Investigation of pair-correlated $0^+$ states in $^{134}$Ba via the $^{136}$Ba($p$, $t$) reaction

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We performed a high resolution study of $0^+$ states in $^{134}$Ba using the $^{136}$Ba($p$, $t$) two-neutron transfer reaction. Our experiment shows fewer $0^+$ states than previously reported, with a significant portion of the $L = 0$ pair-transfer strength concentrated at excited $0^+$ levels in $^{134}$Ba. Potential implications in the context of $^{136}$Xe $\rightarrow$ $^{136}$Ba neutrinoless double beta decay matrix element calculations are briefly discussed.

The even-mass barium isotopic chain ($Z = 56$) is a fertile testing ground for nuclear structure models and also important for nuclear astrophysics studies and tests of fundamental symmetries. For example, theory calculations predict an enhanced octupole collectivity around $^{112}$Ba, which is located on the $N = Z$ line [1, 2]. Possible octupole correlations have been observed in the neutron-deficient $^{118}$Ba $^{[3]}$ and $^{124}$Ba $^{[4]}$ isotopes, while there is clear experimental evidence of octupole deformation in the ground states of neutron-rich Ba nuclei around $N = 88$ $^{[5]}$. Furthermore, for $N \leq 82$, in the $A \sim 130$ region, the even Ba isotopes are expected to be shape transitional $^{[7]}$. Their shape evolution ranges from nearly spherical (semi-magic at $N = 82$) to $\gamma$-soft $^{[8]}$, where the shape changes are characterized by quantum phase transitions (QPTs) $^{[9,10]}$. Within the interacting boson model (IBM), the $^{134}$Ba isotope was identified as a potential $E(5)$ symmetry critical point $^{[11]}$ for a second-order QPT. Independently, from a nuclear astrophysics perspective, fractional abundance ratios of odd-to-even barium isotopes as well as relative elemental ratios such as $[^{136}$Ba/$^{40}$Fe] and $[^{136}$Ba/$^{54}$Eu] etc, offer insight into the r and s-process neutron capture contributions $^{[12,13]}$ to heavy element nucleosynthesis in stellar environments. This is particularly relevant in metal-poor stars, where the dominant contribution to elemental abundances is expected to be from the r-process $^{[14]}$. One interesting example is the subgiant HD140283, in which case the fractional barium abundances obtained from independent spectral analyses have yielded inconsistent results. These discrepancies have stirred a debate on the assumed r-process origin of the odd Ba isotopes during the early stages of galactic evolution $^{[15,16]}.

Finally, $^{136}$Ba is the daughter nucleus in $^{136}$Xe double beta decay, an attractive candidate to search for the lepton-number-violating neutrinoless double beta ($0\nu 2\beta$) transformation. Observation of such decays would unequivocally show that the neutrinos are their own antiparticles (i.e. they are Majorana fermions). In such a scenario, other useful information on lepton-number-violating new physics or the absolute neutrino mass scale, etc. can only be obtained if the nuclear matrix element (NME) for the decay is accurately known $^{[20,21]}$. To this end, a variety of many-body techniques are used to evaluate $0\nu 2\beta$ decay NMEs in several candidate nuclei. These calculations have yielded significantly discrepant results for individual cases $^{[20]}$. Addressing this apparent model dependence in all double beta decaying nuclei remains an important issue. We focus on this aspect here.

