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GAMMA-DECAY OF THE DEEPLY-BOUND HOLE STATES POPULATED IN THE ^{102}Pd(^{3}He, α)^{101}Pd REACTION AT 70 MeV

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The γ-decay of deeply-bound hole states in ^{101}Pd formed in the ^{102}Pd(^{3}He, α) reaction at 70 MeV has been studied. The sharp peak at $E_x = 2.4$ MeV containing a large fraction of the $g_{9/2}$ hole strength decays to the $7/2^+$ state at 0.261 MeV with an M1-E2 mixing ratio $\delta = -0.35^{+0.12}_{-0.15}$. The broad bump around $E_x = 4$ MeV with $\Gamma \approx 1$ MeV decays statistically indicating the complete spreading of the hole strength over the underlying non-collective states.

The spreading mechanism of deeply-bound hole states is a topic of interest. Below the neutron threshold, the experimentally observed width is solely due to the spreading of the hole strength over the underlying states. This spreading is believed to occur in two stages. In the early stage of the fragmentation the strength of the deeply-bound hole state spreads over collective doorway states, e.g. collective 3-qp (quasiparticle) and 5-qp [1–5], or isospin core-polarized states [6], which then are damped statistically over the many degrees of freedom of the nucleus. Experimentally, deeply-bound hole states have been observed [1,7] as giant-resonance-like structures in pickup reactions with widths up to several MeV.

To obtain experimental information on the spreading mechanism, the γ-decay of the deeply-bound hole states has been studied. Pickup reactions such as the (^{3}He, α) populate the residual states via their single-hole components, whereas the γ-decay transition probability is very sensitive to admixtures of collective and/or non-collective components to the hole states. Since the $1g_{9/2}$ single-hole strength in ^{101}Pd is divided mainly into two excitation energy regions both lying below the neutron threshold [5], this nucleus is especially suitable for such a study. In the ^{102}Pd(^{3}He, α) reaction a sharp peak is observed at an excitation energy $E_x = 2.4$ MeV in ^{101}Pd with a large fraction of the $g_{9/2}$ hole strength (spectroscopic factor $C^2S = 2.0$) and a broad bump is observed around $E_x \approx 4$ MeV with $\Gamma_{\mathrm{fwhm}} \approx 1$ MeV ($C^2S \approx 2$ for $g_{9/2}$). While the sharpness of the peak at $E_x = 2.4$ MeV appears to result from the early fragmentation stage of spreading, the broad bump seems to indicate a full spreading over underlying non-collective states. The broad bump possibly also contains $l = 1$ and 3 strength from the next inner shell [5].

The γ-decay properties of deeply-bound hole states in ^{101}Pd excited in the ^{102}Pd(^{3}He, α) reaction at 70 MeV were studied by measuring the γ-ray spectrum in coincidence with the α-particles. The ^{3}He beam was provided by the KVI cyclotron and the α-particles were detected by the QMG/2 magnetic spectrograph [8]. The ^{102}Pd target was an isotopically enriched (> 80%) metallic foil with a thickness of 300 μg/cm^2. The spectrograph was set at $\theta_{\mathrm{lab}} = 0°$ with respect to the beam where the pickup cross sections of the deeply-bound hole states have their maximum values. The ^{3}He beam was stopped after the first dipole magnet of the spectrograph which shielded the γ-detectors from γ-rays and neutrons originating from the Faraday cup. The solid angle of the spectrograph was 6.9 msr. Coincident γ-ray spectra were measured simultaneously with a ≈100 cm^3 high-purity Ge detector and with a 12.7 cm ϕ × 15.2 cm NaI(Tl) detector. The Ge detec-

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tor was positioned at −135° throughout the experiment. The α–γ angular correlation was measured by placing the NaI(Tl) detector at 90°, 120°, 135° and 150° with respect to the beam axis. A 2 mm thick Pb plate was put in front of the NaI(Tl) detector to attenuate low-energy γ-rays. The γ-ray detection efficiency of the NaI(Tl) detector was almost constant for γ-ray energies >300 keV. Due to the detection of the α-particles at 0° only the $M = \pm 1/2$ magnetic substates in ^{101}Pd are populated.

