PHYSICAL REVIEW C VOLUME 18, NUMBER 3 SEPTEMBER 1978

Decay of mass-separated ^{126}Cd

M. L. Gartner and John C. Hill
Ames Laboratory-USDOE and Department of Physics, Iowa State University, Ames, Iowa 50011

(Received 17 May 1978)

The decay scheme of neutron-rich ^{126}Cd is reported for the first time. Sources of mass-separated ^{126}Cd were produced using an in-beam target ion source combination. The ^{126}Cd half-life was measured to be 0.506 ± 0.015 sec. Of 11 γ rays observed, 10 were placed in a ^{126}In level scheme consisting of 6 excited states at 260, 308, 555, 585, 626, and 688 keV. The level density of low-spin excited states is less than that for ^{124}In, and most of our levels are describable in terms of a single proton hole coupled to a single neutron hole. Surprisingly, most of the β strength feeds one level in ^{126}In at 688 keV.

[RADIOACTIVITY ^{126}Cd [from ^{235}U(n,f)]; measured $T_{1/2}$, E_γ, I_γ, $\gamma\gamma$-coin, Ge(Li) detectors; ^{126}In deduced levels, J, π, logft. Mass separated ^{126}Cd activity.]

I. INTRODUCTION

The development of an in-beam integrated target ion source for use with the TRISTAN on-line mass-separator system has made possible the study of the level structure of very neutron-rich Cd, In, and Sn nuclei populated by the decay of Ag, Cd, and In isotopes with half-lives as short as a few tenths of a second. The odd-odd In nuclei are of interest in that their low-lying states should be describable in terms of a $g_{9/2}$ or $p_{1/2}$ proton hole coupled to an $h_{11/2}$, $g_{7/2}$, $d_{3/2}$, $d_{5/2}$, or $s_{1/2}$ neutron particle (hole). In most cases the In ground and isomeric states are describable as $\pi(g_{9/2})^{-1}\nu(g_{7/2})$. This work was undertaken in order to extend the systematics of low-spin states in odd-odd In nuclei to $A = 126$ by studying the decay of ^{126}Cd.

No decay scheme for ^{126}Cd is available, and no information on its decay exists in the published literature. Its existence has been reported in an internal publication[1] by the group at the OSIRIS separator. They observed a half-life of 0.53 ±0.1 sec and two γ rays with energies of 261 and 428 keV. There is also no information on excited states in ^{126}In from reaction experiments. Some information is available on levels in odd-odd In nuclei from $A = 106$ to 124. A notable feature is the existence of a low-spin and generally one or more high-spin isomers. In most cases the low-spin isomer is the ground state. Its J^π is 2^+ or greater for $A = 106$ through 110 changing to 1^+ for $A = 112$ through 122. Fogelberg *et al.*[2] postulated J^π to change back to 2^+ for $A = 124$.

Studies of the decays of even-even Cd or Sn nuclei to levels in odd-odd In nuclei only provide information on the low-spin levels. Although some information is available on the decays of ^{108}Sn, ^{110}Sn, ^{118}Cd, ^{120}Cd, ^{122}Cd, and ^{124}Cd, excited states in In were observed to be populated only in the ^{108}Sn,[3] ^{110}Sn,[4] and ^{124}Cd (Ref. 2) cases. The ^{124}In case is of special interest since a number of low-spin ($J = 0, 1$) positive parity states were postulated in ^{124}In which cannot be described in terms of the coupling of one proton hole to one neutron hole. No In excited states were observed in the decays of ^{118}Cd,[5] ^{120}Cd,[6] and ^{122}Cd[6]. This fact, as well as β feedings of >96% and >94%, respectively, to the In ground states, was used to justify a J^π of 1^+ for the ^{120}In and ^{122}In ground states.[6] By analogy, Fogelberg *et al.*[2] used the observation of strong γ transitions in the ^{124}Cd decay to justify a J^π of 2^+ for the ^{124}In low-spin isomeric state.