The dominant contribution to a $0\nu 2\beta$ decay NME arises from the transformation of nucleon pairs that couple to total angular momentum $J = 0$ $^{[22,24]}$. Such a decay corresponds to spherical superfluid parent and daughter nuclei. The $J \neq 0$ contributions to the matrix element arise from higher seniority $^{[22,23]}$ components in the wavefunctions, due to broken Cooper pairs of nucleons. These lead to cancellations and effectively reduce the $0\nu 2\beta$ decay amplitude. An additional reduction in the NME is expected if there is a seniority mismatch between the initial and the final wavefunctions $^{[25]}$. This would be the case if the parent and the daughter have different intrinsic shapes $^{[20]}$, that are driven by multi-pole correlations. It is now established that these collective correlations (other than pairing) play an important role in $0\nu 2\beta$ NME calculations $^{[20]}$ and could further quench calculated NMEs $^{[20]}$. As examples, one can look at two traditionally used many-body methods, the Interacting Shell Model (ISM) and the Quasiparticle Random Phase Approximation (QRPA). In the former, the treatment of correlations is exact, with comparatively smaller valence spaces. On the other hand, the QRPA calculations use larger model spaces, with relatively simpler configurations for the valence nucleons. The pairing between like nucleons is treated via a transformation to the quasiparticle regime, within the Bardeen-Cooper-
Schrieffer (BCS) approximation \[27\]. Such BCS pairing smears the Fermi surfaces in the parent and the daughter (as one would expect in a superfluid), while the RPA correlations admix higher seniority components in the wavefunctions \[23, 25\]. In this context, \((p, t)\) \[28\] and \((^3\text{He}, n)\) \[29\] two-nucleon transfer experiments offer valuable insight into pairing correlations between like nucleons \[30\]. For reactions on even-even nuclei, strong population of the ground states (relative to excited 0\(^+\) states) would imply that both the target and residual nucleus ground states are nearly superfluid, and well described by BCS wavefunctions \[28, 30\].

For the case of \(^{136}\text{Xe} \rightarrow ^{136}\text{Ba}\), the 0\(\nu_2\beta\) decay NME differs more than a factor of four, depending on the many-body technique used \[31\]. This is an important issue as \(^{136}\text{Xe}\) decay is a promising candidate to search for 0\(\nu_2\beta\) decays \[31\]. In fact, several planned large-scale time projection chamber (TPC)-based experiments aim to measure \(^{136}\text{Xe} 0\nu_2\beta\) decay \[32, 35\]. From a nuclear structure perspective this is an interesting case, because of its location in a shape-transitional region of the Segrè chart. While the nearly spherical \(^{138}\text{Xe}\) has a closed shell at \(N = 82\), the daughter \(^{136}\text{Ba}\) has \(N = 80\).

In light of the above, we recently benchmarked the \(J = 0\) part of the \(^{136}\text{Xe} 0\nu_2\beta\) decay NME, via a study of neutron pairing correlations using the \(^{138}\text{Ba}(p, t)\) reaction \[31\]. Contrary to what one would expect for spherical superfluid systems \[30\], we observed for the first time a strong population of higher lying 0\(^+\) states, relative to the ground state in \(^{136}\text{Ba}\). Nearly 50\% of the ground state \(L = 0\) \((p, t)\) strength was distributed over excited 0\(^+\) states, with about 35\% concentrated at the \(0_1^+, 0_2^+\) and \(0_3^+\) levels. This was clear evidence of a breakdown of the BCS approximation for neutrons in \(^{136}\text{Ba}\). The results also implied significantly different ground state wavefunctions for the spherical \(^{138}\text{Ba}\) and the (final-state) \(^{136}\text{Ba}\) nuclei. If this were the case, one can expect nearly identical ground state wavefunctions for the \(N = 82\) \(^{138}\text{Ba}\) and \(^{136}\text{Xe}\) nuclei, a sizable difference in deformation (seniority mismatch) between the parent and the daughter in \(^{136}\text{Xe} \rightarrow ^{136}\text{Ba} \beta\beta\) decay cannot be ruled out.

Further investigations of shape-transitional barium isotopes around \(A \sim 130\) are relevant in context of the above. Previous data from \((p, t)\) reactions on barium isotopes show inconclusive evidence in this regard. For the \(^{136}\text{Ba}(p, t)\) case, Cáta-Danil \textit{et al.} \[30\] observe around 34\% of the ground state strength distributed over excited 0\(^+\) states in \(^{134}\text{Ba}\). However their measured \(L = 0\) strength distribution disagreed with subsequent work by Pascu \textit{et al.} \[37\]. In comparison, measured \(^{134,132,130}\text{Ba}(p, t)\) cross sections do not show a similar fragmentation of the monopole strength \[36, 39\].