Fig. 1a shows a singles α-particle spectrum. The sharp peak at $E_x = 2.4$ MeV and a broad bump at around $E_x \approx 4$ MeV with $\Gamma_{\mathrm{fwhm}} \approx 1$ MeV are clearly seen. The spectrum in fig. 1b is a total-energy spectrum obtained by adding the energy of coincident γ-rays in the NaI(Tl) detector to the α-energy of the sin-

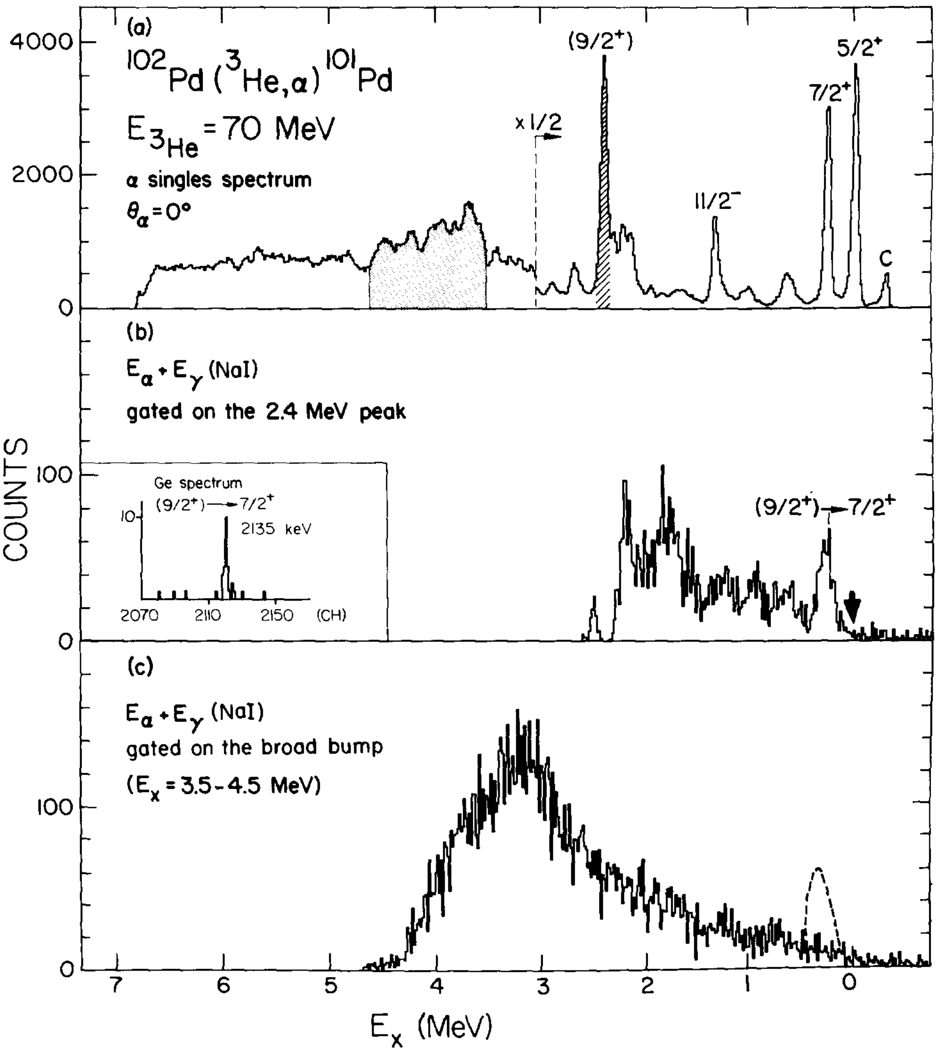

Fig. 1. (a) The singles α-spectrum from the ^{102}Pd(^{3}He, α)^{101}Pd reaction at $\theta_\alpha = 0°$. The peak due to the target impurity is indicated by C. (b) The total-energy spectrum $E_\alpha + E_\gamma$(NaI) obtained by gating on the peak at $E_x = 2.4$ MeV of the α-spectrum [hatched area in (a)]. (c) Same but with a gate on the broad bump at around $E_x \approx 4$ MeV [dotted area in (a)]. The inset is a part of the γ-ray spectrum observed with the Ge detector. For details see text.

gle peak at 2.4 MeV (dashed area in fig. 1a). A comparison with the singles α-spectrum in fig. 1a readily leads to the identification of the final states into which the 2.4 MeV peak decays. The strong γ-decay feeding the low-lying $7/2^+$ state at 0.261 MeV is clearly seen. In the inset, a part of the Ge spectrum corresponding to the decay of the 2.4 MeV peak to the $7/2^+$ state at 0.261 MeV is also shown. It is interesting to note that the 2.4 MeV structure consists most likely of only one peak (2.396 MeV) within the 2.5 keV resolution of the Ge detector.

