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Systematic Studies Of $E0$ Transitions In ^{54,56,58}Fe

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Doubly magic nuclei and their near neighbours serve as an ideal testing ground for the nuclear shell model, and, consequently, enable us to define effective nuclear interactions. Collective states in nuclei near ^{56}Ni can be attributed to multiparticle-multihole excitations from the $1f_{7/2}$ to the $2p_{3/2}$, $1f_{5/2}$ and $2p_{1/2}$ orbits across the $N, Z = 28$ shell gap. These features are usually associated with shape coexistence. Properties of excited 0^+ states, as well as $E0$ and $E2$ transition strengths are sensitive probes of the underlying nuclear structure. The aim of this work is to identify and characterize excited 0^+ states and corresponding $E0$ transitions in ^{54,56,58}Fe to search for shape coexistence around the $N, Z = 28$ shell closure. In order to obtain experimental information, $E0$ transitions between the lowest excited 0^+ states and ground states were measured for the stable even-even iron isotopes using the superconducting electron spectrometer ,"Super-e", at the Australian National University. Additional information on angular distributions, angular correlations, and $\gamma-\gamma$ coincidences was obtained with the CAESAR detector array (at ANU) under the same experimental conditions. In order to deduce $E0$ strengths, the experimental data were evaluated with lifetime information from Doppler-shift attenuation measurements following inelastic neutron scattering, carried out at the University of Kentucky.

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1. Shape coexistence and *E*0 transitions

Shape coexistence is related to multiparticle-multihole (*mp-mh*) excitations across nuclear shell gaps, causing deformation of the nuclear distribution. Shape coexistence is now believed to occur all over the nuclear chart, but is more prominent around closed major shells where the energy gaps are greater. In a deformed nuclear potential, the single-particle energy is lowered for certain orbitals and raised for others. The type and degree of deformation determine how the shell structure is altered. The attractive neutron-proton interaction drives deformation and compensates for the relatively large energy for the excitation to occur in the spherical frame. This lowers the observed energy of the final state and these types of excitations may thus become energetically favourable, particularly around large energy gaps. Further, multinucleon excitations generally couple to spin zero, and low-lying excited 0^+ states are associated with shape coexistence. Shape-coexisting states studied from single-particle and collective points of view are likely to lead towards a unified description, and a better understanding of nuclear interactions. Readers are referred to a detailed review on shape coexistence in Ref. [1]. It is natural that the mean-square radius of a nucleus changes when its intrinsic shape is altered following an excitation (or de-excitation). Electric monopole transitions are directly related to changes in the mean-square charge radius, i.e., the *E*0 strength is defined by the difference in mean-square charge radii between the initial and final configurations. Hence, large *E*0 strengths indicate large differences in the mean-square radii, and are useful probes of shape coexistence. However, the electric monopole strength also depends on the mixing of the two shape-coexisting configurations [2]. This means that even with a large difference in mean-square radii between two configurations, the *E*0 strength could be vanishingly small due to weak mixing. It is therefore important to note that while large *E*0 strengths indicate shape coexistence, small *E*0 strengths do not contradict its occurrence.

2. Experiments

The electric monopole transtitions were measured with the superconducting electron spectrometer, "Super-e" [3], at the Heavy Ion Accelerator Facility at the Australian National University (ANU). Both conversion electrons and electron-positron pairs were measured. The setup consists of a 2.1-T superconducting solenoid, an axially-symmetric baffle system, and a six-fold 9-mm thick Si(Li) detector array at the end. The baffle system shields the detector against γ rays, but allows for transport of emitted conversion electrons and e^-e^+ pairs by the magnetic field. The spectrometer is illustrated in Fig. 1. Particles reaching the detector are confined within a momentum window, defined by the magnetic field, particle energy and characteristics of the baffle system, i.e., the measured energy range is defined by the magnetic field. The momentum window increases with energy, and the relative detec-

