

## “No-spin” states and low-lying structures in $^{130}\text{Xe}$ and $^{136}\text{Xe}$

T.J. Ross<sup>1,2,a</sup>, E.E. Peters<sup>1</sup>, A. Chakraborty<sup>2</sup>, B.P. Crider<sup>2</sup>, A. Kumar<sup>2</sup>, S.H. Liu<sup>1,2</sup>, M.T. McEllistrem<sup>2</sup>, F.M. Prados-Estévez<sup>1,2</sup>, J.R. Vanhoy<sup>3</sup>, and S.W. Yates<sup>1,2,b</sup>

<sup>1</sup>Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506 USA

<sup>2</sup>Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506 USA

<sup>3</sup>Department of Physics, United States Naval Academy, Annapolis, Maryland 21402

**Abstract.** Inelastic neutron scattering on solid  $^{130}\text{XeF}_2$  and  $^{136}\text{XeF}_2$  targets was utilized to populate excited levels in  $^{130}\text{Xe}$  and  $^{136}\text{Xe}$ . When calculating nuclear matrix elements vital to the understanding of double-beta decay, it is important to have a clear understanding of the low-lying level structure of both the parent and daughter nucleus. Of particular relevance to double-beta decay searches are the assignments of  $0^+$  states. We show here that in the case of  $^{130}\text{Xe}$  there are several discrepancies in the adopted level structure. We found that one previous  $0^+$  candidate level (1590 keV) can be ruled out and assigned two additional candidates (2223 and 2242 keV). In  $^{136}\text{Xe}$  we question the previous assignment of a  $0^+$  level at 2582 keV. Excitation function and angular distribution measurements were utilized to make spin and parity assignments of levels and place new transitions.

### 1 Introduction

Aside from tin, xenon has the longest chain of stable isotopes on the nuclear chart, and yet the low-energy structure remains relatively unstudied due to xenon’s gaseous nature. Recently, several studies have been performed to reveal the structure of the xenon isotopes, searching for mixed-symmetry states [1, 2], octupole transition rates [3] and pair transfer properties [4–6].

Xenon isotopes are also of timely interest for neutrinoless double-beta decay applications. If the ultra-rare process is discovered, it would confirm the neutrino as its own anti particle and the neutrino mass could be extracted.  $^{136}\text{Xe}$  is of interest because it is a candidate “parent” nucleus for the process, decaying to  $^{136}\text{Ba}$ . Indeed, it is a particularly strong candidate because the reaction medium itself (a large mass of  $^{136}\text{Xe}$ ) can also be used as a detection medium for the process. If one is to extract a neutrino mass, following a direct observation of the process, it is important that one understands the nuclear structure of the isotopes involved, as they play a major role in the calculation of nuclear matrix elements, [7]. Similarly,  $^{130}\text{Xe}$  is of interest as it is the daughter nucleus following  $\beta\beta$  decay of  $^{130}\text{Te}$ .

Here we present results concerning excited  $0^+$  (“no-spin”) states in  $^{130}\text{Xe}$  and  $^{136}\text{Xe}$ . Such states are important both from the point-of-view of understanding the nuclear structure in this region and for nuclear matrix element calculations.

