Structure of \(^{70}\text{Fe}\): Single-particle and collective degrees of freedom

A. Gade,\(^{1,2}\) R. V. F. Janssens,\(^{3}\) J. A. Tostevin,\(^{4}\) D. Bazin,\(^{1,2}\) J. Belarge,\(^{1,4}\) P. C. Bender,\(^{1,4}\) S. Botoni,\(^{5,4}\) M. P. Carpenter,\(^{5}\) B. Elman,\(^{1,2}\) S. J. Freeman,\(^{6}\) T. Lauritsen,\(^{7}\) S. M. Lenzi,\(^{7}\) B. Longfellow,\(^{1,2}\) E. Lunderberg,\(^{1,2}\) A. Poves,\(^{8}\) L. A. Riley,\(^{9}\) D. K. Sharp,\(^{6}\) D. Weisshaar,\(^{1}\) and S. Zhu\(^{5}\)

\(^{1}\)National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA

\(^{2}\)Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA

\(^{3}\)Department of Physics and Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599, USA

\(^{4}\)Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom

\(^{5}\)Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

\(^{6}\)School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom

\(^{7}\)Dipartimento di Fisica and Astronomia dell’Università, INFN, Sezione di Padova, I-35131 Padova, Italy

\(^{8}\)Departamento de Física Teórica e IFT-UAM/CSIC, Universidad Autónoma de Madrid, E-28049 Madrid, Spain

\(^{9}\)Department of Physics and Astronomy, Ursinus College, Collegeville, Pennsylvania 19426, USA

(Received 5 August 2018; revised manuscript received 28 September 2018; published 2 January 2019)

Excited states in the neutron-rich \(^{70}\text{Fe}\) nucleus were populated in a one-proton removal reaction from \(^{71}\text{Co}\) projectiles at 87 MeV/nucleon. A new transition was observed with the \(\gamma\)-ray tracking array GRETINA and shown to feed the previously assigned \(4^+\) state. In comparison to reaction theory calculations with shell-model spectroscopic factors, it is argued that the new \(\gamma\) ray possibly originates from the \(6^+\) state. It is further shown that the Doppler-reconstructed \(\gamma\)-ray spectra are sensitive to the very different lifetimes of the \(2^+\) and \(4^+\) states, enabling their approximate measurement. The emerging structure of \(^{70}\text{Fe}\) is discussed in comparison to LNPS-new large-scale shell-model calculations.

DOI: 10.1103/PhysRevC.99.011301

A goal of nuclear science is to achieve an understanding of nuclei and their properties rooted in the fundamental nucleon-nucleon interactions while demonstrating predictive power for the shortest-lived species located at the fringes of the nuclear chart. In the quest to extrapolate knowledge to the most neutron-rich systems, including those that may remain beyond the normal-order (spherical) ones \([1]\). Such islands of inversion are characterized by rapid structural changes and shape coexistence \([2,3]\), providing insight into nuclear structure physics far from stability \([4]\). \(^{70}\text{Fe}\) has 12 neutrons more than the heaviest stable iron isotope, whereas the heaviest one discovered to date is \(^{76}\text{Fe}\) \([5]\), a nucleus predicted to display collectivity and shape coexistence \([2]\) just two protons below \(^{78}\text{Ni}\). Indeed, within the iron isotopic chain, \(^{70}\text{Fe}\) is located on the path between the \(N = 40\) and \(N = 50\) islands of inversion \([2]\) with the latter remaining a challenge for next-generation rare-isotope facilities presently under construction. \(^{70}\text{Fe}\) has also been used as a seed nucleus in \(r\)-process calculations and associated sensitivity studies \([6,7]\). Spectroscopic information on \(^{70}\text{Fe}\), limited to the identification of two states, the first \(2^+\) level and another with a tentative \(4^+\) assignment, comes thus far from the population of excited states in \(\beta\) decay \([8]\) and a \((p,\,2p)\) reaction study \([9]\).

Here, we present the high-resolution spectroscopy of \(^{70}\text{Fe}\) in the direct one-proton removal reaction \(^{9}\text{Be}(^{71}\text{Co},\,^{70}\text{Fe} + \gamma)X\) at 87 MeV/u, leading to a newly observed \(\gamma\)-ray transition and the determination of partial cross sections. The latter are discussed quantitatively in comparison to eikonal reaction...
theory [10] with LNPS-new shell-model spectroscopic factors [11,11]. The rather simple $^{70}$Fe $\gamma$-ray spectrum observed with only three peaks is at odds with the predicted strong population of highly excited states. On the experimental side, we propose, as a solution to this puzzle, the so-called pandemonium effect [12] arising from a sizable fragmentation of the proton spectroscopic strength in $^{70}$Fe. This fragmentation is larger than predicted within the limited configuration spaces of shell-model calculations on the theoretical side. Although such challenges may actually be rather universal for $\gamma$-ray tagged direct reactions leading to collective even-even nuclei, it is argued that observables, such as yrast excitation energies and transition strengths, are nevertheless well described. From the present data, approximate lifetimes for the $2^+_\gamma$ and $(4^+_\gamma)$ states were extracted through a Doppler-shift analysis and found to be consistent with the results of LNPS-new shell-model calculations.