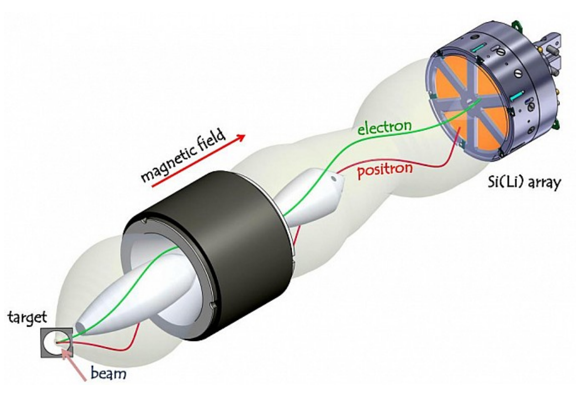

Figure 1: Illustration of the "Super-e" spectrometer.

tion efficiency follows likewise. Figure 2 shows the calculated single-electron detection efficiency along with a ^{170}Lu source measurement. The relative pair detection efficiencies depend on the

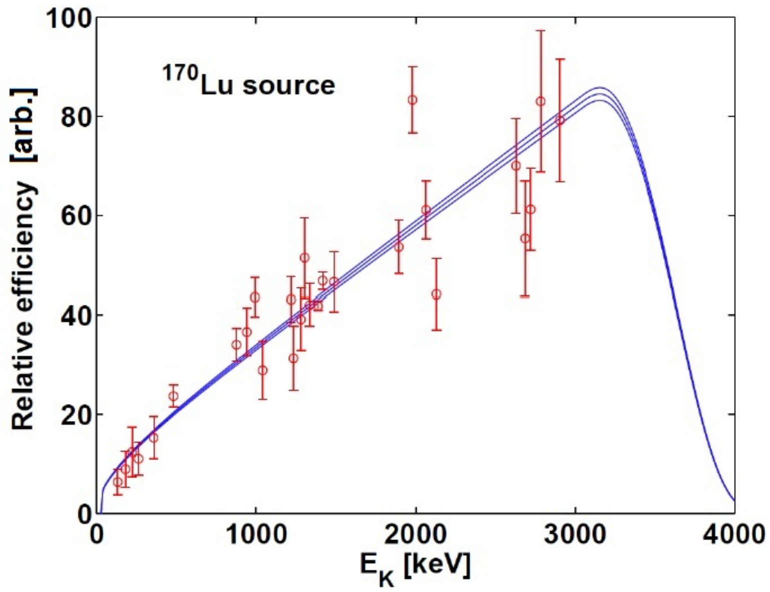

Figure 2: Calculated single electron efficiency (solid line) and a ^{170}Lu source measurement (data points).

separation angle, θ_s, and the energy distribution of the pair, given in terms of positron energy, E_{e^+}. The pair efficiencies were evaluated with Monte Carlo simulations, which took into account the double-differential pair-emission probabilities (θ_s, E_{e^+}), the transmission of the spectrometer, and the geometry of the detector array. The double-differential probabilities were calculated within the Born approximation with a Coulomb correction [4, 5, 6, 7]. The total absolute efficiency of the setup is 3% of 4π for single-electron events, and the detector array fully stops electrons/positrons up to a kinetic energy of 3.5 MeV.

The excited states of ^{54,56,58}Fe were populated using (p, p') scattering at beam energies of 6.9 MeV (^{54}Fe), 6.7 MeV (^{56}Fe) and 7.0 MeV (^{58}Fe). The $\sim$1 mg/cm^2 target foils were positioned at 45° relative to the beam direction, to optimize the production rate and emission towards the spectrometer, which was mounted perpendicular to the beam line. In addition to the spectrometer setup, a HPGe detector located $\sim$1.5 m from the target was used for monitoring γ rays. The magnetic field was controlled by a computer, and a Hall probe was used for monitoring it. Sampling time was determined from the integrated beam current in the beam dump. The events were sorted offline, and the spectra were deduced with gates on the momentum window.

In addition to the conversion electron and pair measurements, angular distributions, angular correlations, and $\gamma - \gamma$ coincidences were obtained with the CAESAR array, also at ANU. The CAESAR array consists of nine Compton-suppressed and two unsuppressed HPGe detectors, the latter optimised for low-energy γ rays and X rays. In this experiment, eight of the nine Compton-suppressed detectors were in operation.

The necessary lifetime information was obtained from Doppler-shift attenuation measurements following inelastic neutron scattering (DSAM-INS) [8], carried out at the University of Kentucky. These lifetimes were used to deduce monopole strengths of the measured $E0$ transitions.