<sup>a</sup>e-mail: ph51tr@gmail.com

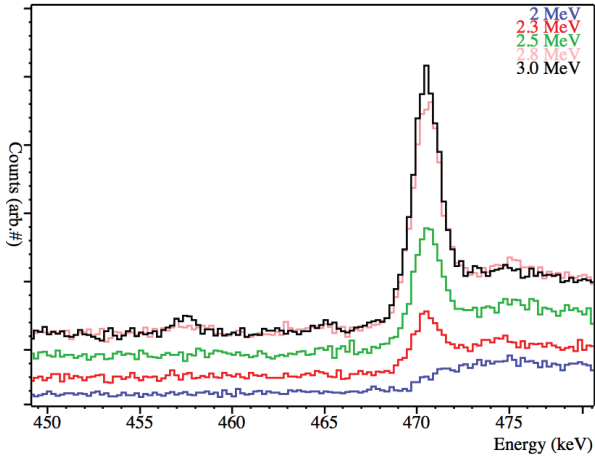
<sup>b</sup>e-mail: yates@uky.edu

### 2 Experiment

The data were taken at the University of Kentucky Accelerator Laboratory (UKAL) using the 7 MV Van de Graaff accelerator. A proton beam incident on a tritium gas cell, pressurized to 1 atmosphere, was used to produce almost mono-energetic neutrons via the  $^3\text{H}(p,n)^3\text{He}$  reaction. The resultant neutrons were then used to populate excited states in  $^{130}\text{Xe}$  and  $^{136}\text{Xe}$  via inelastic neutron scattering on samples of  $^{130}\text{XeF}_2$  and  $^{136}\text{XeF}_2$ . A Compton-suppressed high-purity germanium detector was used to detect  $\gamma$  rays. The detector was mounted on a goniometer 1.2 m from the scattering sample. Excitation function measurements (up to 3.2 MeV excitation energy for  $^{130}\text{Xe}$  and 4.1 MeV for  $^{136}\text{Xe}$ ) were performed at a detection angle of  $90^\circ$  for both samples. From these data, level thresholds and spin/parity information were deduced by comparison with statistical model calculations. Gamma-ray data were also taken at a variety of angles on both isotopes allowing  $\gamma$ -ray angular distribution, level lifetime and, therefore, transition strength measurements.

### 3 Results

In  $^{130}\text{Xe}$ , almost all previously observed levels were populated; 31 new level lifetimes were measured using the Doppler-shift attenuation method and 18 new levels assigned at energies greater than 2.3 MeV. In section 3.1, new information concerning three previously observed  $0^+$  states (1590, 1794 and 2017 keV) and two newly assigned levels (2223 and 2242 keV) will be presented. Information concerning the first excited  $0^+$  state in  $^{136}\text{Xe}$  will be presented in section 3.2.



**Figure 1.** The 470-keV  $\gamma$  ray is only observed at incident neutron energies greater than 2.2 MeV.

### 3.1 States in $^{130}\text{Xe}$

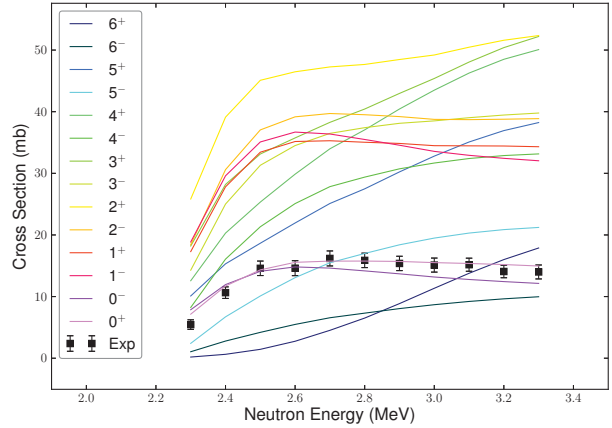
**1590-keV level.** A 1590-keV level is included in the Nuclear Data Sheets [8] with two associated transitions (469 keV decaying to  $2_2^+$  and 1053 keV decaying to  $2_1^+$ ). This level originates from a thermal-neutron capture study, on natural xenon, where it was tentatively assigned  $J^\pi = 0^+$  [9]. The level is also listed in the more recent paper by Coquard *et al.*, which utilizes Coulomb excitation [1]. However, inspection of the footnotes of the Coquard work suggest the level is populated only very weakly if at all.

Due to the non-selective nature of the inelastic neutron scattering technique, we would expect to populate this level if indeed it has  $J^\pi = 0^+$ . Our spectra show no evidence for a 1053-keV  $\gamma$  ray. A  $\gamma$  ray is detected at 470 keV (see Figure 1) but only at energies greater than 2.3 MeV (800 keV higher than the level threshold). This 470-keV  $\gamma$  ray is associated with the previously established  $4^-$  level at 2103 keV. Based upon the present non-observation, we eliminate the 1590-keV state from the level scheme.

**1794-keV level.** The second excited level currently assigned  $J^\pi = 0^+$  in the Nuclear Data Sheets [8] has excitation energy 1794 keV with two associated  $\gamma$  rays. The 670-keV  $\gamma$  ray to the  $2_2^+$  level at 1122 keV cannot be separated from a much stronger transition (669 keV) between the  $4_1^+$  and  $2_1^+$  states.

The higher energy  $\gamma$  ray (1256 keV), which decays to the first excited state at 536 keV is also difficult to clearly identify. In this case, a  $\gamma$  ray of very similar energy, which originates from the fluorine also present in the scattering sample, makes observation impossible. Due to our failure to clearly observe either  $\gamma$  ray, we make no comment on the assignment of this level.