The $^{71}$Co secondary beam was produced from projectile fragmentation of a 140-MeV/u stable $^{82}$Se beam provided by the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory (NSCL) [13], impinging on a 444-mg/cm$^2$ $^9$Be production target and separated using a 240-mg/cm$^2$ Al degrader in the A1900 fragment separator [14]. The momentum acceptance of the separator was restricted to 2%, yielding on-target rates of typically 65 $^{71}$Co/s. About 9.5% of the beam was $^{71}$Co with $^{72,73}$Ni and $^{74}$Cu as the most intense components.

The secondary $^9$Be reaction target (376-mg/cm$^2$ thick) was located at the target position of the S800 spectrometer. Reaction products were identified on an event-by-event basis in the S800 focal plane with the standard detector systems [15]. The particle identification was performed with the measured energy loss and time-of-flight information as demonstrated in Ref. [16] for the equivalent reaction on a $^{61}$V projectile beam. The inclusive cross section for the one-proton removal from $^{71}$Co to $^{70}$Fe was deduced to be $\sigma_{\text{inc}} = 11.0(8)$ mb.

The high-resolution $\gamma$-ray detection system GRETINA [17,18], an array of 36-fold segmented high-purity germanium detectors grouped into modules of four crystals each, was used to measure the prompt $\gamma$ rays emitted by the reaction residues. The nine detector modules available at the time were detectors grouped into modules of four crystals each. One in a forward detector module was not working at almost 40% of the speed of light. The fact that the crystal in a forward detector module was not working was taken into account. The peak areas were determined from the spectrum of $^{70}$Fe without addback, avoiding uncertainties associated with the addback efficiency [18]. Partial proton-removal cross sections to the specific final states were determined from the efficiency-corrected $\gamma$-ray peak areas with discrete feeding subtracted relative to the number of incoming $^{71}$Co projectiles and the number density of the target: $\sigma(0^+) = 1.0(6)$, $\sigma(2^+) = 4.0(8)$, $\sigma(4^+) = 4.1(6)$, and $\sigma(J^+) = 1.85(30)$ mb.

One nucleon removal is a direct reaction with sensitivity to single-particle degrees of freedom. The cross sections for the population of individual $^{70}$Fe final states depend sensitively on the projectile to final-state one-body overlaps and on their normalizations, i.e., the spectroscopic factors [10]. Shell-model calculations with the LNPS-new effective interaction predict a $7/2^-$ $^{71}$Co ground state, in agreement with $\beta$-decay results [19], and a low-lying (200-keV) $1/2^-$ isomer that has not yet been observed.

Using the one-nucleon removal methodology detailed in Ref. [20] together with the LNPS-new [11,11] spectroscopic factors for incident $^{71}$Co in the $7/2^-$ and $1/2^-$ states, the partial cross sections to bound $^{70}$Fe shell-model final states...
were calculated and confronted with experiment in Fig. 2. With reference to the nucleon removal reaction systematics [21], a reduction factor $R_c = 0.4(1)$ was assumed between the calculated and the measured cross sections, based on the final-states yields-weighted proton separation energy $S_p \approx 18$ MeV, resulting in a proton and neutron separation energy asymmetry of $\Delta S = S_p - S_n \approx 12$ MeV for $^{71}$Co [22]. The presence of both the ground and the isomeric states in the incoming $^{71}$Co beam cannot be ruled out and the measured cross-section distribution may correspond to a linear combination of both.

For both possible initial states, the predicted population pattern is at odds with that measured and with the simple $\gamma$-ray spectrum observed. A strong population of high-lying states, such as the $6_2^+$, $4_1^+$, or $3_1^+$ levels, would lead to the presence of several strong additional transitions, connecting the populated high-lying states to the level scheme reported here. For each assumed $^{71}$Co initial state, the sums of the partial cross sections to all bound shell-model final states below $S_n = 5.32(64)$ MeV [22] are $\sigma_{inc}^{7/2^-} = 15.6(40)$ and $\sigma_{inc}^{1/2^-} = 11.6(30)$ mb, slightly higher than the measured inclusive cross section of $\sigma_{inc} = 11.0(8)$ mb.