3. Results

This work is focused on the first excited 0^+ states of ^{54,56,58}Fe. In the case of ^{54}Fe, which has a relatively clean energy spectrum (Fig. 3), the $E0$ transition from the second excited 0^+ state to the ground state was also measured. This is the first observation of this transition to our knowledge.

All three iron isotopes in question have the 2_1^+ state located between the 0_2^+ state and the 0_1^+

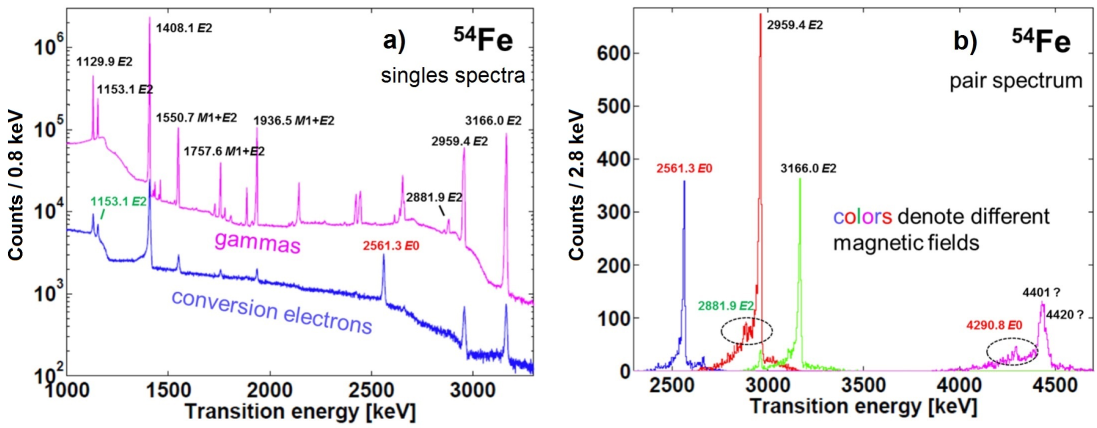

Figure 3: Measured energy spectra for ^{54}Fe. Panel a) shows γ-ray and singles e$^-$ spectra, and panel b) shows the pair spectrum.

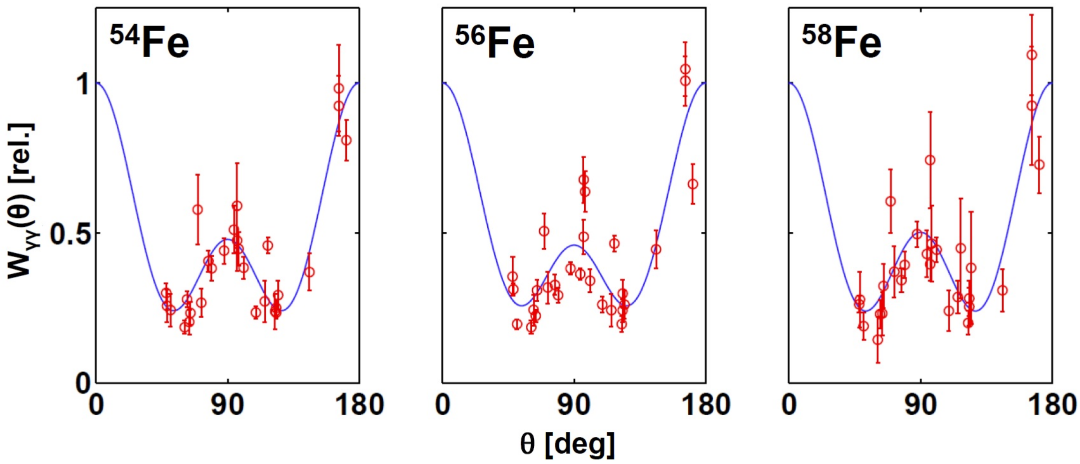

Figure 4: Angular correlations for the $0_2^+ \rightarrow 2_1^+ \rightarrow 0_1^+$ cascade in the three iron isotopes.