**2017-keV level.** A third excited  $0^+$  state at 2017 keV is the subject of several discrepancies in the recent literature. Two decays are assigned to the level in the Nuclear Data Sheets [8]: 894 keV to the  $2_1^+$  state and 1481 keV to the  $2_2^+$  state. Whilst relative intensities of  $(I_\gamma(894 \text{ keV}) / I_\gamma(1481 \text{ keV})) = 100 / 6$  are adopted, there has been confusion cast upon this state with several works quoting very different



**Figure 2.** Excitation function of the 1686-keV  $\gamma$  ray from the 2222-keV level compared with statistical model calculations for various values of  $J^\pi$  initial.

relative  $\gamma$ -ray intensities, closer to  $(I_\gamma(894 \text{ keV}) / I_\gamma(1481 \text{ keV})) = 1 / 3$  [9, 10].

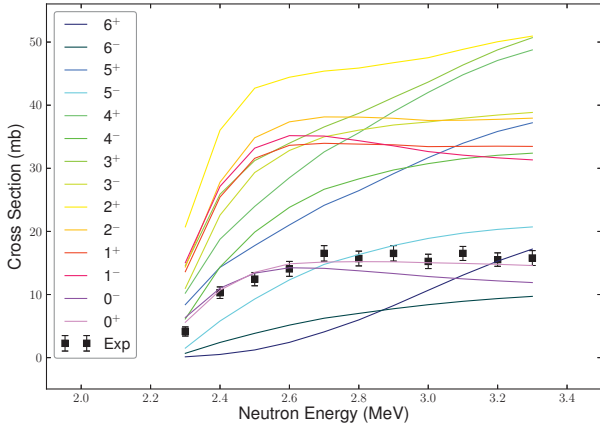
The recent work by Coquard *et al.* [1] sheds some light on the issue. They observe the 1481-keV  $\gamma$  ray but *not* the 894-keV peak. They also observe a weak 2017-keV  $\gamma$  ray, which rules out a  $0^+$  assignment. They, therefore, assign the level at 2017 keV,  $J^\pi = 2^+$ .

In this work, we observe both  $\gamma$  rays, but also find evidence which contradicts the  $0^+$  assignment. The angular distribution of the more intense  $\gamma$  ray (1481 keV) has a measurable mixing ratio and is strongly quadrupole in nature. A flat distribution would be expected following population of a “no-spin” state.

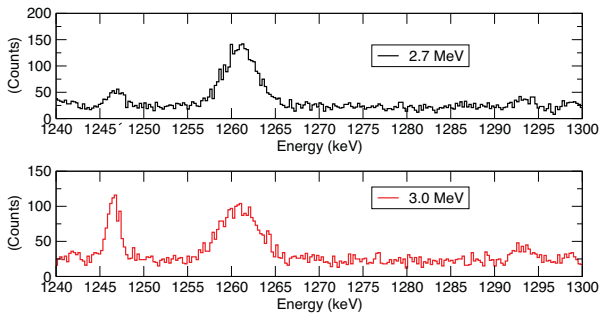
The  $\gamma$ -ray excitation functions are similar in shape (but not magnitude) and have the same energy threshold, 2.0 MeV. When compared with the statistical model calculations, the data are not well reproduced by any single calculation. If the two excitation functions are *separately* compared to the theory, the 1481-keV  $\gamma$ -ray yield is reproduced by the calculation for a  $2^+$  level and the 894-keV  $\gamma$ -ray yield is in agreement with the  $0^+$  calculation. It is also notable that the addition of the calculations corresponding to  $0^+$  and  $2^+$  fits the summed data very well. This information, combined with the non-observation of the 894 keV gamma ray in Ref. [1], is suggestive of a level doublet at 2017 keV with spins/parities of  $J^\pi = 0^+$  and  $2^+$ .

Unfortunately, if indeed there exist two levels very close in energy, we are unable to establish relative  $\gamma$ -ray intensities for the two levels, other than to say that  $2^+$  candidate decay is dominated by a transition of energy 1481 keV, and the  $0^+$  candidate level decay is dominated by the 894-keV transition. This scenario would explain, although not clear up, some of the recent confusion over the relative  $\gamma$ -ray intensities. The relative intensities measured in this work are  $(I_\gamma(894 \text{ keV}) / I_\gamma(1481 \text{ keV})) = 38 / 100$ .

