10 keV) using the $^{138}\text{Ba}(d, \alpha)$ reaction. In our case, the reaction selectivity was not restricted only to the 1^+ excitations and other multipoles were populated as well. It is anticipated that our results will aid NME calculations for the $0\nu\beta\beta$ decay of ^{136}Xe beyond the closure approximation.

3. Experimental details

The states of interest in ^{136}Cs were produced using the $^{138}\text{Ba}(d, \alpha)$ reaction with a 22 MeV, 500 nA deuteron beam from the tandem accelerator at Maier-Leibnitz-Laboratorium (MLL) in Garching (Germany). The beam was incident on a 99.9% enriched $40\mu\text{g}/\text{cm}^2$ -thick Ba_2CO_3 target evaporated on a carbon foil. The reaction products were momentum analyzed with a high resolution one quadrupole three dipole (Q3D) magnetic spectrometer [13] and detected on a 1-m long cathode-strip focal plane detector [14]. The quadrupole lens of the Q3D was used to focus and optimize the resolution of the ejectiles from the desired reaction channel while the 3 dipole magnets allowed to separate the ejectile trajectories based on their magnetic rigidity (momentum-to-charge ratio) on the focal plane. The focal plane detector consisted of two proportional counters filled with isobutane gas at 500 mbar to measure the energy loss of the incident particles and a 7mm thick plastic scintillator to completely stop them. One of the proportional counters was coupled to a cathode-strip foil in order to determine the position of the light ejectiles with a precision better than 0.1 mm. Fig. 2 shows schematic views of the Q3D magnetic spectrometer and of the focal plane detectors. The alpha particle spectra

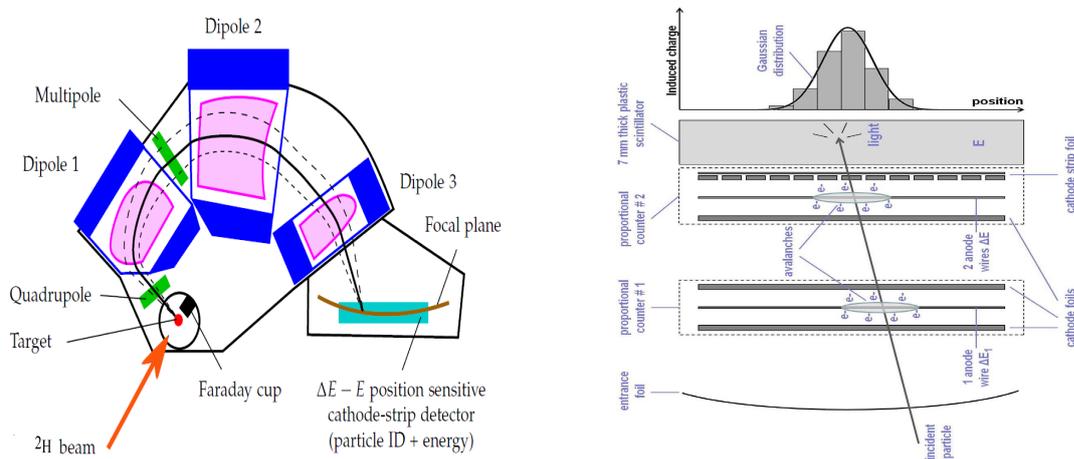


Figure 2. Left panel: The Munich Q3D spectrometer. Right panel: Schematic of the focal plane detectors.

were collected at laboratory angles ranging between 5° and 45° . We also performed angular distribution measurements for elastically scattered deuterons between an angular range of 10° and 60° . The focal plane spectrum was calibrated using well known states in ^{90}Y produced by the $^{92}\text{Zr}(d, \alpha)$ reaction. Fig. 3 shows the spectra from the $^{138}\text{Ba}(d, \alpha)^{136}\text{Cs}$ and $^{92}\text{Zr}(d, \alpha)^{90}\text{Y}$ reactions respectively.

