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Prompt gamma ray-spectroscopy of *N* = 50 fission fragments

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Abstract. Excited states in the nuclei ^{83}As and ^{84,86}Se have been studied via prompt γ-ray spectroscopy. The nuclei were produced by the proton-induced fission of a ^{238}U target, at the accelerator of the University of Jyväskylä. The JUROGAM-II array was used to detect prompt γ-rays and a triple-γ coincidence analysis performed. A comparison of the $N = 50$ nuclei with shell-model calculations reproduces the low-lying states in ^{83}As and ^{84}Se well. The inclusion of particle-hole excitations is necessary to correctly describe the states above ~ 3.5 MeV.

1. Introduction

It is an open question as to whether ^{78}Ni is a doubly magic nucleus, suitable for use as a closed core in shell-model calculations. To date, experimental studies of excited states in this nucleus, or its immediate neighbors have not been possible. One way of testing the interactions and effective single-particle energies used in shell-model calculations is to study the mass ~80 nuclei at, or close to, the $A = 50$ shell closure. These neutron-rich nuclei are not well studied and the determination of excited level energies and spins allows the predictions of shell-model calculations to be tested. The neutron-rich nuclei of the $A = 80$ region have previously been studied via prompt γ-ray spectroscopy of fission fragments produced following the spontaneous fission of ^{252}Cf, or ^{248}Cm, fission sources, as for example in [1]. Deep-inelastic reactions have also been used to populate the nuclei of this region [2] as have light-ion induced fission reactions [3]. In the present work proton-induced fission of a thick ^{238}U target was used to create $A \sim 80$ fission fragments. This projectile-target combination produces a very neutron-rich compound nucleus which is lighter than either of the spontaneous fission sources mentioned above. This has the result of giving higher fission yields in the $A = 80$ region than these two spontaneous fission sources. On average, only 6 neutrons are evaporated per fission event, meaning the

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fragments remain neutron rich [4]. The neutron-rich compound nucleus and low neutron evaporation also give fission products which are on average more neutron-rich than those produced by other light-ion induced fission and deep-inelastic reactions. In the present work the nuclei ^{83}As and ^{84,86}Se have been populated and studied via prompt γ-ray spectroscopy. This has allowed the level schemes of these nuclei to be extended and demonstrates the use of this reaction for populating high-spin states in the nuclei of this region. The nuclei ^{83}As and ^{84}Se have 50 neutrons, which is a closed shell. Hence at low energy the excited states will be made up only of proton excitations and therefore allow sensitive tests of the proton-proton two-body matrix elements of the interactions used in the calculations.

2. Experimental details

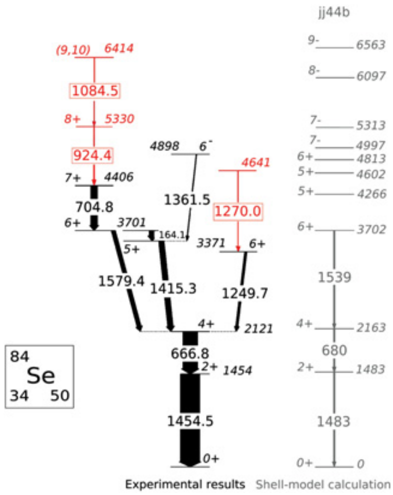
Fission fragments were produced by impinging a 25-MeV proton beam on a 74-mg/cm^2 ^{238}U target. The target sat at the center of the JUROGAM-II Ge array, which was used to detect γ-rays. The beam current was ~0.1 pnA giving an estimated fission rate of around 10^5 fission/s. The experiment ran for one week. The JUROGAM-II spectrometer contained 24 Clovers and 15 single crystal Ge detectors. Each Clover detector consists of four Ge crystals. The acquisition system was run in a total-data-readout mode and coincident events were constructed offline. The detection of three, or more, unsuppressed Ge detector signals in a 150-ns time window was used to define an event. Events were sorted in to a three-dimensional cube, which were built and analyzed using the Radware software package [5]. As over 100 nuclei are produced in this fission reaction then an $E_\gamma - E_\gamma - E_\gamma$ triple coincidence analysis is necessary to cleanly select transitions in a nucleus. This implies either that at least two transitions have already been identified in the nucleus of interest, or the most likely complementary fission fragment. The most likely complementary nucleus can be deduced knowing that 6 neutrons are evaporated on average in this reaction [4]. More precisely the mass dependence of two partner isotopic chains was investigated in detail by gating on a fission fragment and determining the average mass of the complementary fragment from the intensity of the different $2^+ \rightarrow 0^+$ transitions. This allowed a mass correlation plot to be constructed and this allows a mass assignment for new transitions. No protons were found to be evaporated in this reaction in the experimental data.

3. Experimental results

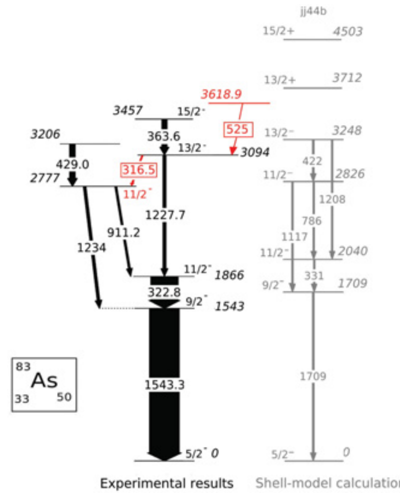
The level scheme of ^{84}Se has been extended by gating on transitions previously reported for this nucleus [2, 6]. The nuclei ^{149,151}Pr have been observed in coincidence with this nucleus, which are the expected complementary nuclei and correspond to 8 and 6 evaporated neutrons, respectively. Three new transitions have been found in the present work with energies of 924.4-, 1084.5- and 1270.0-keV and placed in the level scheme shown in Figure 1a. Our level scheme is in agreement with the ones previously reported in [1, 2, 6], except the tentative 492- and 1360-keV transitions reported in [2] and [1]. The new 5330-keV state is assigned a spin of 8_1^+ state from a comparison with the shell-model calculations reported in [2]. The new level at 6414-keV, which feeds the 5330-keV state is therefore likely to have a spin of (9,10).

