Quasifree Neutron Knockout from ^{54}Ca Corroborates Arising $N = 34$ Neutron Magic Number

jizheng Bo, junzhe Liu

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A few points

- This paper: a $N = 34$ subshell gap $\rightarrow$ the variations of the magic numbers across the nuclear chart
- Quasifree one-neutron knockout reactions from a ^{54}Ca beam striking on a liquid hydrogen target

Experimental details & information

- The experiment was carried out at the Radioactive Isotope Beam Factory (RIBF), operated by the RIKEN Nishina Center and the Center for Nuclear Study, the University of Tokyo.
- To get ^{54}Ca: A ^{70}Zn primary beam was impinged on a 10-mm-thick ^{9}Be target

Experimental details

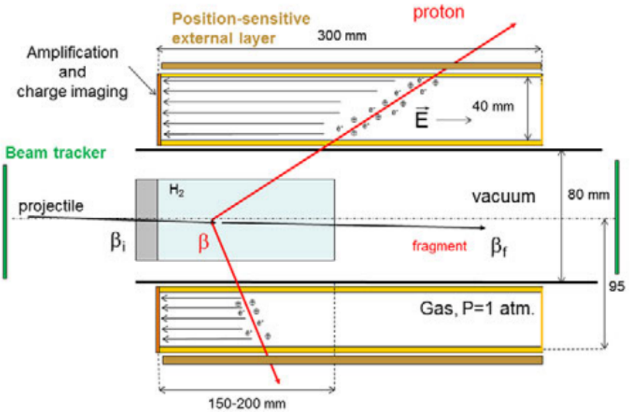


Figure: Principle scheme of the MINOS device, where the ^{54}Ca beam bombarded the liquid hydrogen target .

Reference: MINOS: A vertex tracker coupled to a thick liquid-hydrogen target for in-beam spectroscopy of exotic nuclei. DOI 10.1140/epja/i2014-14008-y

Image

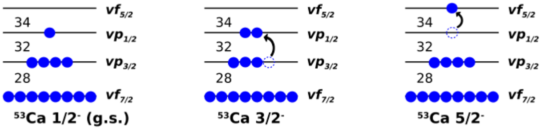


Figure: ^{53}Ca's shell model picture: the ground state of ^{53}Ca and the 2 excited states of ^{53}Ca

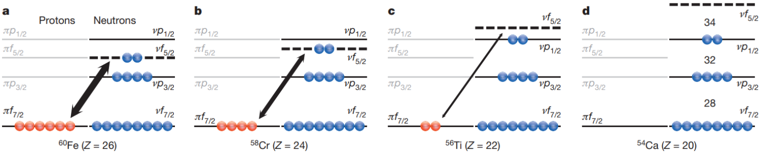


Figure: The attractive interaction between the proton $\pi f_{7/2}$ and neutron $\nu f_{5/2}$ single-particle orbitals for $N = 34$ isotones. The interaction decreases with the number of protons decreasing.

Experimental results

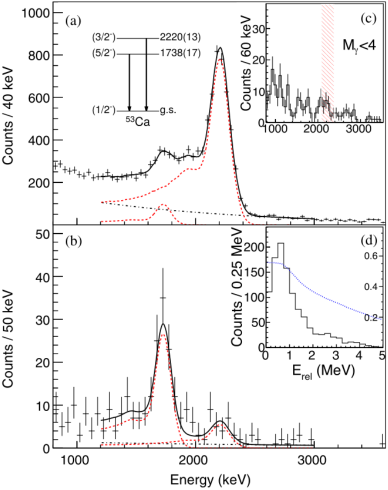


Figure: (a) Doppler-corrected γ-ray spectrum in coincidence with the $^{54}Ca(p, pn)^{53}Ca$ channel. (b) Same Doppler-corrected γ-ray spectrum, but in coincidence with a detected neutron.