ground state, hence $0_2^+ \rightarrow 2_1^+$ $E2$ transitions were available for the analysis. Figure 4 shows angular correlations from CAESAR for the $0_2^+ \rightarrow 2_1^+ \rightarrow 0_1^+$ transitions in the three isotopes. The angular correlations were fitted with the following formula

$$W_{\gamma\gamma}(\theta) = N\left(1 + a_2\cos^2(\theta) + a_4\cos^4(\theta)\right) , \tag{3.1}$$

where a_2 and a_4 are fit parameters, and N is a scaling factor. The fit coefficients tabulated in Tab. 1 agree well with $a_2 = -3$ and $a_4 = 4$ corresponding to a $0^+ \rightarrow 2^+ \rightarrow 0^+$ cascade, and support that the states of interest are indeed of 0^+ nature.

Nucleus	a_2	a_4
^{54}Fe	-2.8(6)	3.9(7)
^{56}Fe	-2.6(9)	3.7(10)
^{58}Fe	-2.8(8)	3.8(9)

Table 1: Fit coefficients for the angular correlations in Fig. 4.

Since the decays of the first excited 0^+ states have $E2$ components, the $E0$ strengths could be deduced from the $E2$ intensities and their partial lifetimes $\tau(E2)$. First of all, the monopole strength is defined as

$$\rho^2(E0) = \left|\frac{\langle f|\hat{T}(E0)|i\rangle}{eR^2}\right|^2 , \tag{3.2}$$

where $\hat{T}(E0)$ is the electric monopole operator, e the unit of electric charge, and R the nuclear radius. The $E0$ transition rate $W(E0)$ is given by

$$W(E0) = \frac{1}{\tau(E0)} = \rho^2(E0)\cdot\Omega_{\text{tot}} , \tag{3.3}$$

where Ω_{tot} is the sum of the electronic factors [9], which describe the atomic properties. All the nuclear properties are contained in the monopole strength $\rho^2(E0)$. The ratio of the $E0$ and $E2$ intensities (in terms of K-shell electrons)

$$q_K^2 = \frac{I_K(E0)}{I_K(E2)} , \tag{3.4}$$

can be combined with the theoretical conversion coefficient, $\alpha_K = I_K/I_\gamma$, and electronic factor, Ω_K, as well as the partial $E2$ lifetime, $\tau(E2) = W_\gamma(E2)^{-1}$, to deduce the monopole strength

$$\rho^2(E0) = q_K^2\cdot\frac{\alpha_K(E2)}{\Omega_K(E0)}\cdot W_\gamma(E2) . \tag{3.5}$$

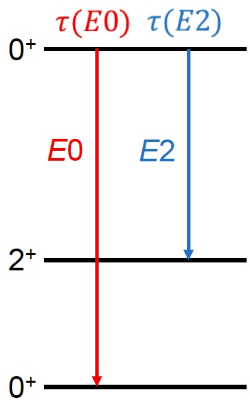

Figure 5: Observed decay of the 0_2^+ states in ^{54,56,58}Fe.

The calculations were performed with conversion coefficients and electronic factors obtained from BrICC [10]. In the preliminary analysis, we deduced a much larger monopole strength in ^{54}Fe, $\rho^2(E0)\times10^3 \sim 90$, than in the other isotopes, which were in the range $\rho^2(E0)\times10^3 \sim 1-10$. Shape coexistence seems to occur in ^{54}Fe, which has a closed $N = 28$ shell. The reduction in strength in ^{56,58}Fe might indicate that the filling of the next neutron shell inhibits *mp-mh* excitations because they become less favourable. If this is the case, *mp-mh* neutron excitations seem to be likely candidates for the shape coexistence in ^{54}Fe. However, the weak $E0$ strengths in ^{56,58}Fe might also be caused by weak configuration mixing and should be studied further. There is also reasonably good agreement between the two $E0$ strengths deduced for ^{54}Fe, both $\rho^2(E0) \times 10^3 \sim 90$, and there was no observed transition between the second and first excited 0^+ states. This indicates that these states have the same or similar deformation. Further interpretation of the results is currently ongoing. Very little experimental data are available regarding $E0$ transitions around the $N,Z = 28$ shell closures, and further measurements would be very important in the campaign to characterize shape coexistence in this region. Further lifetime measurements to complement $E0$ information in this region would also be of high value.

Acknowledgments

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