Levels in odd-odd In nuclei near stability from $A = 108$ to 116 have been studied using (α, n),[7,8] (^{6}Li$, 4n)$,[7] (p, n),[3,8,9] (d, p)[10,11] (d, d),[10] (d, t),[10] and (n, γ)[11] reactions. Although much information was obtained for levels with $J \geq 3$, the information on low-spin levels is quite limited. In most cases three or less levels with $J^\pi = 1^+$ or 2^+ were observed between 0 and 1 MeV. One can obtain a 1^+ and a 2^+ state from $(\pi g_{9/2}{}^{-1})(\nu g_{7/2}{}^{-1})$ and a 2^+ state from $(\pi g_{9/2}{}^{-1})(\nu d_{5/2}{}^{-1})$. More complete data on low-spin states are available for ^{108}In (Ref. 3) and ^{116}In.[10,11] In both cases the number of 1^+ and 2^+ states between 0 and 1 MeV is too large to be explained in terms of simple two-hole excitations. It has been suggested that the additional states can be described in terms of three neutron hole states coupled to a $g_{9/2}$ proton hole[11] or hole-phonon couplings.[11]

Studies of low-spin levels in ^{124}In populated in the ^{124}Cd decay have revealed two 1^+, one 2^+, and one 1^- states below 300 keV which are impossible to explain in terms of single-hole excitations.[2] We have undertaken this study of the low-spin levels in ^{126}In to see if the high density of low-spin positive-parity states persists as a neutron pair is added to ^{124}In.

II. EXPERIMENTAL METHODS AND RESULTS

Sources of mass separated ^{126}Cd for this study were produced with the TRISTAN on-line isotope-separator located at the Ames Laboratory Research Reactor. This system is essentially the same as that described earlier,[12] however, TRISTAN now has a new ion source, similar to the one at the OSIRIS separator.[13] The target ion source combination, which contains a target consisting of a few grams of ^{235}UO$_2$, is situated directly in the neutron beam (flux—$3 \times 10^9 n/\text{cm}^2$ sec) and makes possible the separation of a number of nongaseous fission products, one of which is the subject of this study. The details of this ion source will be presented in a future publication.

γ rays from the decay of ^{126}Cd were observed using Ge(Li) (large volume coaxial with 15% efficiencies) and LEPS (low energy photon spectrometer) detectors located near the point of beam deposition. γ singles measurements were made to determine γ-ray energies and intensities, γ-spectrum multiscaling was used to determine the half-life of ^{126}Cd, and $\gamma\gamma$-coincidence measurements were made to determine transition placements.

Sixteen time bins, each 0.1 sec in duration, were used for the half-life measurement. Multiscaling was started after the beam had been collected on a movable tape for 2 sec. At the end of the multiscaling cycle the tape was moved and a new sample collected. This procedure was repeated for a total of 15 h. Figure 1 shows the decay curves for the 260- and 428-keV γ rays. Weighted least-squares fits to the data yield a half-life of 0.509 ± 0.01 sec for the 260-keV γ ray and a half-life of 0.504 ± 0.01 sec for the 428-keV γ ray. We propose therefore that the half-life of ^{126}Cd is 0.506 ± 0.015 sec. This value is consistent with the value of 0.53 sec reported by Grapengiesser.[1]

Two different γ singles measurements were made to enhance the ^{126}Cd and ^{126}In activity, respectively. Both experiments lasted about 15 h. The ^{126}Cd activity was enhanced by simultaneously collecting the beam on the tape and counting for 2 sec and subsequently moving the sample away from the detector before collecting a fresh sample. ^{126}In activity was enhanced by collecting the beam for 6 sec, moving the tape so that the sample was shielded from the beam, delaying for 3 sec to allow the ^{126}Cd activity to die away, and then counting for 6 sec. Representative LEPS γ spectra from 0 to 115 keV are shown in the top half of Fig. 2. The part labeled (a) is the ^{126}Cd enhanced spectrum, and the part labeled (b) is the ^{126}In enhanced spectrum. In the bottom half of Fig. 2 representative Ge(Li) γ spectra are shown,