Results & simulation

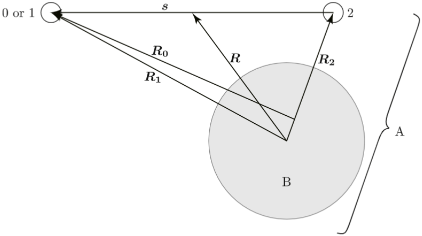
	J^π	$-1n$	σ_{-1n}	DWIA σ_{sp}	GXPF1Bs E_x (keV)	GXPF1Bs C^2S	GXPF1Bs σ^{th}_{-1n}	$NNLO_{sat}$ E_x (keV)	$NNLO_{sat}$ C^2S	$NNLO_{sat}$ σ^{th}_{-1n}	$NN+3N$ (lnl) E_x (keV)	$NN+3N$ (lnl) C^2S	$NN+3N$ (lnl) σ^{th}_{-1n}
g.s.	$1/2^-$	$p_{1/2}$	15.9(17)	7.27	0	1.82	13.2	0	1.56	11.3	0	1.58	11.6
2220(13)	$3/2^-$	$p_{3/2}$	19.1(12)	6.24	2061	3.55	22.2	2635	3.12	18.5	2611	3.17	17.0
1738(17)	$5/2^-$	$f_{5/2}$	1.0(3)	4.19	1934	0.19	0.8	1950	0.01	0.1	2590	0.02	0.1
Inclusive			36.0(12)				36.2			29.9			28.7

Figure: Inclusive and exclusive cross sections for the $^{54}Ca(p,pn)^{53}Ca$ reaction compared with theoretical values from the DWIA framework and some other frameworks.

- The f wave component is far less than the p wave component.

DWIA model

Distorted Wave Impluse Approximation model



$$T_{\mu_1\mu_2\mu_B\mu_0\mu_A} = \Big\langle \phi_{\boldsymbol{K}_1}\left(\boldsymbol{R}_0\right)\eta^{(1)}_{1/2,\mu_1}\zeta^{(1)}_{1/2,\nu_1}\phi_{\boldsymbol{k}_2\ \mathrm{B}}\left(\boldsymbol{R}_2\right)\eta^{(2)}_{1/2,\mu_2}\zeta^{(2)}_{1/2,\nu_2}\Phi_{I_\mathrm{B}\mu_\mathrm{B},t_\mathrm{B}\nu_\mathrm{B}}\left(\epsilon_\mathrm{B},\xi_\mathrm{B}\right)$$

$$\times\left|V_\beta\right|\hat{\Omega}^{(+)}\phi_{\boldsymbol{K}_0}\left(\boldsymbol{R}_0\right)\eta^{(0)}_{1/2,\mu_0}\zeta^{(0)}_{1/2,\nu_0}\Phi_{I_\mathrm{A}\mu_\mathrm{A},t_\mathrm{B}\nu_\mathrm{B}}\left(\epsilon_\mathrm{A},\xi_\mathrm{A}\right)\Big\rangle$$

DWIA model

Distorted Wave Impluse Approximation model

The distorted wave for particle 0:

$$\left(-\frac{\hbar^2}{2\mathcal{M}_{0\ \mathrm{A}}}\nabla^2_{\boldsymbol{R}_0} + U_{0\ \mathrm{A}} - \frac{\hbar^2}{2\mathcal{M}_{0\ \mathrm{A}}}K_0^2\right)\chi^{(+)}_{0,\boldsymbol{K}_0,\mu_0}(\boldsymbol{R}_0) = 0$$

The spin direction of particle 0 may change

$$\chi^{(+)}_{0,\boldsymbol{K}_0,\mu_0}(\boldsymbol{R}_0) = \sum_{\mu_0'}\chi^{(+)}_{0,\boldsymbol{K}_0,\mu_0'\mu_0}(\boldsymbol{R}_0)\,\eta^{(0)}_{1/2,\mu_0'}$$

DWIA model

Distorted Wave Impluse Approximation model

The resulting distorted wave

$$\left(T_{\boldsymbol{R}_0} + T_{\boldsymbol{R}_2} + U^{*}_{1\ \mathrm{B}} + U^{*}_{2\ \mathrm{B}} - \mathcal{E}_f\right) \Xi^{(-)}_{\boldsymbol{K}_1,\boldsymbol{K}_2,\mu_1,\mu_2}\left(\boldsymbol{R}_1, \boldsymbol{R}_2\right) = 0$$

where

$$T_{\boldsymbol{R}_0} + T_{\boldsymbol{R}_2} - \mathcal{E}_f \approx -\frac{\hbar^2}{2\mathcal{M}_{1\ \mathrm{B}}}\nabla^2_{\boldsymbol{R}_1} - \frac{\hbar^2}{2\mathcal{M}_{1\ \mathrm{B}}}K_1^2 - \frac{\hbar^2}{2\mathcal{M}_{2\ \mathrm{B}}}\nabla^2_{\boldsymbol{R}_2} - \frac{\hbar^2}{2\mathcal{M}_{2\ \mathrm{B}}}K_2^2$$