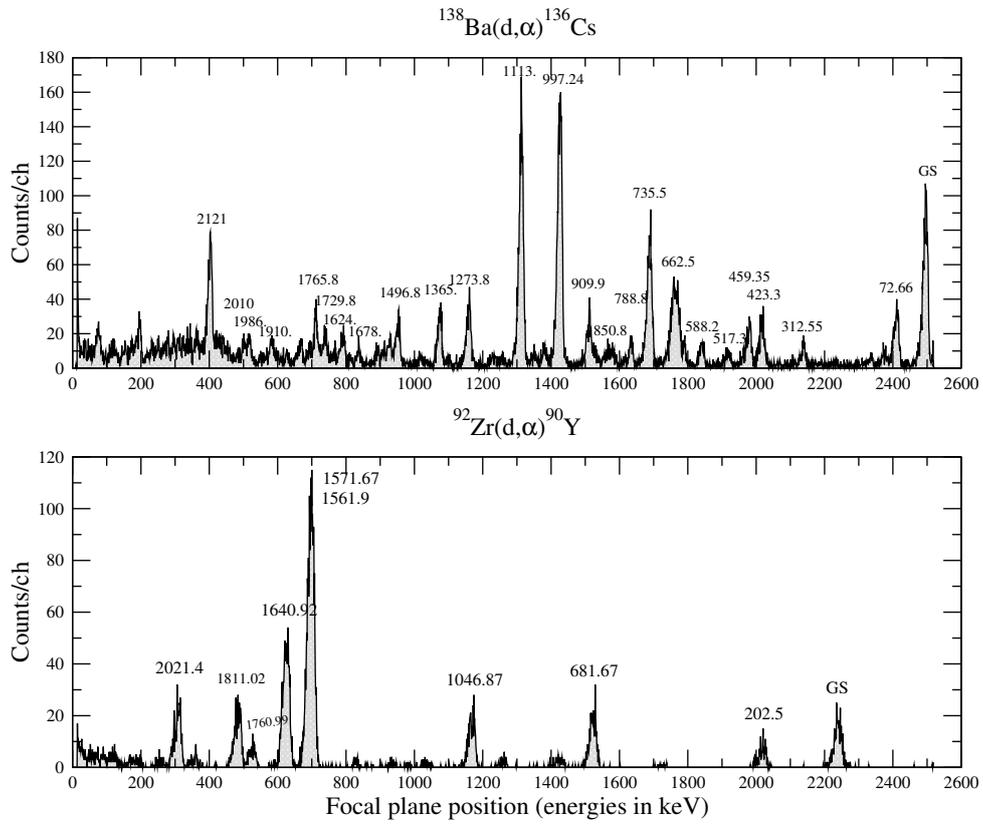


Figure 3. Preliminary results. Top panel: focal plane spectrum for $^{138}\text{Ba}(d, \alpha)^{136}\text{Cs}$. Bottom panel: $^{92}\text{Zr}(d, \alpha)^{90}\text{Y}$ calibration spectrum.

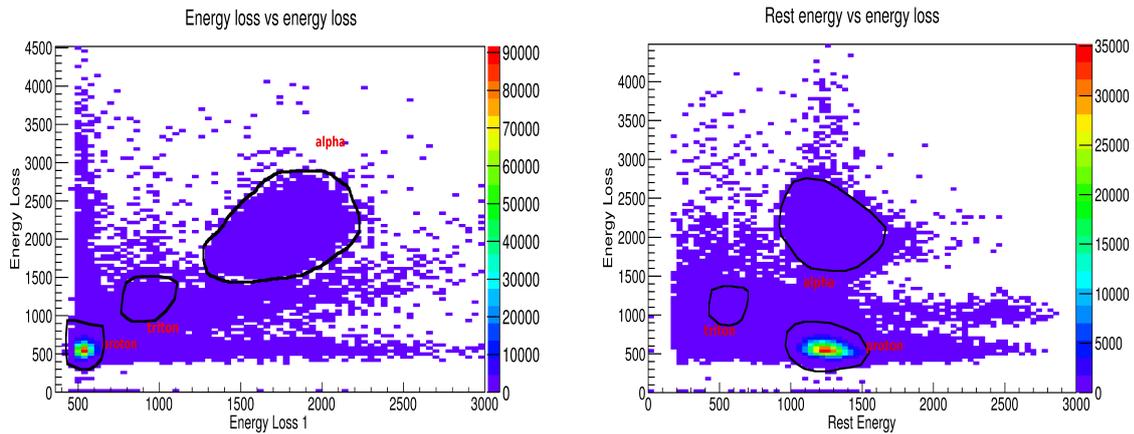


Figure 4. Particle identification spectra - left panel: $\Delta E_1 - \Delta E$, energy lost by the ejectiles in the two proportional counters and right panel: $\Delta E - E$ energy lost in the second proportional counter vs total energy deposited when ejectile loses all of its energy in the plastic scintillator. The various ejectiles produced are identified and gates are set on the alpha particles corresponding to the $^{138}\text{Ba}(d, \alpha)$ reaction channel.

4. Data Analysis and Preliminary Results

Depending on their charge, different particles lose energy differently in the proportional counters. Thus, comparing the energy lost by the particles in the proportional counters ($\Delta E_1, \Delta E$) with the total energy deposited in the plastic scintillator (E), it was possible to identify the charged particles corresponding to different reaction channels. Fig. 4 shows the two-dimensional particle identification spectra that were used to identify the various reaction products. Accordingly, gates were set on the alphas to select focal plane spectra from the (d, α) channel alone. These spectra were used to obtain excitation energies and differential scattering cross sections. As shown in Fig. 3 we identified approximately 25 new states in ^{136}Cs below 2.5 MeV. The measured angular distributions were compared to the theoretical predictions from Distorted Wave Born Approximation (DWBA) calculations. These calculations, performed using the DWUCK4 code [15], were used in conjunction with the data to identify the orbital angular momentum (L) transferred for each observed excited state. The elastic scattering and the reaction cross section angular distributions were calculated using the optical model [16] to generate the distorted waves in the DWBA calculations. For these data we first used the global deuteron and alpha optical model parameters (OMPs) from [17,18] and [19] respectively. The OMPs were input into the DWUCK4 code to calculate the angular distributions. The measured elastic scattering cross sections at various angles were compared with the DWBA predictions to validate the parameters that would eventually be used for the $^{138}\text{Ba}(d, \alpha)$ two-nucleon transfer cross sections. Based on this comparison, it was decided that the deuteron OMPs from [17] were better suited for our analysis. These parameters were used to obtain multiple angular distributions corresponding to various L -transfers for specific states of interest in ^{136}Cs with given angular momentum and parity. Fig. 5 shows the predicted angular distributions obtained for the ground state assuming various L values. On comparison with the measured distribution, one can easily assign a spin and parity of $J^\pi = 5^+$ for the ground state of ^{136}Cs , thus lending support to our calculations. A similar analysis for the excited states is currently in progress.

