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Spectroscopy of neutron-rich Pd and Cd isotopes near A=120

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New high-spin levels have been identified in the nucleus ^{120}Pd from analysis of the coincidence gamma rays observed in the ^{238}U$(\alpha, f\gamma\gamma\gamma)$ reaction. Recoiling fragments were detected with the Rochester heavy-ion detector array, CHICO, in coincidence with gamma-rays using Gammasphere. An A=110-130 mass-gated $\gamma - \gamma - \gamma$ cube from this experiment was constructed and analyzed for coincident gamma-rays in several nuclei near A=120. New results for neutron-rich ^{118}Pd and ^{120}Pd have been obtained. The ^{120}Pd level scheme was extended to spin of 10^+ by building on the new low-energy gamma rays identified in decay studies of ^{120}Rh. The details of the ^{118}Pd level scheme derived from this work are compared to previous work. The systematics of the yrast levels in even-even Pd and Cd isotopes are presented and the symmetry of energy levels around $N = 68$ is discussed. A new 10^+ level in ^{124}Cd has been observed. The population intensity of even-even neutron-rich Cd isotopes is deduced, indicating that nuclides near ^{120}Cd are preferentially populated following alpha-induced fission of ^{238}U.

1. INTRODUCTION

The structure of neutron-rich isotopes has been extensively studied for about 40 years by detecting the prompt gamma-rays from recoiling fragments following nuclear fission [1–3]. For many neutron-rich nuclides, fission is the only production mechanism available for which sufficient and useful data can be obtained. Modern studies involve the use of large arrays of high-purity intrinsic Ge detectors, such as Gammasphere or Eurogam, in order to distinguish individual nuclides from the plethora of gamma-rays produced from

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the hundreds of fission fragments immediately following fission. Recent studies of the spontaneous fission (SF) of ^{252}Cf [4] and ^{248}Cm [5] have provided rich data sets containing not only new nuclear structure information for nuclides in this neutron-rich region of the chart of nuclides, but also important information regarding the dynamics of the fission process itself. Many studies utilize thick-sources in order to stop all fission fragments quickly and mitigate Doppler effects of the observed gamma-rays.

Complementary information can be obtained using thin sources and auxiliary particle detectors coupled with these large Ge arrays. For example, ternary fission of ^{252}Cf [6] has been investigated using solar cells. Also, recent work using parallel-plate avalanche counters in conjunction with Gammasphere has extended level schemes of many neutron-rich nuclei to higher spin [7]. These experiments feature several advantages, including a) improved isotopic selectivity by utilizing a mass-gate in addition to gamma-ray coincidences; b) unambiguous determination of the origin of the gamma-rays from either the heavy or light fission fragment; and c) application of Doppler-shifts to the observed gamma-rays removes the limitation of studying excited states with lifetimes longer than the stopping time of the fission fragments [8].

In the present study of the ^{238}U$(\alpha, f\gamma\gamma\gamma)$ fusion-fission reaction [9], both the population of excited states has been extended to higher spins and the mass distribution for a given isotope chain is broader than obtained using SF sources. This experiment was carried out at the 88-inch cyclotron facility of the Lawrence Berkeley National Laboratory by bombarding a thin 300 μg/cm^2 ^{238}U target with a beam of α-particles at E_{lab} = 30 MeV. Fission fragments were detected by the Rochester highly-segmented 4π heavy-ion detector, CHICO[10], in coincidence with the detection of the de-excitation gamma-rays using Gammasphere. A total of $\sim$ 600 million events, with two fragments and at least three gamma-rays in coincidence, were collected. The deduced masses from the measured fission kinematics have a resolution of 12 mass units, which reflects the achieved time resolution of $\sim$ 500 ps. The achieved position resolution, $\sim 1^\circ$ in polar angle and 4.6° in azimuthal angle, is consistent with prior CHICO performance[11].

The spectroscopy of some of the neutron-rich Pd isotopes has been studied extensively [8,12,13]. Recently, the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions in ^{120}Pd have been identified at 438 keV and 618 keV, respectively[14]. In an attempt to extend the systematics of neutron-rich Pd isotopes to near spin 10^+, an $A = 110 - 130$ mass-gated $\gamma - \gamma - \gamma$ cube was analyzed using RADWARE[15] for ^{118}Pd and ^{120}Pd gamma-ray coincidences and a search for ^{122}Pd gamma-ray coincidence was performed.

