3rd Year Physics Nuclear Configuration Exercise

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1 Introduction

The aim of this exercise was to establish the energy levels, angular momentum and configurations of a nucleus which has three valence particles. See the paper submitted to PASA for details.

The class were divided into six groups: included in this document are the six briefing papers. Some included hand-drawn level diagrams: we are working on including these, but can fax you them in the interim, if desired.

2 Argonne Briefing Paper

C31 Spectroscopy Exercise/

Assignment 1

A sequence of gamma-rays have been observed in the heavy-ion evaporation reaction ^{208}Pb(^{7}Li,4n)^{211}At. The ordering of the gamma-rays can be determined by changing the energy of the incident ^{7}Li beam and looking at the relative production rates. Eight gamma-rays have been identified with energy and ordering: 1067,254,96,511,713,1535,204 and 435 keV. These gamma-rays are all in coincidence with each other, ie they identify eight distinct states. Your task is to identify correctly the configurations associated with the states determined by these gamma-rays.

Particle Transfer Experts

(Argonne)

Your have been doing experiments looking at particle transfer reactions on the doubly magic $^{208}_{82}$Pb nucleus. These reactions add or subtract a single nucleon to the Pb core nucleus. Energy measurements from these reactions allow you to work out the relative excitation energies associated with moving a single valence particle between different shell model orbits.

Four distinct nuclei can be formed by adding or removing one particle from $^{208}_{82}$Pb. These are $^{209}_{82}$Pb, $^{207}_{82}$Pb, $^{209}_{83}$Bi, and $^{207}_{81}$Tl. The level schemes for each of these nuclei are indicated below. (The energy scales have been altered to express energies relative to the energy of the ground state in $^{208}_{82}$Pb.)

The energy differences in each of these nuclei give the separation of the shell model orbitals. For example in $^{209}_{83}$Bi the excitation of a single proton from the $h_{9/2}$ orbit (which forms the ground state of ^{209}Bi) to the $f_{7/2}$ orbit (which forms the first excited state in ^{209}Bi) costs an energy of 897 keV.

Energy level schemes for one-particle nuclei outside the Pb core

3 Canberra Briefing Paper

C31 Spectroscopy Exercise/
Assignment 1

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Multipolarity Measurement Experts

Canberra

The angular momentum of the emitted photons (gamma-rays) can be determined by measuring the angular distribution of the radiation is space. The angular momentum of the photon, the initial state and the final state must form a closed vector sum. For example if a dipole photon which has angular momentum 1 $\hbar$ deexcites a state of angular momentum 4 $\hbar$ then the final state must have angular momentum 3,4 or 5. In heavy-ion evaporation reactions it is more usual for deexcitation to occur to states with lower angular momentum and in most cases the transtions are stetched, ie the change in angular momentum between the initial and final states is the same as the angular momentum of the photon.

The measurement of the angular distribution is not sensitive to the *parity or character* of the radiation so that the distribution for an electric quadrupole (E2) gamma-ray is the same as for a magnetic quadrupole (M2) gamma-ray. One measurement that is sensitive to whether transitions are of electric or magnetic character is a measurement of the rate of *internal conversion.* The character of the radiation is related to the change in parity of the between initial and final states in the following way:

E1	parity change
M1	no parity change
E2	no parity change
M2	parity change
E3	parity change
M3	parity change

Your group has measured the angular distributions and internal conversion coefficients for the gamma-rays from ^{211}At and determined the following:

1067	E2
254	E2
96	E2
511	M1
713	E3
1535	M1
204	M1
435	E3

You are now able to work out the spin (total angular momentum) and parity for all of the observed states.

4 GSI Briefing Paper

C31 Spectroscopy Exercise/ Assignment 1

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Lifetime Experts
(GSI)

Your have also been doing experiments with the ^{208}Pb(^{7}Li,4n)^{211}At reaction, but you have been looking at the lifetimes present ^{211}At.

You have identified three isomeric states. One at the state depopulated by the 96 keV transition of meanlife 51 ns, one at the state depopulated by the 713 keV transition of meanlife 73 ns and a third at the state depopulated by the 435 keV transition.

Isomeric states can occur for three main reasons: i) low gamma-ray energies, ii) high transition multipolarities and iii) small nuclear matrix elements connecting the initial and final states.

You suspect that the lowest isomer occurs for the first reason and that for the other two are high multipolarity transitions where the nuclear matrix elements are actually quite large.

Looking at the data available for the region you see that similar isomeric transitions have been identified in other nuclei and have often been associated with initial and final configurations which differ only in the presence of the $i_{13/2}$ and $f_{7/2}$ orbitals.