DWIA model

Distorted Wave Impluse Approximation model

the equation becomes separable

$$\Xi^{(-)}_{\boldsymbol{K}_1,\boldsymbol{K}_2,\mu_1,\mu_2}(\boldsymbol{R}_1,\boldsymbol{R}_2) \approx \chi^{(-)}_{1,\boldsymbol{K}_1,\mu_1}(\boldsymbol{R}_1)\,\chi^{(-)}_{2,\boldsymbol{K}_2,\mu_2}(\boldsymbol{R}_2)$$

The transition matrix:

$$T_{\mu_1\mu_2\mu_\mathrm{B}\mu_0\mu_\mathrm{A}} = \langle \chi^{(-)}_{1,\boldsymbol{K}_1,\mu_1}(\boldsymbol{R}_1)\,\zeta^{(1)}_{1/2,v_1}\,\chi^{(-)}_{2,\boldsymbol{K}_2,\mu_2}(\boldsymbol{R}_2)\,\zeta^{(2)}_{1/2,v_2}\left| t^{\mathrm{free}} \right| \chi^{(+)}_{0,\boldsymbol{K}_0,\mu_0}(\boldsymbol{R}_0)$$

$$\zeta^{(0)}_{1/2,v_0}\,\Psi_{I_\mathrm{B}\mu_\mathrm{B}I_\mathrm{A}\mu_\mathrm{A},t_\mathrm{B}\nu_\mathrm{B}t_\mathrm{A}v_\mathrm{A}}(\boldsymbol{R}_2)\rangle$$

DWIA model

Distorted Wave Impluse Approximation model

where overlap function

$$\Psi_{I_{\mathrm{B}}\mu_{\mathrm{B}}I_{\mathrm{A}}\mu_{\mathrm{A}},t_{\mathrm{B}}\nu_{\mathrm{B}}t_{\mathrm{A}}\nu_{\mathrm{A}}}\left(\boldsymbol{R}_2\right) \equiv \left\langle \Phi_{I_{\mathrm{B}}\mu_{\mathrm{B}},t_{\mathrm{B}}\nu_{\mathrm{B}}}\left(\epsilon_{\mathrm{B}},\xi_{\mathrm{B}}\right) \mid \Phi_{I_{\mathrm{A}}\mu_{\mathrm{A}},t_{\mathrm{A}}\nu_{\mathrm{A}}}\left(\epsilon_{\mathrm{A}},\xi_{\mathrm{A}}\right)\right\rangle_{\xi_{\mathrm{B}}}$$

So the transition matrix

$$T_{\mu_1\mu_2\mu_{\mathrm{B}}\mu_0\mu_{\mathrm{A}}} = \left\langle \chi^{(-)}_{1,\boldsymbol{K}_1,\mu_1}\left(\boldsymbol{R}_1\right)\zeta^{(1)}_{1/2,\nu_1}\chi^{(-)}_{2,\boldsymbol{K}_2,\mu_2}\left(\boldsymbol{R}_2\right)\zeta^{(2)}_{1/2,\nu_2}\right| t^{\text{free}} \left| \chi^{(+)}_{0,\mathbf{K}_0,\mu_0}\left(\boldsymbol{R}_0\right)\right.$$

$$\left.\zeta^{(0)}_{1/2,\nu_0} \times \sum_{lj\mu_j} S^{1/2}_{nlj\nu_{\mathrm{N}}}\left(j\mu_j I_{\mathrm{B}}\mu_{\mathrm{B}} \mid I_{\mathrm{A}}\mu_{\mathrm{A}}\right)\varphi_{nlj}\left(R_2\right)\zeta^{(\mathrm{N})}_{1/2,\nu_{\mathrm{N}}}\left[Y_l\left(\hat{\mathbf{R}}_2\right)\otimes\eta^{(\mathrm{N})}_{1/2}\right]_{j\mu_j}\right\rangle$$

where the spectroscopic amplitude

$$S_{nljv_{\mathrm{N}}}^{1/2} \equiv \left(t_{\mathrm{B}} v_{\mathrm{B}} \frac{1}{2} v_{\mathrm{N}} \mid t_{\mathrm{A}} v_{\mathrm{A}} \right) \vartheta_{nljv_{\mathrm{N}} l_{\mathrm{B}} t_{\mathrm{B}} v_{\mathrm{B}}; l_{\mathrm{A}} t_{\mathrm{A}} v_{\mathrm{A}}}$$