The spectroscopy of neutron-rich isotopes of Cd has been investigated[16,17]. The level schemes of ^{122}Cd and ^{124}Cd by analyzing the $A = 110-130$ mass-gated $\gamma-\gamma-\gamma$ cube and building upon the radioactive decay data [18]. Negative parity states are also observable.

2. ^{117}Pd Analysis

A preliminary series of double gates on the 438-keV and 618-keV transitions, utilizing a wider gate width, contained gamma-rays belonging to ^{117}Pd and a weaker transition at 738 keV in coincidence with a weaker decay sequence. This work confirms the lower transitions in ^{117}Pd and extends the level scheme to that shown in Figure 1. Prior work for ^{117}Pd is discussed in [19]. Two additional strong transitions at 767 and 864 keV can be clearly assigned as members of the ground band of ^{117}Pd. A sum of all possible double gates on the 438-, 618-, 767-, and 864-keV transitions resulted in the identification of several more transitions in ^{117}Pd. Based on coincidence relationships, examination of many single and double gated spectra, and the relative intensities of gamma-rays, the level scheme shown in Fig. 1 was constructed for ^{117}Pd. The 848-keV transition was chosen as the $31/2^- \rightarrow 27/2^-$ of the ground band because of its larger intensity than the 903-keV or 952-keV transitions. No multipolarity measurements were performed. The widths of the arrows indicate the relative intensities of the transitions based on the assumption of $E2$ multipolarity for the ground band, and include corrections for the small internal conversion coefficients.

Note that the side band feeding the $27/2^-$ level, consisting of several lower energy transitions, is tentatively assigned here without spins and parities. While this side band is in coincidence with several gamma-rays from ^{117}Pd, its overall intensity when double gating on transitions within the side band seems anomalously high, and thus it cannot be excluded that this is a band structure from another nucleus in this mass region contributing to the background of one of the ^{117}Pd gates. It cannot also be excluded that a short-lived isomeric state (with respect to the time it takes a fission fragment to fly from the source and stop in the detector of approximately 10 ns) exists in ^{117}Pd that would distort the apparent relative intensities between this band and the ground band. The Doppler-shift correction cannot be properly applied for the in-flight delayed gamma-ray decay.

3. ^{118}Pd Analysis

Much work has been performed on the ^{118}Pd level scheme[8,12,13], resulting in some discrepancies in interpretation of this nucleus. For the systematics discussed later in this paper, it was necessary to reanalyze the data to see if some consistency could be achieved between the different experiments. It should be noted that the level schemes were constructed from different sets of data in different experiments, which might tend to emphasize the population of different nuclear states within the nucleus. M. Houry, *et al.*[13] used heavy-ion (^{12}C) induced fission of ^{238}U to populate ^{118}Pd. Zhang, *et al.*, used a ^{252}Cf SF[12] source to populate ^{118}Pd with a modest independent yield of 0.13%, while the present alpha-particle induced fission of ^{238}U experiment was used to populate ^{118}Pd [8]. A recent reanalysis of the ^{252}Cf SF data[20] has produced a modified and independently derived ^{118}Pd level scheme in almost total agreement with the level scheme derived from the Rochester ^{238}U(α,f) experiment [8] – the notable discrepancy being the selection of the $8^+ \rightarrow 6^+$ transition in the yrast-band. Thus, a reanalysis was performed of the present ^{238}U(α,f) experimental data by a different collaborator to attempt to resolve this discrepancy. Based on many single and double gates, relative intensities of the transitions, and coincidence relationships between the transitions, a level scheme was deduced from this effort and is shown in Fig. 2.

