Collectivity of Exotic Heavy Fe Isotopes

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Abstract.

The properties of exotic neutron-rich nuclei between the proton shell closures $Z = 20$ and $Z = 28$ are of particular interest for the understanding of the shell structure for large neutron excess. Effects related to the energy gap between the neutron $fp$ and $1g_9/2$ shells lead to a strong variation of collectivity for nuclei around $N = 40$. Whereas $^{68}$Ni was found to have doubly magic properties, this was not observed in neighbouring nuclei. Recent shell model calculations for the neutron rich iron isotopes clearly reveal the difficulty to describe nuclei in this mass region and resulted in large deviations of the predicted collectivity depending on the valence space. However, no experimental data on the transition strength existed for the very exotic nucleus $^{66}$Fe at $N = 40$. Here we present the newest results on absolute transition strengths of the lowest excited states in $^{62,64,66}$Fe measured model independently using the recoil distance Doppler-shift (RDDS) method. The experiments were performed at NSCL at Michigan State University with the Cologne/NSCL plunger device using Coulomb excitation in inverse kinematics at energies of 80 MeV/u. Our results yield a much higher collectivity for $^{64,66}$Fe than expected and allow tests of new calculations.

1. Introduction

The investigation of collectivity is crucial for understanding the nuclear properties especially in exotic regions, i.e., in nuclei with extreme ratios of protons and neutrons. It was already shown that shell structures can change under such conditions as functions of the neutron and proton numbers [1, 2]. Collectivity is correlated with the dimension of the valence space. By measuring the collectivity of an atomic nucleus we can learn about the validity of magic numbers
in such exotic regions. Subshell closures influence nuclear structure too, which can also lead to nuclei with doubly magic characteristics. But in many cases such subshell closures can be absent already in neighboring nuclei and collectivity is observed.

In even-even nuclei the quadrupole collectivity is related to the reduced transition probability of the $2^+_1$ state to the ground state $B(E2, 2^+_1 \rightarrow 0^+_1)$. In this work we investigate the neutron rich nuclei $^{62,64,66}$Fe. The key issue is the degree of quadrupole collectivity in $^{66}$Fe due to the $N = 40$ harmonic oscillator shell closure. A doubly magic character was observed in $^{68}$Ni [3]. Only nickel isotopes show typical signatures of magicity with a high excitation energy of the $2^+_1$ state and a low $E2$ excitation strength of this state both for $Z = 28$ and $N = 40$ as compared to the neighboring isotopes of iron, chromium, selenium, and krypton. If the $N = 40$ shell closure is absent in $^{66}$Fe, maximum collectivity is expected for this nucleus relative to the other iron isotopes. This is because this nucleus lies midshell regarding the magic neutron numbers $N = 28$ and $N = 50$. The low excitation energy of the $2^+_1$ state in $^{66}$Fe of 575 keV [4] (as compared to $E(2^+_1) = 2034$ keV in $^{68}$Ni) already indicates a fragility of the $N = 40$ subshell closure in $^{66}$Fe. In addition, an increase of the $B(E2, 2^+_1 \rightarrow 0^+_1)$ values was already identified from $^{62}$Fe to $^{64}$Fe [5]. However, for a proof of the absence of the $N = 40$ shell closure in iron isotopes the $B(E2, 2^+_1 \rightarrow 0^+_1)$ value in $^{66}$Fe has to be measured.

In the present work we investigate the quadrupole collectivity in the exotic neutron rich isotopes $^{62,64,66}$Fe from absolute $E2$ transition strengths of the $2^+_1$ state. Further, we aim at the investigation of the underlying symmetry inferred from the excitation energies of the $2^+_1$ state of nuclei in the vicinity of the $Z = 28$ shell closure. The excitation energies of nuclei in this region hint at a symmetry relative to $Z = 30$ rather than to the magic number $Z = 28$. The transition strengths determined in this work allow clear evidence for this symmetry relative to $Z = 30$ as is pointed out in section 3.