approximation to the distorted waves

$$\begin{aligned}
\chi_{1,\boldsymbol{K}_1,\mu_1'\mu_1}^{(-)}(\boldsymbol{R}_1) &= \chi_{1,\boldsymbol{K}_1,\mu_1'\mu_1}^{(-)}(\boldsymbol{R}+\boldsymbol{s}/2) \approx \chi_{1,\boldsymbol{K}_1,\mu_1'\mu_1}^{(-)}(\boldsymbol{R}) e^{i\boldsymbol{K}_1\cdot\boldsymbol{s}/2}, \\
\chi_{2,\boldsymbol{K}_2,\mu_2'\mu_2}^{(-)}(\boldsymbol{R}_2) &= \chi_{2,\boldsymbol{K}_2,\mu_2'\mu_2}^{(-)}(\boldsymbol{R}-\boldsymbol{s}/2) \approx \chi_{2,\boldsymbol{K}_2,\mu_2'\mu_2}^{(-)}(\boldsymbol{R}) e^{-i\boldsymbol{K}_2\cdot\boldsymbol{s}/2}, \\
\chi_{0,\boldsymbol{K}_0,\mu_0'\mu_0}^{(+)}(\boldsymbol{R}_0) &= \chi_{0,\boldsymbol{K}_0,\mu_0'\mu_0}^{(+)}(\boldsymbol{R}-\alpha_R\boldsymbol{R}+\alpha_s\boldsymbol{s}/2) \\
&\approx \chi_{0,\boldsymbol{K}_0,\mu_0'\mu_0}^{(+)}(\boldsymbol{R}) e^{-i\alpha_R\boldsymbol{K}_0\cdot\boldsymbol{R}} e^{i\alpha_s\boldsymbol{K}_0\cdot\boldsymbol{s}/2}
\end{aligned}$$

T matrix becomes

$$T_{\mu_1\mu_2\mu_0\mu_j} = S_{nlj\nu_\mathrm{N}}^{1/2} \sum_{\mu_1'\mu_2'\mu_0'\mu_\mathrm{N}} \tilde{t}^{\mathrm{free}}_{\kappa'\mu_1'\mu_2'\nu_1\nu_2,\bar{\kappa}\mu_0'\mu_\mathrm{N}\nu_0\nu_\mathrm{N}} \times \int d\boldsymbol{R}\chi^{(-)*}_{1,\boldsymbol{K}_1,\mu_1'\mu_1}(\boldsymbol{R})\chi^{(-)*}_{2,\boldsymbol{K}_2,\mu_2'\mu_2}(\boldsymbol{R})\chi^{(+)}_{0,\boldsymbol{K}_0,\mu_0'\mu_0}(\boldsymbol{R})e^{-i\alpha_R\boldsymbol{K}_0\cdot\boldsymbol{R}} \times \sum_m \left(\mathrm{lm}\,\frac{1}{2}\mu_\mathrm{N} \mid j\mu_j\right)\psi_{nljm}(\boldsymbol{R}).$$

with

$$\tilde{t}^{free}_{\kappa'\mu_1'\mu_2'\nu_1\nu_2,\kappa\mu_0'\mu_\mathrm{N}\nu_0\nu_\mathrm{N}} \equiv \langle e^{i\kappa'\cdot s}\eta^{(1)}_{1/2,\mu_1'}\zeta^{(1)}_{1/2,\nu_1}\eta^{(2)}_{1/2,\mu_2'}\zeta^{(2)}_{1/2,\nu_2}\left| t^{\mathrm{free}} \right| e^{i\kappa\cdot s}\eta^{(0)}_{1/2,\mu_0'}\zeta^{(0)}_{1/2,\nu_0}\eta^{(\mathrm{N})}_{1/2,\mu_\mathrm{N}}\zeta^{(\mathrm{N})}_{1/2,\nu_\mathrm{N}}\rangle$$

Summary

1. The measured cross section to the $p_{3/2}$ state of ^{53}Ca is far larger than the one to the $f_{5/2}$ state.
2. Such little f wave component $\rightarrow$ the $N = 34$ subshell closure.

Thank you for your listening.