**2222-keV level.** A  $\gamma$  ray is observed for the first time at 1686 keV. Due to its energy threshold of 2.2 MeV (see Fig. 2), the  $\gamma$  ray can *only* decay to the  $2_1^+$  state at 536 keV. It is therefore associated with a previously observed level at 2222 keV. By comparison of the excitation function with



**Figure 3.** Excitation function of the 1706 keV gamma ray from the 2242-keV level compared with statistical model calculations for various values of  $J^\pi$  initial.



**Figure 4.** Region of the spectrum where one would expect the 1269-keV  $\gamma$  ray.

statistical model calculations, the level becomes a candidate  $0^+$  state. The angular distribution of the  $\gamma$  ray is also approximately isotropic, a signature of the populated level having spin zero.

**2242-keV level.** A second new  $\gamma$  ray is observed just 20 keV higher in energy at 1706 keV. Again, the energy threshold dictates that it can only be a transition from a level at 2242 keV to the first excited state at 536 keV. The  $\gamma$  ray is therefore associated with a previously observed level at 2242 keV. No other transitions are observed which can be associated with the level and the comparison with the statistical model calculations is suggestive of  $J^\pi = 0^+$ , (see Fig. 3). As in the case of the 1686-keV  $\gamma$  ray, the angular distribution is approximately isotropic. This level is suggested as a second new candidate  $0^+$  state.

### 3.2 States in $^{136}\text{Xe}$

In semi-magic  $^{136}\text{Xe}$  ( $N = 82$ ), it is expected that we have a good understanding of the nuclear structure utilizing a

seniority scheme picture. Indeed, upon inspection of the Nuclear Data Sheets [11], it is clear that the majority of the expected lowest-lying structures have been identified. In the case of the excited  $0^+$ , which owes its origin to the  $(\pi d_{5/2})^2$  configuration, an assignment was made in an electron spectroscopy study, following  $\beta^-$  decay of  $^{136}\text{I}$  [12]. An E0 transition was observed at an energy of 2582 keV and a level was established at this energy and assigned  $J^\pi = 0^+$ . It was commented upon in that work that, expected, decays by  $\gamma$  ray emission to other excited states were not observed due to low detection efficiency. In the present experiment, one would expect to observe these  $\gamma$  rays.

The  $\gamma$ -ray spectrum, expanded around the region where one would expect to observe a 1269-keV  $\gamma$  ray to the  $2_1^+$  state, is shown in Fig. 4. No  $\gamma$  rays are observed in this energy region and we, therefore, call into question the assignment of the excited  $0^+$  in  $^{136}\text{Xe}$ .

## 4 Conclusion

Inelastic neutron scattering on enriched  $^{130}\text{XeF}_2$  and  $^{136}\text{XeF}_2$  scattering samples was used to obtain new information about the  $0^+$  states in both  $^{130}\text{Xe}$  and  $^{136}\text{Xe}$ . In  $^{130}\text{Xe}$ , one level (1590 keV) was eliminated from the level scheme and two other states were assigned  $J^\pi = 0^+$  for the first time. In  $^{136}\text{Xe}$ , doubt is cast upon the spin/parity assignment of the excited  $0^+$  state due to the absence of transitions to other excited states.

## Acknowledgments

This material is based upon work supported by the U.S. National Science Foundation under Grant no. PHY-1305801. The authors gratefully acknowledge H.E. Baber for his assistance in maintaining the UK accelerator.

## References

- [1] L. Coquard *et al.*, Phys. Rev. C **82**, 024317 (2010)
- [2] L. Betterman *et al.*, Phys. Rev. C **79**, 034315 (2009)
- [3] W.F. Mueller *et al.*, Phys. Rev. C **23**, 014316 (2006)
- [4] B.P. Kay *et al.*, Phys. Rev. C **87**, 011302 (2013)
- [5] B.P. Kay *et al.*, Phys. Rev. C **84**, 024325 (2011)
- [6] T. Bloxham *et al.*, Phys. Rev. C **82**, 027308 (2010)
- [7] F.T. Avignone, S.R. Elliott, I.J. Enge, Rev. Mod. Phys. **80**, 481 (2008)
- [8] B. Singh, Nuclear Data Sheets. **93**, 33 (2001)
- [9] S.A. Hamada *et al.*, J. Phys. G: Nucl. Phys. **14**, 1237 (1988)
- [10] W. Gelletly *et al.*, Phys. Rev. C **9**, 6 (1974)
- [11] A.A. Sonzogni, Nuclear Data Sheets. **95**, 837 (2002)
- [12] P.F. Mantica *et al.*, Phys. Rev. C **43**, 4 (1991)