In the case of ^{83}As two new transitions were added to the level schemes reported in [8, 9]. The new 316.5-keV transition decays from the 3094-keV state to the one at 2777-keV, which was not assigned a spin in [8]. From a comparison with the shell-model calculations presented, and the decays out of and to this state, a spin of $11/2^-$ can be assigned. Decays in the fission-fragment partners of ^{83}As, ^{150}Nd, ^{151}Nd and ^{152}Nd, were all seen in coincidence with the observed transitions in the level scheme Figure 1b.

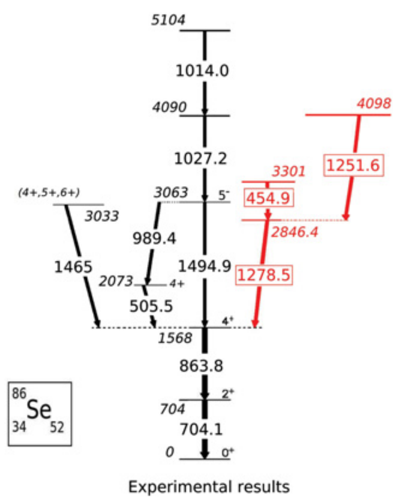
Three new transitions have also been added to the level scheme of ^{86}Se compared to that reported in [7], as presented in Figure 1c. Only the three decays below the 2073-keV level were reported in [1]. The position and order of these new transitions was determined by setting different gates and comparing their relative intensities.



(a) ^{84}Se



(b) ^{83}As



(c) ^{86}Se

Figure 1. Level schemes of (a) ^{84}Se, (b) ^{83}As and (c) ^{86}Se deduced from this work. New transitions are boxed and shell-model calculations are presented for (a) ^{84}Se and (b) ^{83}As on the right of the experimental level scheme.

4. Discussion

The states below 4-MeV in the $N = 50$ nuclei ^{83}As and ^{84}Se have been interpreted using shell-model calculations performed with the $jj44b$ interaction using a ^{56}Ni closed core. The $jj44b$ interaction [10] uses the $Z = N = 28$–50 valence space.

Shell-model calculations for ^{84}Se have been reported in [2, 6] using a variety of interactions. In both works the states below the 6^+ level at 3.7-MeV are reasonably well produced considering only proton excitations. The 0^+_1, 2^+_1 and 6^+_1 states have strong $\pi f^4_{5/2} p^2_{3/2}$ components and the $\pi f^4_{5/2} p^1_{3/2} p^1_{1/2}$ configuration makes up more than 20% of the 4^+_1 and 6^+_1 states too. The agreement between the experimental measurements and the calculations has been shown to be improved if the $\nu(g^{-1}_{9/2}, d^1_{5/2})$ particle-hole configuration is included for the 5^+ and 6^+ states [2, 6]. This configuration lies outside the valence space used in the calculations presented. Furthermore, without the inclusion of this core-excited configuration the 7^+ and 8^+ states, experimentally identified at 4406-keV in [2, 6] and 5330-keV in the present work lie some 2.5- and 3.5-MeV too high in energy. The spin of the 6615-keV state in the present work is likely to be 9, though no current calculations report such a state, probably due to the limited valence spaces used.

The low-lying $5/2^-$ to $13/2^-$ states in the $N = 50$ nucleus ^{83}As have strong $\pi[p_{3/2}f_{5/2}]^5$ configurations with up to two broken pairs in the present work, in agreement with what is previously reported in [8]. From a comparison with the shell-model calculations and the feeding and decaying pattern of the 2777-keV state a spin of $11/2^-$ can be assigned to this level. The spins of the 3204- and 3629-keV levels is not clear. A $13/2^+$ state is predicted at 3712-keV in the calculations and this would be expected to feed the 1866-keV $11/2^-$ state, which is not observed. A spin of 15/2 would seem likely for both states, though the lowest lying predicted level with this spin lies at 4503-keV, and has positive parity. These states may therefore have a considerable contribution from particle-hole configurations, as described above for ^{84}Se. This would implies that the valence space used in the calculations should be extended. One notes that the $15/2^-$ state at 3457-keV previously identified in [8, 9] is not predicted by the calculations.

The configurations of the excited states in the $N = 52$ nucleus ^{86}Se are much more mixed and contain both proton and neutron components. Shell-model calculations for this nucleus are currently incomplete and will not be presented in this work.

5. Conclusion

New transitions in the nuclei ^{83}As and ^{84,86}Se have been identified, extending the level schemes of these $N = 50$ and $N = 52$ nuclei. The low-energy structure of the $N = 50$ nuclei is well reproduced by shell-model calculations using the pure proton excitations. Above about 3.7-MeV particle-hole excitations have clearly to be included, as reported in previous works. The use of proton-induced fission of ^{238}U has been shown to be a good reaction to populate the excited states of neutron-rich nuclei in the $A = 80$ region.

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