The apparent simplicity of the observed population of final states in $^{70}$Fe is rather puzzling. We note that the $\gamma$-ray spectrum reported here is consistent with that reported from the $(p,2p)$ reaction where no $\gamma$ rays other than those associated with the $2_1^+ \rightarrow 0_1^+$ and $(4_1^+ \rightarrow 2_1^+$ transitions were observed [9]. Although the cross sections from our $^8$Be-induced proton removal and $(p,2p)$ may differ quantitatively, qualitatively they would populate the same proton-hole configurations, and the respective cross sections should scale with the same spectroscopic factors. The modest energy resolution accomplished with a scintillator array in the $(p,2p)$ measurement of Ref. [9] likely prevented the identification of the (weak) 1110-keV peak due to a disadvantage in the peak-to-background ratio. However, their superior detection efficiency should have enabled the clear observation of intense feeding transitions from high-lying states in view of their predicted strong population. Such concentration of proton spectroscopic strength in low-lying yrast states in the $N = 40$ region has also been reported for other proton removal reactions leading to $^{66,68}$Fe [23], $^{60}$Ti [16], and $^{72}$Fe [9].

One must consider the pandemonium effect [12], a situation where modestly efficient $\gamma$-ray spectroscopy of discrete transitions misses the population of high-lying states ultimately deexciting to the yrast states through a large number of weak transitions. This effect, thus, attributes high-lying strengths to the yrast states that act as collectors for weak feeding transitions escaping observation. This is a possibility given the extreme level density predicted by the shell model— with more than 100 states below $S_n = 5.32$ MeV in $^{70}$Fe—but would actually require a larger fragmentation of the strength than that predicted. Specifically, further fragmentation would be expected beyond that to one or two high-lying states as the latter would certainly have their strongest transitions observed. Such a scenario of sizable fragmentation could also explain the slight mismatch between the calculated and measured inclusive cross sections as increased fragmentation would likely shift spectroscopic strength to energies beyond $S_n$. Hence, an understanding of spectroscopic strengths in even-even nuclei of the $N = 40$ island of inversion may demand yet larger model spaces and more complex mixed configurations, requiring the inclusion of orbitals beyond $v_{9/2}$ and $v_{15/2}$ that were already identified as critical for describing the region [1]. Assuming such an interpretation of the present data, we suggest the newly established level at 2448(4) keV to correspond to the $(6_1^+)$ state or a higher-lying $4^+$ state. The energies of the transitions from the $2^+$ and $4^+$ states reported in the $\beta$-decay work [8] were used here to deduce the level energy due to a significant sensitivity to excited-state lifetimes in the present in-beam data as discussed below. For the two possible $^{71}$Co initial states, the strongly populated $6^+$ levels (7/2− initial state) and $4^+$ and $3^+$ levels (1/2+ isomeric initial state) would, in a pandemonium picture, ultimately feed into the yrast $6_1^+$ and $4^+$ states. We note the very good agreement with the LNPS-new shell-model calculation that places the $6_1^+$ state at 2.48 MeV within 30 keV of the measured value proposed here, whereas the closest higher-excited $4^+$ level is predicted to be located 200 keV higher.

Unlike any other shell-model effective interaction for this mass region, LNPS (new) [1,11] has demonstrated predictive power for collective observables, such as for the $B(E2)$ transition strengths and energies of the lowest-lying $2^+$ and $4^+$ states [1,9,16,24,25]. For the measurements reported here,
the γ-ray spectra reveal effects attributed to excited-state lifetimes that can inform on the expected collectivity of 70Fe. The inset of Fig. 3(a) demonstrates a distinct shift in energy of the 2+ transition detected in the GRETINA detectors mounted in the 58° and 90° rings when corrected for the Doppler shift assuming the midtarget beam velocity. This indicates that the 2+ state decays on average with a velocity lower than the mid-target one, i.e., when the 70Fe ions lost more energy. This is also the reason for the mismatch between the transition γ-ray energy reported here and that from β decay, 477 vs 483 keV. Using GEANT [26], the lifetimes can be determined by matching to simulations the peak shapes and peak positions observed in detector groups at different polar angles, such as forward and 90°. We note that for long lifetimes the peak shape and peak position are impacted whereas shorter lifetimes largely affect the peak position only. Essential for this simulation is the precise knowledge of the transition energy and the target position along the beam axis. A target offset of 0.3(3) mm downstream from the center of GRETINA was determined with the help of a known γ-ray transition in a contaminant. This value is small as compared to the actual ≈2-mm target thickness. Using the transition energies of 483 and 855 keV from β decay [8] and the target offset, effective lifetimes for the 2+ and 4+ states were extracted from a logarithmic-likelihood minimization procedure that takes into account the feeding by the 4+ level (the 1110-keV transition was too weak for such an analysis and was assumed to be prompt). The results are shown in Fig. 3 where the spectra for each ring of GRETINA are overlaid with the GEANT simulation that minimized the negative logarithmic-likelihood surface, given as an inset [Fig. 3(b)]. To illustrate the sensitivity of the present measurement to the different lifetimes in more detail, Fig. 4 provides simulated line shapes for the two transitions of interest for various lifetime values. For longer lifetimes, the primary sensitivity is to the tails of the spectrum (strong tails) and short τ(4+) (shifting peak position — indicated by vertical lines) values.