Note that some weaker transitions, mainly at the tops of bands, have not been included and at least one new transition (the 681-keV transition feeding the 2622.4-keV level) has been added. The main discrepancy, whether the $8^+ \rightarrow 6^+$ transition in the yrast band is the 539-keV or the 821.5-keV transition, may still exist, but from this work, based on systematics and the factor of 2 larger relative intensity for the 821.5-keV transition, it has

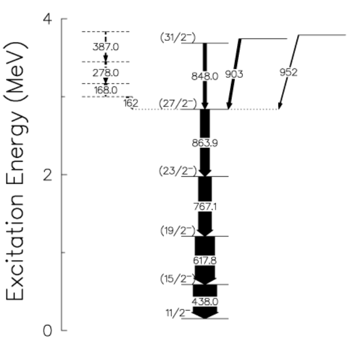


Figure 1. ^{117}Pd level scheme deduced from this work. Note the tentative assignment of the side-band (dashed lines) to this nucleus and see discussion in the text. The $11/2^-$ band is built on a 19.1 ms isomeric state at 203.2 keV.

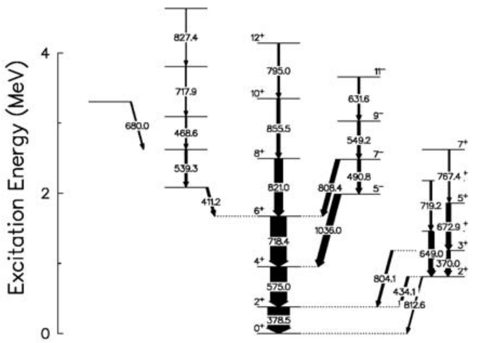


Figure 2. ^{118}Pd level scheme deduced from this work. The widths of the arrows indicating observed transitions are proportional to the relative intensities of the transitions.

been chosen for the yrast band. The order of the 411-keV and the 539-keV transitions is difficult to determine due to nearly identical relative intensities and lack of distinguishing transitions feeding or de-populating either level.

4. ^{120}Pd Analysis

Motivated by the report of the two lowest transitions in ^{120}Pd from the beta decay studies of ^{120}Rh [14], and the observation of a weaker transition in the ^{117}Pd gated spectrum, a re-examination of the double gates on the 437-keV and 618-keV transitions, with a narrower gate width, was performed. A sum gates spectrum identifies a few more transitions, but the decay sequence is weak (100 counts in peaks). The statistics of the ^{120}Pd spectra are generally poorer than comparable ^{118}Pd spectra, indicating population of this nuclide following fission is less than that of ^{118}Pd. Indeed, the ratio of the $4^+ \rightarrow 2^+$ transitions, $^{120}\text{Pd}/^{118}\text{Pd} = 0.16 \pm 0.04$. Coincidence relationships, and a variety of double gated spectra, enable the construction of the tentative level scheme for ^{120}Pd shown in Figure 3. It is interesting to observe that for only the $6^+ \rightarrow 4^+$ and higher transitions do the gamma-ray energies diverge from the ^{117}Pd sequence. This is the first observation of such a “degeneracy” of transition energies in closely related neutron-rich nuclei where one partner is an odd-A nucleus and the other an even-even nucleus. It should be noted that the observed transitions are weak and are only tentatively assigned to ^{120}Pd based on the ^{120}Rh decay data. These transitions were not observed in either ^{252}Cf SF data [20] nor the recent deep inelastic (DI) reaction data (^{64}Ni + ^{238}U , Se + U and Se + Pb experiments) from Argonne [21]. It should be noted that in the SF experiment, ^{120}Pd should be populated much less and in the DI reactions the background is higher than in the α + U experiment because there was not a fission fragment coincidence required.

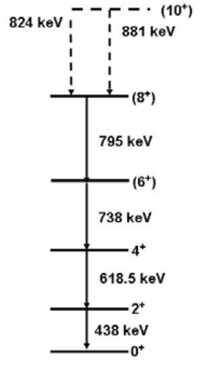


Figure 3. Decay sequence for ^{120}Pd deduced from a series of double gated spectra and coincidence relationships and discussed in the text.

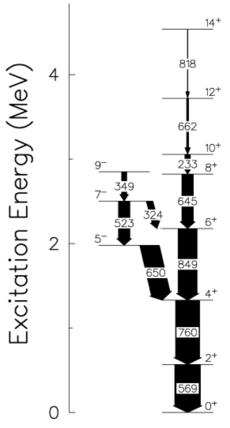


Figure 4. ^{122}Cd level scheme deduced from this work. The widths of the arrows indicating observed transitions are proportional to the relative intensities of the transitions.