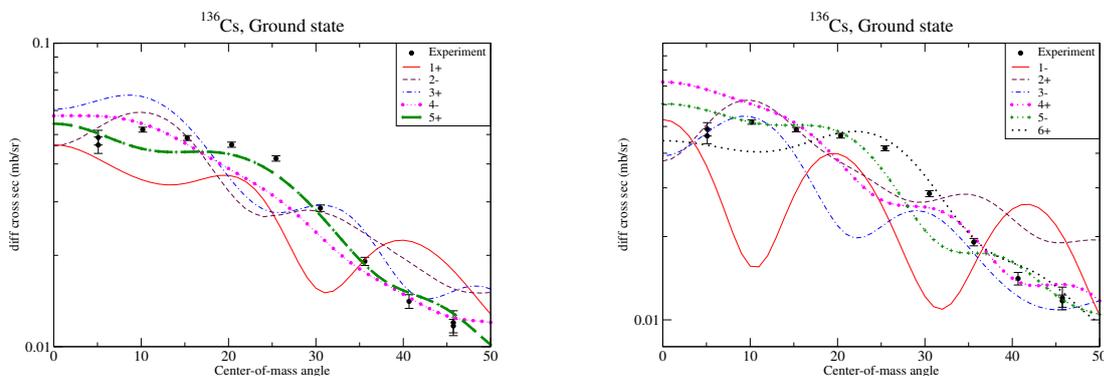


Figure 5. Measured angular distribution for the ground state (black points) of ^{136}Cs compared with the angular distributions obtained from DWUCK4 for different combinations of (L) transfers leading to states of natural parity $J^\pi = 1^-, 2^+, 3^-$, etc (right panel) and unnatural parity $J^\pi = 1^+, 2^-, 3^+$, etc (left panel). The different colors for the angular distribution curves obtained from DWUCK4 correspond to the spin-parity state resulting from the different L transfers. Natural parity states in a (d, α) reaction are populated by the $L = J$ transfer. For states of unnatural parity, two values $L = J \pm 1$ contribute for the same total angular momentum J . The spin-parity assignment of 5^+ for the ground state of ^{136}Cs (left panel, bold, green dashed line) is made based on this comparison.

References

- [1] Griffiths DJ *Introduction to Elementary Particles*, John Wiley & Sons.
- [2] Gonzalez-Garcia MC and Maltoni M 2008 *Phys. Rept.* **460**, 1-129.
- [3] Ahmad QR *et al.* 2002 *Phys. Rev. Lett* **89**, 011302.
- [4] Vogel P 2012 *J. Phys. G: Nucl. Part. Phys.* **39**, 124002.
- [5] Albert JB *et al.* 2014 *Nature* **510**, 229.
- [6] Horoi M and Stoica S 2010 *Phys. Rev. C* **81**, 024321.
- [7] Sen'kov R, Horoi M and Brown BA 2014 *Phys. Rev. C* **89**, 054304.
- [8] Senkov RA and Horoi M 2013 *Phys. Rev. C* **88**, 064312.
- [9] Ackerman N 2011 *Phys. Rev. Lett.* **107** 212501.
- [10] KamLAND-Zen Collab. 2013 *Phys. Rev. Lett.* **110**, 062502.
- [11] XMASS Collab. 2013 *J. Phys.: Conf. Series* **120** 042022.
- [12] Puppe P *et al.* 2011 *Phys. Rev. C* **84**, 051305(R).
- [13] Löffler L, *et al.* 1973 *Nucl. Instrum. Methods* **111**, 1.
- [14] Wirth H-F *et al.* 2000. New Q3D Focal Plane Detector with Cathode-strip Readout Became Operational, Maier-Leibnitz-Laboratorium Jahresbericht, p.71.
- [15] Kunz PD 1978 DWUCK4 DWBA Program, University of Colorado, Unpublished.
- [16] Hodgson PE *Nuclear Reactions and Nuclear Structure*, Clarendon Press, Oxford
- [17] Han Y, Shi Y and Shen Q 2006 *Phys. Rev. C* **74**, 044615.
- [18] An H and Cai C 2006 *Phys. Rev. C* **73**, 054605.
- [19] Burnett SM, Baxter AM, Hinds S and Pribac F 1985 *Nucl. Phys. A***442**, 289-299.