2. Experiment

The experiments were performed at the NSCL coupled cyclotron facility of Michigan State University. A $^{76}$Ge beam with an energy of 130 MeV/u was produced by the coupled cyclotrons impinging on a 277.82 mg/cm$^2$ $^9$Be production target. The resulting secondary beam was purified with the A1900 fragment separator [6] resulting in a $^{62}$Fe beam with a purity of about 85%, an energy of 97.8 MeV/u and a rate of $3.4 \times 10^4$ pps. For $^{64}$Fe ($^{66}$Fe) a beam with about 65% (25%) purity, $6 \times 10^3$ pps ($1 \times 10^3$ pps) and 95.0 MeV/u (88.3 MeV/u) was produced. These beams were focussed on the Cologne/NSCL differential plunger device mounted at the target position of the S800 mass spectrograph [7] which served to identify scattered particles. The beam nuclei were Coulomb excited in a 300 µm thick Au plunger target and degraded in a 300 µm ($^{62,66}$Fe) and 400 µm ($^{64}$Fe) thick Nb foil, respectively. Lifetimes of excited states were measured with the recoil distance Doppler-shift method (RDDS). The high potential of the combination of these experimental methods was proven in earlier experiments [8, 9]. Typical recoil velocities were in the case of $^{64}$Fe $v/c = 0.354$ between target and degrader and $v/c = 0.298$ after the degrader. Doppler shifted $\gamma$ rays were observed with the Segemented Germanium Array (SeGA). The 15 32-fold segmented HPGe detectors were mounted in two rings under angles of 30° and 140° relative to the beam axis. Data were taken using the NSCL digital data acquisition system [10]. Spectra of Doppler-shifted $\gamma$-rays of the deexcitation of the $2^+_1$ states in these nuclei were measured at 5–7 different target–degrader distances between 0 and 20 mm. The data at large distances were used to examine contributions from Coulomb excitation in the degrader [8, 11].

The lifetimes of the $2^+_1$ states in $^{62,64,66}$Fe were obtained by a simultaneous fit to the fast and slow components of the emitted $\gamma$-ray lines where a simulation characterizes the line shape [8, 11]. Details of the lineshape analysis can be found in [12]. Fig. 1 shows spectra of the $2^+_1 \rightarrow 0^+_1$ decay transition for the isotopes of interest for different target–degrader distances including the fits of the line shapes. Absolute $E2$ transition strengths of the $2^+_1$ states in $^{62,64,66}$Fe were determined.
Figure 1. Spectra of $^{62-66}$Fe for different target–degrader distances in the range of the fully Doppler-shifted and degraded component of the $2^+_1 \rightarrow 0^+_1$ transition under a forward angle of 30 degrees relative to the beam axis. The blue lines give the simulation that characterizes the line shapes.

from level lifetimes.

3. Discussion

With the new data on the $2^+_1 \rightarrow 0^+_1$ transition strengths in $^{62,64,66}$Fe we can investigate the evolution of collectivity for even-even nuclei with $Z = 24 – 36$ and $N = 22 – 58$. Fig. 2 illustrates the experimental results on the $B(E2, 2^+_1 \rightarrow 0^+_1)$ values of iron, chromium, nickel, and zinc in the vicinity of $N = 40$ including the new results on $^{62,64,66}$Fe from this work (red stars). In addition, Fig. 3 gives the excitation energies of the $2^+_1$ states in these nuclei. Only the nickel isotopes show characteristics of shell closures both at $N = 28$ and $N = 40$ due to small transition strengths of the $2^+_1$ state and high $2^+_1$ excitation energies. In all other isotopes with $Z = 26 – 36$ the $N = 40$ shell closure vanishes. The new data confirm the increase of collectivity in $^{62,64}$Fe from [5] and provide a first evidence that enhanced collectivity persists in $^{66}$Fe. This is obvious from the large $E2$ transition strength and the low excitation energy even though its closeness to $^{68}$Ni$_{40}$ with pronounced doubly magic character.

An interesting feature is further notable in Fig. 3. Clear similarities are visible when comparing the excitation energies of isotones of iron (Fe, $Z = 26$) and selenium (Se, $Z = 34$), for chromium (Cr, $Z = 24$) and krypton (Kr, $Z = 36$), and for zinc (Zn, $Z = 30$) and germanium (Ge, $Z = 32$). These isotopic chains show a similar behavior regarding the (low) excitation energy of the $2^+_1$ state and thus a similar high collectivity is foreseen. More important to note is the similar characteristics of pairs of isotopic chains: For the Fe/Se chains a decrease of $E(2^+_1)$ starts at $N = 36$, for Cr/Kr already at $N = 32$ and for Zn/Ge at $N = 38$, whereas even the excitation energies of the $2^+_1$ states in the corresponding isotones are nearly identical. However, this observation is in contradiction to the concept of the valence proton symmetry (VPS) [15, 8]
Figure 2. $B(E2, 2_1^+ \rightarrow 0_1^+)$ systematics for nuclei in the vicinity of $N = 40$. The large $E2$ transition strength in $^{66}$Fe gives evidence for an enhanced collectivity in this nucleus. Data for $^{62,64,66}$Fe from this work are displayed as red squares.

Figure 3. Excitation energies of the $2_1^+$ states for nuclei in the nickel region. The low $2_1^+$ excitation energy in all isotopes with $N = 40$ besides $^{68}$Ni hints for the fact that the $N = 40$ shell closure vanishes in all these nuclei. Data for $^{64}$Cr are from [13], for $^{68}$Fe are from [14].

around the shell closure $Z = 28$ but rather gives a hint to a symmetry relative to $Z = 30$ as will be pointed out in more detail below. The VPS concept correlates a pair of isotones with the same number of valence proton particles and holes with respect to a closed shell. The same valence space results in a similar collectivity. The validity of this concept was investigated in detail for nuclei in the vicinity of the $Z = 50$ shell closure, e.g., in the palladium/xenon isotopes [8].