In this paper we report remeasurements of the relative population of 0\(^+\) states in \(^{134}\text{Ba}\), with the \(^{136}\text{Ba}(p, t)\) reaction. The experiment was performed at the Maier-Leibnitz-Laboratorium (MLL), operated jointly by the Ludwig-Maximilian Universität (LMU) and Technische Universität München (TUM), in Garching, Germany. 22 MeV protons from the MLL tandem accelerator were directed onto a 40 \(\mu\text{g/cm}^2\), 93\% isotopically enriched \(^{136}\text{BaO}\) target, that was evaporated on a thin carbon foil. The light reaction products were momentum analyzed with the high-resolution Q3D magnetic spectrograph \[40, 41\]. The focal plane detector for the spectrograph comprised two gas proportional counters and a 7-mm-thick plastic scintillator \[41\]. The energy losses of the charged ejectiles in the proportional counters and the residual energy deposited in the plastic scintillator were used to discriminate the tritons from other ejectiles (as shown in Fig. \[1\]). A cathode strip foil in the second proportional counter provided high-resolution position information for the tritons.

We collected triton spectra at five magnetic field settings and at ten angles, ranging from 5\(^\circ\) to 50\(^\circ\) (in 5\(^\circ\) increments). The Q3D field settings allowed us to study excited states in \(^{134}\text{Ba}\) up to \(\sim 4.0\) MeV, with \(\lesssim 10\) keV energy resolution. The triton energies were calibrated.

![FIG. 1. Particle identification spectra using energy losses registered in the two proportional counters and the total energy deposited in the plastic scintillator. The triton groups are highlighted.](Image330x570 to 549x740)
in-situ, using well known states in $^{134}$Ba [42]. A sample spectrum is shown in Fig. 2.

During the course of the experiment, we also collected $^{136}$Ba($p,p$) data over an angular range of $10^\circ$–$60^\circ$. These elastic scattering data served to accurately determine the effective $^{136}$Ba areal density and also verify the appropriate global optical model potential (OMP) parameters for a distorted wave Born approximation (DWBA) analysis of the ($p,t$) angular distributions. Both the ($p,p$) and the ($p,t$) data sets were analyzed as described in Ref. [31], given the similarity between the two experiments. To summarize, these data were analyzed using the DWUCK4 code [43], with Woods-Saxon potentials and global OMP parameters. Based on our $^{136}$Ba($p,p$) data and the $^{135}$Ba($p,p$) analysis over a large angular range in Ref. [31], we chose the OMP parameters recommended by Varner et al. [44] for the incoming proton channel of the $^{136}$Ba($p,t$) DWBA analysis. For the triton channel we chose the OMPs recommended by Li, Liang, and Cai [45], as they resulted in a better agreement with our measured ground state angular distribution for $^{134}$Ba. This is shown in Fig. 3. The two-neutron transfer form factor was obtained using the OMPs from Ref. [48], assuming a $(0h_{11}/2)_2$ configuration. For each state, the depth of the potential was adjusted such that each transferred neutron had a binding energy $(S_{2n} + E_x)/2$, where $S_{2n}$ is the two neutron separation energy of $^{136}$Ba and $E_x$ is the excitation energy in the residual $^{134}$Ba nucleus.

The above DWBA prescription was used to perform an angular distribution analysis of all the peaks shown in Fig. 2 that corresponded to states in $^{134}$Ba. We identify six $0^+$ states in $^{134}$Ba. These include the ground state and a previously unreported level at 3528 keV.

