Probing properties of the nuclear force in ‘extreme’ conditions

O. Sorlin (GANIL, Caen, France)

PART 1:

Testing the spin-orbit force with a ‘bubble’ nucleus

PART 2:

Proton-neutron forces at the drip-line

‘May the force be with you’
Obi-Wan Kenobi ‘Star Wars’
Part I:
Test of the spin-orbit interaction by using the doubly-magic ‘bubble’ nucleus $^{34}\text{Si}$

$^{34}\text{Si}$ doubly magic: High $2^+$ energy, low $B(E2)$, weak $\rho(E0)$...

Enders et al. PRC 65 (2002) 034318 + talk S. Grévy
Proton density depletion in $^{34}$Si?

\[ \Delta(2s_{1/2}) \text{ between } ^{36}\text{S and } ^{34}\text{Si using } (-1p) \text{ reaction} \]

Proton orbits $C^2S$

1d$_{3/2}$ $\cdots$ 0.2
2s$_{1/2}$ $\cdots$ 1.8
1d$_{5/2}$ $\cdots$ 6

$^{36}\text{S}(d,^3\text{He})^{35}\text{P}$
Khan et al. PLB 156 (1985)

Proton orbits $C^2S$

1d$_{3/2}$ $\cdots$
2s$_{1/2}$ $\cdots$ 0.17(3)
1d$_{5/2}$ $\cdots$ 5.76(7)

$^{34}\text{Si}_{20}$
$^{34}\text{Si}(-1p)^{33}\text{Al}$
Mutschler et al. in prep.

J.P. Ebran DDME2 interaction

NSCL/S800 with Gretina
Gamma-gated $p_{\parallel}$ of fragments
Proton occupancies in $^{34}$Si using (-1p) reaction

Gamma-ray spectrum at 90°

Preliminary A. Mutschler

$^{34}$Si (-1p) $^{33}$Al

So far very small $L_p=0$ knock-out observed -> in agreement with a ‘bubble’ nucleus
The spin-orbit (SO) interaction

\[ V_{\tau}^{\ell s}(r) = -\left[ W_1 \frac{\partial \rho_{\tau}(r)}{\partial r} + W_2 \frac{\partial \rho_{\tau \neq \tau}(r)}{\partial r} \right] \vec{l} \cdot \vec{s} \]

Density dependence

\[ \rho(r) \]

Normal nucleus

Bubble nucleus (SHE)

Reduced SO splitting in bubble nucleus for orbits probing the interior of the nucleus such as L=1

Isospin dependence

\[ W_1 \approx 2W_2 \quad (MF) \]

\[ W_1 \approx W_2 \quad (RMF) \]

No isospin dependence in RMF

Looking at neutron \( p_{3/2} - p_{1/2} \) SO evolution when depleting the proton central density -> test density and isospin dep. of SO

Asymmetric splitting of \( j \) orbits
$^{34}\text{Si}(d,p)$ reaction in inverse kinematics at GANIL

$^{34}\text{Si}$ $10^5$ pps 20A.MeV GANIL

Tracking detectors (CATS)

$^{34}\text{Si}(d,p)$ reaction in inverse kinematics at GANIL, IPN Orsay, CEA Saclay IPHC Strasbourg

CD$_2$ target 2.6mg cm$^{-2}$

GANIL, IPN Orsay, CEA Saclay IPHC Strasbourg

CHIO + plastic

MUST2

EXOGAM

Target 2.6mg cm$^{-2}$

Ionization chamber (CHIO)

Annular detector (S1)

DSSD 128+128 300$\mu$m

Si(Li) 4.5mm

CsI(PD) 4cm

ASICS 16 channels E and T

Triton

Deuton

Proton

Energy (MeV) vs. Angle
Spin-orbit splittings in $^{35}\text{Si}$ using $^{34}\text{Si}(d,p)^{35}\text{Si}$

L assignments from proton angular distributions
Accurate energy of states with $\gamma$-ray detection