The decay pattern of the 2.4 MeV state is shown in fig. 2a. It was obtained from the energy and intensity relations of the γ-rays measured with the Ge detector and by making use of the known level scheme [9] of ^{101}Pd. The data were corrected for accidental coincidences and for internal conversion. Combined with the $l = 4$ assignment from the (d, t) reaction [5] our results for the decay pattern strongly suggest that the spin-parity of the 2.4 MeV state is $9/2^+$.

Fig. 1c is again the total energy spectrum but gated on the broad bump around $E_x \approx 4$ MeV (dotted area in fig. 1a) which has almost the same strength of the $l = 4$ ($g_{9/2}$) deeply-bound hole state as the 2.4 MeV peak [5]. Therefore one might also expect a strong γ-decay to the $7/2^+$ state at 0.261 MeV. The spectrum, however, shows no strong γ-decay connecting the broad bump with low-lying excited states in striking contrast to the decay pattern of the 2.4 MeV peak. This might be taken as evidence that for this bump the spreading over the many degrees of freedom of the nucleus has set in and therefore only statistical γ-decay takes place. The dashed curve in fig. 1c is drawn to indicate the γ-ray peak that would be observed if the $l = 4$ bump around 4 MeV were to decay to the $7/2^+$ state at 0.261 MeV with an intensity equal to that of the 2.4 MeV peak.

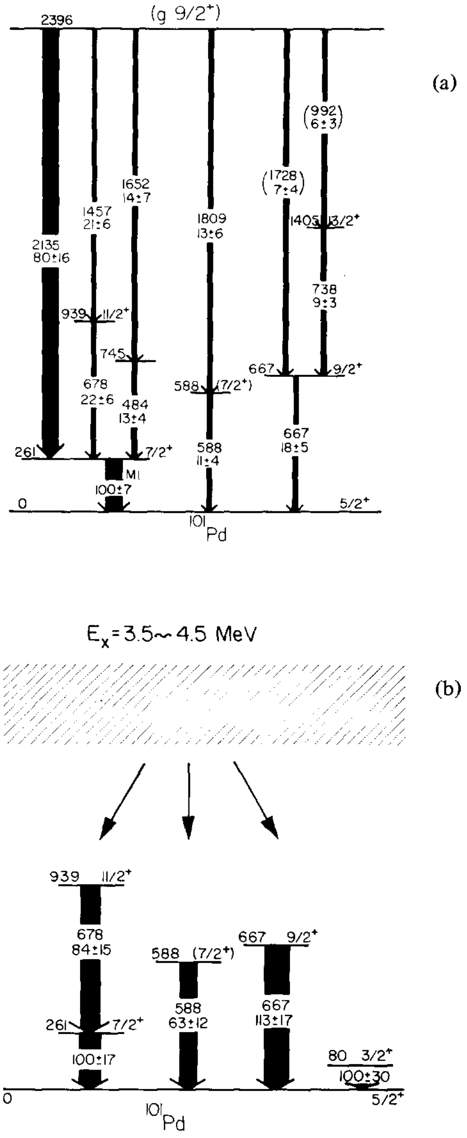

Fig. 2. The γ-decay pattern from the sharp peak at 2.4 MeV (a) and from the broad bump at around 4 MeV (b). Spin-parity assignments are according to ref. [9]. The excitation energies are given in keV. The intensity normalized to that of the transition of the $7/2^+$ state at 261 keV to the ground state is given in percent.

Fig. 2b shows the γ-decay pattern from the broad bump as seen in the Ge detector. Only few γ-ray lines could be identified. Low-spin states in the low excitation region such as the $3/2^+$ state at $E_x = 80$ keV are strongly populated, in contrast with the decay of the sharp peak at 2.4 MeV which populates states with $J \geqslant 7/2$. This is probably due to the $l = 1$ strength in the broad bump, which is reported in ref. [5], since the low-spin deeply-bound hole states such as $J^\pi = 3/2^-$ or $1/2^-$ decay preferentially to low-spin final states. It is interesting that the decay of deeply-bound hole states also populates non-hole states such as the $11/2^+$ state at 0.939 MeV or $9/2^+$ state at 0.667 MeV which are considered to be particle-rotation coupled states [10].