1 An additional $0^+$ state is reported at 2379 keV [42], which was
TABLE I. Measured $L = 0$ $^{136}$Ba$(p, t)$ strength distribution over excited $0^+$ states in $^{134}$Ba, relative to the ground state. For comparison we also list the results from previous work [36, 37].

| $E_x$ [keV] | $\epsilon_l$ [%] | $E_x$ [keV] | $\epsilon_l$ [%] | $E_x$ [keV] | $\epsilon_l$ [%] |
|------------|---------------|------------|---------------|------------|---------------|
| 1759       | 3.73          | 1761       | 2.6(1)        | 1760       | 10.4(3)       |
| 2161       | 14.85         | 2159       | 8.8(3)        | 2159       | 16.8(5)       |
| 2336 ≤1.05 | ...           | ...        | ...           | ...        | ...           |
| 2327       | 0.52          | 2381$^a$   | 0.10(1)       | ...        | ...           |
| 2485       | 6.67          | 2488       | 2.2(1)        | 2488       | 8.0(3)        |
| 2722       | 1.99          | 2728       | 1.0(1)        | 2729       | 4.7(2)        |
| 2874       | 1.81          | 2884       | 0.8(1)        | ...        | ...           |
| ...        | ...           | 2961$^a$   | 0.10(1)       | ...        | ...           |
| 2996       | 0.63          | 3001       | 0.3(1)        | ...        | ...           |
| 3181       | 1.40          | ...        | ...           | ...        | ...           |
| ...        | ...           | 3395       | 0.10(1)       | ...        | ...           |
| 3501       | 1.47          | 3505       | 0.5(1)        | ...        | ...           |
| ...        | ...           | ...        | ...           | ...        | 3528 1.5(2)   |
| 3618       | 1.22          | 3624$^a$   | 0.4(1)        | ...        | ...           |
| ...        | ...           | 3750$^b$   | 0.2(1)        | ...        | ...           |

$\sum \epsilon_l = 34\%$ $\sum \epsilon_l = 17.1(4)\%$ $\sum \epsilon_l = 41.4(7)\%$

$^a$ These states were tentatively assigned with $J^p = 0^+$.  

The measured angular distributions are shown in Fig. 4. These data determined the monopole $(p, t)$ strengths to excited $0^+$ states, using the ratio [31]

$$\epsilon_i = \frac{\langle \frac{d\sigma}{d\Omega} \rangle_{0^+\text{ex}}}{\langle \frac{d\sigma}{d\Omega} \rangle_{\text{DWBA}}} \times \left( \frac{\langle \frac{d\sigma}{d\Omega} \rangle_{\text{G.S.}}}{\langle \frac{d\sigma}{d\Omega} \rangle_{\text{data}}} \right)_{0^+\text{ex}} $$

so that there was negligible contribution from the $Q$ value dependence on the cross sections.

The results are shown in Table I. We find that our extracted value for the integrated strength is more consistent with the result of Cátá-Danil et al. [30] and disagrees significantly with the later work of Pascu et al. [37]. It is also apparent that there are large discrepancies between our work and Refs. [36, 37] for individual states, and that we observe considerably fewer excited $0^+$ states. However, it is difficult to comment any further as both Refs. [36, 37] reported meager $^{136}$Ba$(p, t)$ angular distribution data. Cátá-Danil et al. acquired data at only two angles and chose to identify the $L = 0$ transitions using a single number, the ratio of the cross sections at $\theta_{lab} = 6^\circ$ and $15^\circ$. In comparison, Pascu et al. do not explicitly show relevant angular distribution plots, and used the same procedure to identify $0^+$ states. Adequate descriptions regarding the choice of OMP parameters for their analyses and the procedure to determine target thicknesses were not provided in these references.

It is evident from our results in Table I that a significant portion of the $(p, t)$ strength is distributed over three excited $0^+$ levels in $^{134}$Ba. This is similar to our previously reported $^{138}$Ba$(p, t)$ results [31] and clearly indicates a breakdown of the BCS approximation for neutrons in $^{134}$Ba. The persistence of such behavior (as one moves away from the closed shell at $N = 82$) highlights the shape-transitional nature of these isotopes, indicating significantly different deformations in the ground states of $^{138}$Ba, $^{136}$Ba and $^{134}$Ba. This implies a mismatch between the wavefunctions describing the initial and final states in $^{136}$Xe $\beta\beta$ decay, which would reduce the calculated $0\gamma/2\beta$ decay NME. Both experimental investigations of quadrupole correlations in $^{136}$Ba as well as theoretical studies of deformation effects on the NME (along the lines of Refs. [40, 50]) will be useful in this regard.

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