FIG. 3. Doppler-corrected γ-ray spectra from GRETINA’s forward (58°) and 90° rings (v/c = 0.384; the 4+ → 2+ transition lines up in both rings). A significant energy difference is observed for forward (58°) and peak positions observed in detector groups at different polar angles, such as forward and 90°. We note that for the 2+ → 0+ transition at the mid-target v/c (top inset). Overlaid are GEANT simulations that minimize a negative logarithmic-likelihood surface (bottom inset) of a fit to a large set of simulated lifetimes properly accounting for the 4+ feeding of the 2+ state.

FIG. 4. Line shapes simulated with GEANT for different lifetimes of the 2+ → 0+ transition in the (a) forward and (b) 90° detectors and for various lifetimes of the (4+ → 2+) transition in the (c) forward and (d) 90° detectors (v/c = 0.384). This illustrates the specific sensitivities that the present measurement exhibits for the long τ(2+) (strong tails) and short τ(4+) (shifting peak position — indicated by vertical lines) values.

...
STRUCTURE OF $^{70}$Fe: SINGLE-PARTICLE AND COLLECTIVE OBSERVABLES

To summarize, high-resolution in-beam $\gamma$-ray spectroscopy with GRETINA was performed for the neutron-rich nucleus $^{70}$Fe following one-proton removal from $^{71}$Co projectile with GRETINA was performed for the neutron-rich and line shapes.

To account for the marked discrepancy between measured and calculated population patterns: These present a challenge to the shell-model description if the newly discovered level state at $2.448(4)$ MeV to the $(4^+ 1) \rightarrow 2^+_1$ cascade is found to agree well with the shell-model description if the newly discovered level is the $6^+_1$ state. The pandemonium effect and an implied large fragmentation of spectroscopic strength are proposed

This work was supported by the U.S. National Science Foundation (NSF) under Cooperative Agreement No. PHY-1565546 (NSCL) and Grant No. PHY-1617250 (Ursinus), by the U.S. Department of Energy (DOE) National Nuclear Security Administration under Awards No. DE-NA0003180 and No. DE-NA000979, and by the DOE-SC Office of Nuclear Physics under Grants No. DE-FG02-08ER41556 (NSCL), No. DE-FG02-97ER41401 (UNC), No. DE-FG02-97ER41403 (TUNL), and No. DE-AC02-06CH11357 (ANL). GRETINA was funded by the DOE, Office of Science. Operation of the array at NSCL was supported by the DOE under Grants No. DE-SC0014537 (NSCL) and No. DE-AC02-05CH11231 (LBNL). J.A.T., S.J.F., and D.K.S. acknowledge support from the Science and Technology Facilities Council (U.K.) Grants No. ST/L005743/1 and No. ST/L005794/1, respectively. We also thank T. J. Carroll for the use of the Ursinus College Parallel Computing Cluster, supported by NSF Grant No. PHY-1607335. A.P. was supported, in part, by MINECO (Spain) Grant No. FPA2014-57196 and the Severo Ochoa Programme No. SEV-2016-0597.


This work was supported by the U.S. National Science Foundation (NSF) under Cooperative Agreement No. PHY-1565546 (NSCL) and Grant No. PHY-1617250 (Ursinus), by the U.S. Department of Energy (DOE) National Nuclear Security Administration under Awards No. DE-NA0003180 and No. DE-NA000979, and by the DOE-SC Office of Nuclear Physics under Grants No. DE-FG02-08ER41556 (NSCL), No. DE-FG02-97ER41401 (UNC), No. DE-FG02-97ER41403 (TUNL), and No. DE-AC02-06CH11357 (ANL). GRETINA was funded by the DOE, Office of Science. Operation of the array at NSCL was supported by the DOE under Grants No. DE-SC0014537 (NSCL) and No. DE-AC02-05CH11231 (LBNL). J.A.T., S.J.F., and D.K.S. acknowledge support from the Science and Technology Facilities Council (U.K.) Grants No. ST/L005743/1 and No. ST/L005794/1, respectively. We also thank T. J. Carroll for the use of the Ursinus College Parallel Computing Cluster, supported by NSF Grant No. PHY-1607335. A.P. was supported, in part, by MINECO (Spain) Grant No. FPA2014-57196 and the Severo Ochoa Programme No. SEV-2016-0597.