The γ-ray multiplicity (M_γ) was also deduced by using the coincident NaI(T1) data. The M_γ from the decay of the 9/2$^+$ state at 2.4 MeV and the broad bump at around 4 MeV are 2.2 ± 0.2 and 2.9 ± 0.3, respectively. These values were obtained by normalizing to the M_γ value of the 11/2$^-$ state at 1.34 MeV which is known [9] to be 2.0.

The α–γ angular correlation of the direct transition from the 2.4 MeV state to the 0.261 MeV state (the 2.135 MeV γ-ray) was measured and gave an M1 – E2 mixing ratio [‡1] $\delta = -0.35^{+0.10}_{-0.15}$ as indicated in fig. 3. This value has been corrected for the finite solid angles of the NaI(T1) detector and the spectrograph. The uncertainty quoted for the value of δ corresponds to a 99% confidence limit. The mixing ratio is defined by

$$\delta(\mathrm{M1} - \mathrm{E2}) = \tfrac{1}{120} E\,(\mathrm{MeV})\ [B(\mathrm{E2})/B(\mathrm{M1})]^{1/2},$$

where E is the transition energy and B(M1) and B(E2) are the reduced M1 and E2 transition probabilities, respectively. If we use the single-particle (hole) estimate for B(M1) and if we assume a hindrance factor of 2 to 3 for B(M1) taking into account the core polarization effect for a spin-flip-type transition [12], then we get $B(\mathrm{E2}) = 310^{+320}_{-150}$ to $200^{+210}_{-100}\ e^2\ \mathrm{fm}^4$. This B(E2) value is about 10 to 7 times enhanced compared with the Weisskopf unit. This large enhancement suggests that the $g_{9/2}$ deeply-bound hole state at 2.4 MeV and/or the 7/2$^+$ state at 0.261 MeV may contain substantial collective components, although the 9/2$^+$ state decays mainly by an M1 transition to its 7/2$^+$ spin–orbit partner at 0.261 MeV. If we assume the same enhancement for the possible E2 transition from the 9/2$^+$ state to the 5/2$^+$ ground state, about 23% of the strength of the decay from the 9/2$^+$ state to the 7/2$^+$ state would be expected for the decay from the 9/2$^+$ state to the 5/2$^+$ ground state. However, the direct γ-decay to the 5/2$^+$ ground state is not observed (less than 0.3 WU). The expected position of the possible peak corresponding to the direct γ-decay is indicated by an arrow in fig. 1b. The absence of the direct γ-decay to the ground state is not yet understood.

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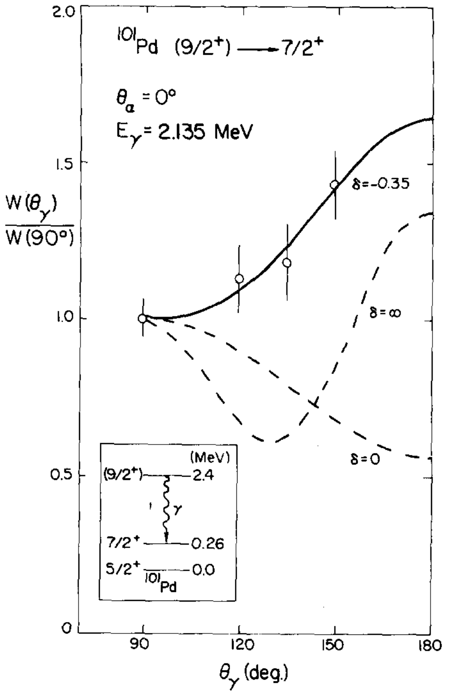

Fig. 3. The angular correlation for the decay of the 2.4 MeV state to the 7/2$^+$ state at 0.261 MeV. The solid curve is the best fit and dashed curves are for δ = 0 and ∞, respectively. The inset shows a portion of the decay scheme.

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[‡1] We use the phase convention of Rose and Brink [11].