5 Jyväskylä Briefing Paper

C31 Spectroscopy Exercise/ Assignment 1

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Residual Energy Experts

Jyväskylä

Your have been looking at the energy levels of nuclei where two particles are coupled together. You realise that to first order the excitation energies are just the sum of the single particle energies, ie the sum of the energies of the appropriate orbits. As a case in point you have been looking at the level scheme $^{210}_{84}$Po shown below.

In this nucleus the lowest 8^+, state at 1558 keV, is understood to arise from the $h^2_{9/2}$ configuration. The second 8^+ state, at 2188 keV, comes from the

$h_{9/2}f_{7/2}$ coupling. The first order estimate of the energy difference between these states should be just the energy required to excite a single proton from the $h_{9/2}$ orbit to the $f_{7/2}$ orbit. This value, 897 keV, can be obtained by looking at the difference in energy between the ground state of the nucleus $^{209}_{83}$Bi (spin $\frac{9}{2}$) and the first excited state (spin $\frac{7}{2}$).

The difference between the expected and observed values is due extra interactions which you call *residual interactions.* The interactions occur between all valence pairs of nucleons.

Except for the residual interaction in which the particles are paired to form the 0^+ state most residual interactions between **pairs of protons** are repulsive, ie they shift the energy of the state up. Pairing shifts the state down by about 1 MeV while most other proton-proton interactions shift the state up by about a few hundred keV.

On the other hand the **proton-neutron** residual interactions are attractive, ie they shift the states dowm in energy and in the lead region are of the order of a few hundred keV for most spin couplings, with values up to -900 keV for the cases where the spins of the proton and neutron are maximally aligned.

Proton-neutron-hole interactions are weakly repulsive, $\approx$ 100 keV.

6 Legnaro Briefing Paper

C31 Spectroscopy Exercise/ Assignment 1

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Excited states in $^{208}_{82}$Pb Experts

(Legnaro)

Your have been doing experiments looking at reactions which excite states in the doubly magic $^{208}_{82}$Pb nucleus. You have been able to work out the level scheme shown below.

From one point of view these states can be considered as collective vibrational excitations, for example the 3^- state is an octupole vibrational excitation. From another point of view, the microscopic picture, you should be able to understand these excitations in terms of excitations of particles within the shell model. In particular these are *particle-hole* excitations.

A number of particle-hole excitations give angular momentum (and parity) 3^-, such as $\pi(h_{9/2}\ d^{-1}_{3/2})$, $\pi(f_{7/2}\ s^{-1}_{1/2})$, $\pi(i_{13/2}\ h^{-1}_{11/2})$, $\nu(g_{9/2}\ p^{-1}_{3/2})$, $\nu(i_{11/2}\ f^{-1}_{5/2})$ and $\nu(j_{15/2}\ i^{-1}_{13/2})$. The observed 3^- state will have a configuration which will be some quantum mechancial mixture of these different configurations.

The next excited state in $^{208}_{82}$Pb, the 5^-, state has a much simpler structure and is largely due to the particle-hole excitation $\nu(g_{9/2}\ p^{-1}_{1/2})$.

Although you have observed particle-hole excitations in ^{208}Pb, there is no reason no to expect them to occur in other nuclei provided sufficient energy is available.

7 Lund Briefing Paper

C31 Spectroscopy Exercise/ Assignment 1

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Coupling of Angular Momentum Experts

(Lund)

You have been looking at the low energy part of the level scheme for $^{210}_{84}$Po. The shell model predicts the $h_{9/2}$ to be the first available orbit above the Z=82 shell gap. The Pauli principle tells us that two identical $h_{9/2}$ particles can couple to a maximum angular momentum of 8 $\hbar$ and they can only couple to give even total angular momentum. The lowest energy state obtained for the $h^2_{9/2}$ configuration will be for the 0^+ coupling because of the energy gain due to pairing. The angular momentum for the lowest energy state for the

$h^3_{9/2}$ configuration will be given by $0^+ \otimes \frac{9}{2}$ ie just $\frac{9}{2}$. The largest angular momentum available for the $h^3_{9/2}$ configuration is again determined by the Pauli principle as the three identical particles must have distinct quantum numbers. This means the maximium m$_j$ values must be $\frac{9}{2}$, $\frac{7}{2}$ and $\frac{5}{2}$ for the three particles, giving a maximum total M$_J$ of $\frac{21}{2}$.

The relative energy splittings for the $h^3_{9/2}$ configuration should be very similar to the splittings for the $h^2_{9/2}$ since, to first order the states may be considered by the coupling ${}^{210}_{84}$Po $\otimes$ $h_{9/2}$.

Low energy part of the level scheme for ${}^{210}_{84}$Po.