Evolution of the $p_{3/2}-p_{1/2}$ SO splitting

No change in $p_{3/2}-p_{1/2}$ splitting between $^{41}\text{Ca}$ and $^{37}\text{S}$

Large reduction of $p_{3/2}-p_{1/2}$ splitting between $^{37}\text{S}$ and $^{35}\text{Si}$, no change of $f_{7/2}-f_{5/2}$
Density and Isospin dependence of the SO interaction

Evolution of the p SO splitting as a function of central depletion

- ----- iso. indep.
- ----- iso. dep.
○ exp

<table>
<thead>
<tr>
<th>Density dependence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isospin dependence</td>
</tr>
</tbody>
</table>

RMF does not have the proper isospin dependence of the SO interaction

Consequences for predicting shell gaps formed by the SO interaction in SHE


\( \rho_p(r) \)

\( ^{29}\text{Ar} \):

\( ^{34}\text{Si} \):

\( ^{36}\text{S} \)

Preliminary...
Part II:
Proton-neutron interactions at the drip-line
Proton-neutron interactions at the drip-line

\[ V_{pn} \approx \sum \frac{(2J+1) \text{int}(J)}{(2J+1)} \]

\[ J = 1, 2, 3, 4 \]

Determine the \( d_{5/2} - d_{3/2} \) proton-neutron force in \(^{26}\text{F}\)

Compare to Shell Model calculations constrained closer to stability

Compare to models using realistic interactions

4 experiments to determine the energy of the J=1-4 states!

J=1, Mass g.s.: Jurado et al., PLB 649 (2007)

J=2, excited state ‘in beam’ Stanoiu et al. PRC 85 (2012)

J=3, unbound state Frank et al., PRC 84 (2011) + a new one

J=4, M3 isomer Lepailleur et al. PRL 110 (2013)
Discovery of a $4^+$ isomer in $^{26}$F
$^{26}$F

GS-GS Q-value = 17.79 MeV

$^{25}$Ne

$^{26}$Ne

Unbound states in $^{26}$F studied at GSI/LAND

From the widths of $p_{\parallel}$ and neutron peak -> Excellent candidate for $J=3^+$ state at 550 keV

M. Vandebruck, preliminary
Excellent agreement with coupled cluster calculations (continuum not yet implemented)

Proton-neutron interaction $d_{5/2} - d_{3/2}$ in $^{26}$F

Lepailleur et al., PRL 110 (2013)
Vandebrouck, preliminary
Frank et al., PRC 84 (2011) – previous

Weak change energies of states in continuum
Centrifugal barrier? Fit with data into continuum?

$^{26}$F$\text{free}$

Int(J) (MeV)

Shell model

3^+

exp (2,3^+)

Coupled cluster

$^{26}$F

3^+

2^+

S_n

2^+

4^+

1^+

USDA

Exp.

NN

NN+3nf

NN+3nf +cont

$^{24}$O

p

n

d_{5/2}

d_{3/2}$
PART I:

$^{34}\text{Si}$ good candidate for proton ‘bubble’, normal neutron density
Reduction of neutron $p_{3/2}-p_{1/2}$ splitting with proton $s_{1/2}$ depletion
Points to density and isospin dependence of SO interaction

PART II:

Spectroscopy of bound and unbound states in $^{26}\text{F}$
No drastic change with SM calculations
Benchmark for testing realistic forces up to continuum
But …Atomic mass of $^{26}\text{F}$ to be confirmed….

Special thank’s to:
GANIL/IPNO: G. Burgunder, A. Lepailleur, A. Mutschler, M. Vandebrouck, A. Lemasson …
The LAND team: T. Aumann, C. Caesar, F. Wamers. D. Rossi …
The NSCL/S800/Gretina teams: D. Weisshar, F. Recchia, D. Bazin, A. Gade, K Wimmer….
Theory: F. Nowacki, T. Otsuka, J. P. Ebran, G. Hagen, G. Jansen, A. Brown