To identify a possible VPS around $Z = 30$ rather than $Z = 28$ for neutron rich nuclei in this region we can now relate the new $B(E2, 2_1^+ \rightarrow 0_1^+)$ values for $^{62,64,66}$Fe from this work to the values known for neighboring isotopes. Fig. 4 depicts these values for the chromium, iron, selenium, and krypton isotopes where the values for selenium and krypton were scaled with the
Figure 4. Comparison of $B(E2, 2^+_1 \rightarrow 0^+_1)$ values of the iron (Fe) and chromium (Cr) isotopes with the scaled values of selenium (Se) and krypton (Kr). As it is the case for the $2^+_1$ excitation energies, a similarity is visible when comparing the $E2$ strengths of the isotonic pairs of Fe/Se and Cr/Kr.

scaling factor [15]

$$S = \left( \frac{Z_L}{Z_H} \right)^2 \cdot \frac{A_L}{A_H} \quad (1)$$

to compensate for charge and mass differences. $A_{L,H}$ and $Z_{L,H}$ are mass and charge numbers of the lighter and heavier nuclei in the corresponding VPS pairs, respectively.

It is notable from Fig. 4 that analogies exist for the pairs of isotones that also show similar characteristics regarding the $2^+_1$ excitation energies. Similar to the situation for the $2^+_1$ excitation energies an increase of collectivity is clearly observable from the transition strengths for iron and selenium for $N = 36$, where for the pairs of chromium and krypton this increase might start beyond $N = 32$. However, in the latter case the lack of experimental data for the $B(E2, 2^+_1 \rightarrow 0^+_1)$ values for the chromium isotopes with $N > 34$ and krypton isotopes for $N < 36$ prevents a clear statement.

As pointed out this observation for both the transition strengths and the $2^+_1$ excitation energies gives evidence for a symmetric behavior relative to the proton number $Z \approx 30$. Thus an explanation within a generalized concept of the VPS is feasible where a change of the magic number $Z = 28$ to $Z \approx 30$ appears in this region of neutron rich nuclei. Details will be published in [12]. This symmetric evolution around $Z = 30$ can be explained in the framework of the nuclear shell model. We consider proton holes in the $1f_7/2$ orbital below $Z = 28$ and protons in the $1f_5/2$ orbital above the $Z = 32$ subshell closure. The $2p_3/2$ orbital is isolated between the $1f_7/2$ and $1f_5/2$ orbitals. The $2p_3/2$ orbital, if it is fully occupied, has no impact on the evolution of collectivity. Thus the effect of a fully empty or fully occupied $2p_3/2$ orbital is identical regarding the VPS and consequently selenium can be the VPS partner of iron and krypton the VPS partner of chromium. This leads to a VPS symmetry around $Z = 30$.

A shell model calculation with the new effective LNPS interaction explains the trends of the $B(E2, 2^+_1 \rightarrow 0^+_1)$ values for $^{62,64,66}$Fe well. A detailed discussion of this calculation will be done in a forthcoming article [12].

A further hint for the enhanced collectivity observed for $^{64,66}$Fe is revealed from a closer look in the shell structure in this region. As pointed out in [16] for the neutron-rich copper isotopes $^{71,73,75}$Cu the observed lowering of the $5/2^+_1$ level with increasing neutron number
with the occupation of the proton $1f_{5/2}$ orbital was attributed to a strong attractive monopole interaction that becomes active when neutrons occupy the $1g_{9/2}$ orbital [17]. This can lead to a rather collective nature of the resulting states which could also explain the observed collectivity in $^{64,66}$Fe.

4. Conclusion

To conclude, we measured the lifetimes of the $2^+_1$ states in the exotic neutron rich iron isotopes $^{62,64,66}$Fe with Coulomb excitation in inverse kinematics with the recoil distance Doppler-shift method and the Cologne/NSCL differential plunger. The experiments were performed at the NSCL coupled cyclotron facility at Michigan State University. Absolute transition strengths of the $2^+_1 \to 0^+_1$ transitions in these nuclei were determined from level lifetimes. These data yielded a high collectivity for the neutron rich iron isotopes. Especially $^{66}$Fe, which is close to $^{68}$Ni, with doubly magic characteristics, depicts a high degree of collectivity.

The results were related to those of neighboring nuclei. An application of the concept of the VPS yielded the need to generalize this concept. It turned out that a valence proton symmetry exists in this region with respect to $Z \approx 30$ rather than $Z = 28$. An interpretation of this observation within the shell model is possible and details will be presented in a forthcoming article [12].

This work was supported by the DFG under Contract DE1516/1-1 and partly under JO391/4-1 and by the U.S. NSF under Grant PHY-0606007.

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