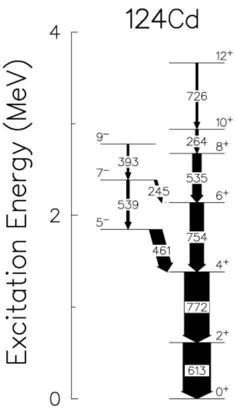
5. ^{122}Cd and ^{124}Cd Analysis

With the help of several double coincidence gated spectra, the ^{122}Cd level scheme shown in Figure 4 was constructed. The data is presented here as confirmation of prior work[16,17], and with the relative intensities observed for alpha-induced fission of ^{238}U.

By utilizing double coincident gated spectra, the ^{124}Cd level scheme shown in Figure 5 was constructed. Several new transitions, which were subsequently observed in other work [17], were observed including the $12^+ \rightarrow 10^+$ transition. The widths of the arrows are proportional to the relative intensities of the transitions.

6. Systematics

The relative intensities of the $4^+ \rightarrow 2^+$ transitions, gated on the $2^+ \rightarrow 0^+$ transitions, corrected for peak and gate efficiency, of even-even Pd isotopes observed in the U(α,f) experiment in arbitrary units are shown in Figure 6 together with the Pd independent yields from 14 MeV neutron-induced fission of ^{238}U, ^{239,240}Pu and from fission spectrum neutron induced fission of ^{238}U. The peak of the population for Pd isotopes is near ^{114}Pd for fission from n + ^{240}Pu and α + ^{238}U (with only one neutron more in the compound



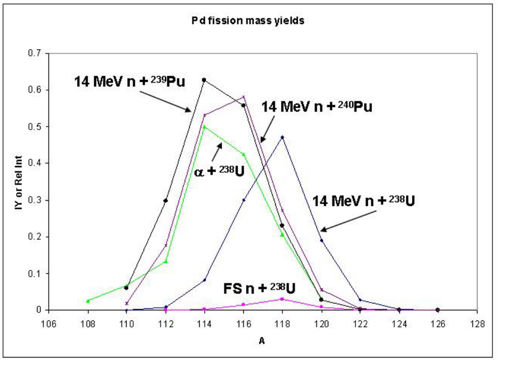


Figure 5. ^{124}Cd level scheme deduced from this work. The widths of the arrows are proportional to the relative intensities of the transitions.

Figure 6. Comparison of the relative intensities of even-even Pd isotopes observed in the ^{238}U(α,f) experiment with independent yields for several neutron induced fissioning systems.

system), dropping nearly an order of magnitude by the time ^{120}Pd is reached. This is in contrast to the ^{238}U neutron-induced fission data where the independent yields for Pd peak around mass 118. The 14-MeV neutron-induced fission of ^{240}Pu is directly comparable with the alpha-induced fission of ^{238}U distribution, and peaks at $A = 114$ with approximately the same FWHM = 6 mass units.

The levels of the even-even Pd nuclides with $50 \leq N \leq 74$ are shown in Figure 7. The new data for ^{118,120}Pd now make it possible to observe several interesting facets of these levels in a systematic fashion. These levels can be classified on the basis of the smooth behavior of the 8^+ levels. For ^{96}Pd$_{50}$ the 6^+ and 8^+ levels are relative pure $\pi(g_{9/2})^2$ seniority 2 proton states, whereas the higher-energy 10^+ level must be a seniority 4 state. When two neutrons are added to make ^{98}Pd, additional two-neutron states are available, in particular the $\nu d_{5/2}\ \nu g_{7/2}$ 6^+ level that lies near 2.1 MeV for ^{98,100,102,104,106}Pd. The p-n interaction among the four proton holes and the neutrons pushes the lower members of the yrast band down away from both the 8^+ and 10^+ levels. For ^{106}Pd with $N = 60$, however, a rather sharp shift in the systematic behavior of the level structure can be observed. At higher spin, this corresponds to the rise in the Fermi level that lowers the energy for the two-neutron $(h_{11/2})$ 10^+ level. Accompanying this 10^+ level will also be a two-neutron 6^+ and 8^+ level. These 6^+ and 8^+ levels mix with the two-proton 8^+ level and the $\nu d_{5/2}\ \nu g_{7/2}$ 6^+ level , generating collective effects that also push these levels down to lower energies that come to a minimum for ^{114}Pd. Perhaps the most interesting feature is the remarkable symmetry of the 2^+ energies nuclides on each side of ^{114}Pd$_{68}$ for neutron numbers $62 \leq N \leq 74$, namely, out to the new data reported in this paper (for example ^{108}Pd and ^{120}Pd have 2^+ energies only 4 keV different). Indeed, the search for levels in

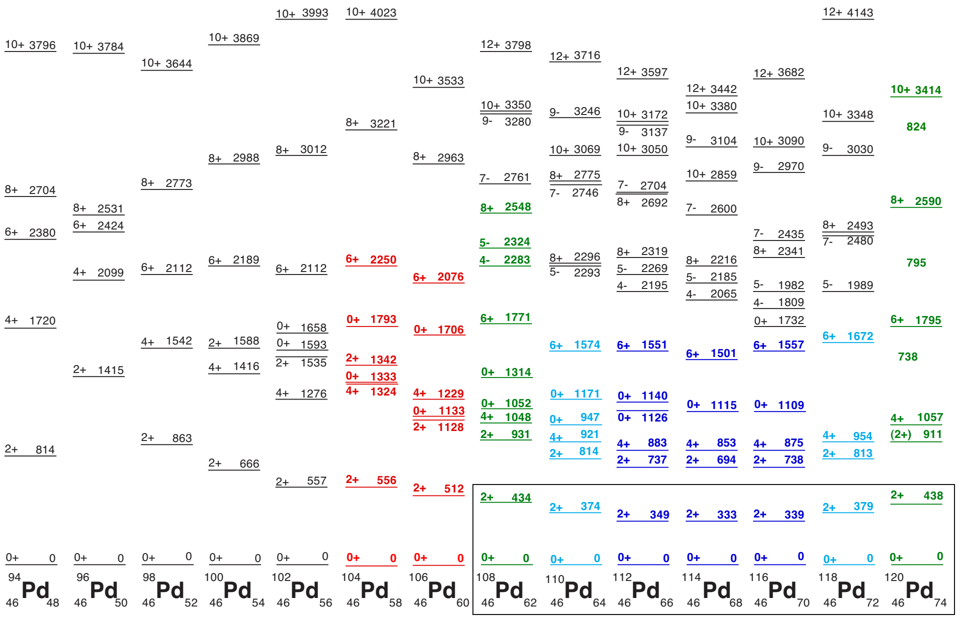


Figure 7. The lowest lying levels in even-even Pd isotopes from the $N = 50$ closed neutron shell to the new ^{120}Pd data discussed in this paper. Several interesting systematic features can be observed and are discussed more fully in the text.

^{122}Pd with a 2^+ energy near 512 keV was stimulated by the construction of this figure. We should also note the rather close values for the 4^+ energies (shown in bold) for these nuclides as well. Beyond ^{122}Pd, one might expect shell properties to begin to dominate over the collective properties as the $N = 82$ closed shell at ^{128}Pd is approached. The excited levels in ^{124}Pd and ^{126}Pd might possibly be influenced by this shell closure and deviate from the symmetric parabola of 2^+ states highlighted with the box in Fig. 7, just as the 2^+ energies deviate for nuclides below ^{106}Pd as one approaches the closed $N = 56$ subshell.

In summary, it can be seen that the determination of the excited states for ^{118,120}Pd has permitted considerable insight into the collective and non-collective behavior of the Pd level structures over a wide range of neutron numbers. Moreover, these data also reveal clear differences between collective and non-collective states as protons are removed from the Sn closed shell for $N = 72$ and $N = 74$ isotones. New gamma-ray transitions in ^{120}Pd have been observed following alpha-particle induced fission of ^{238}U. Transitions in ^{118}Pd have been confirmed, reducing the discrepancy with prior work. A search for gamma-rays in ^{122}Pd was inconclusive. The systematics of neutron-rich isotopes of Pd indicates remarkable symmetry of the 2^+ levels in nuclei surrounding ^{114}Pd. Several new transitions in ^{124}Cd were observed and the level schemes for ^{122,124}Cd were deduced from this work.

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