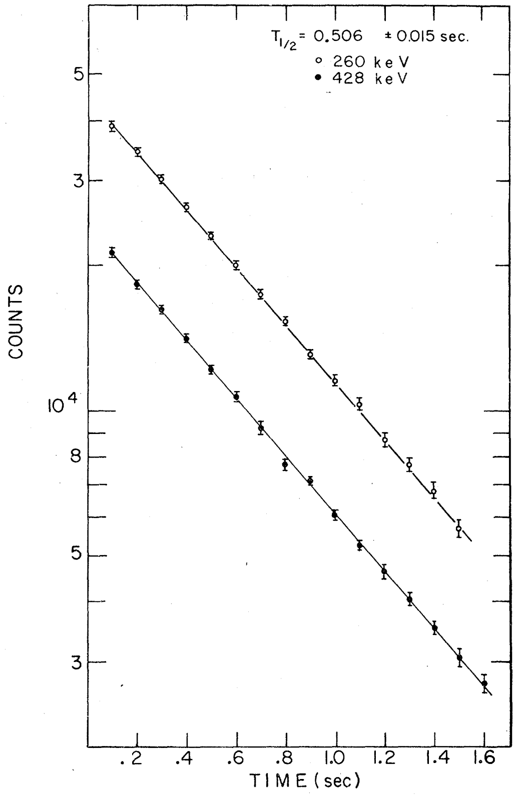

FIG. 1. Decay curves for ^{126}Cd γ rays.

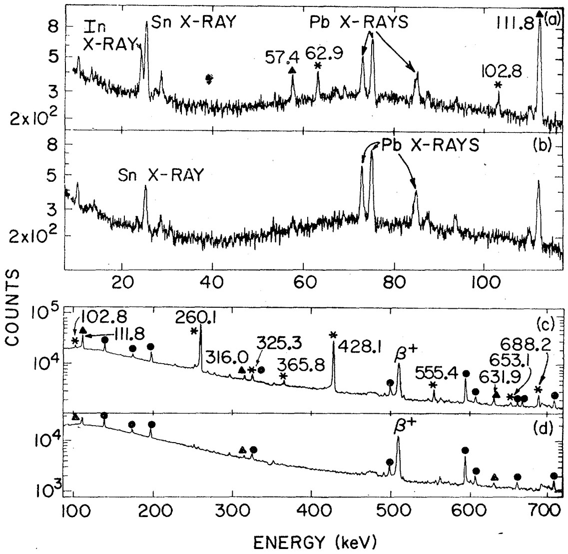

FIG. 2. Spectra of γ rays accompanying the decay of ^{126}Cd. (a) ^{126}Cd enhanced LEPS spectrum from 0 to 115 keV. (b) ^{126}In enhanced LEPS spectrum from 0 to 115 keV. (c) ^{126}Cd enhanced Ge(Li) spectrum from 90 to 700 keV. (d) ^{126}In enhanced Ge(Li) spectrum from 90 to 700 keV. The symbol * indicates ^{126}Cd, ▲ indicates ^{126}In, and ● indicates background.

Table I. γ transitions observed in ^{126}Cd decay.

Energy (keV)	Relative[a] intensity	Placement (keV)
62.93 ± 0.20	16 ± 3	688-626
102.8 ± 0.3	12 ± 4	688-586
260.09 ± 0.09	1000 ± 40	260-0
277.4 ± 0.5[b]	6 ± 2[b]	586-308
325.3 ± 0.4[c]	6 ± 3[c]	586-260
365.82 ± 0.20	23 ± 6	626-260
428.11 ± 0.06	837 ± 28	688-260
555.40 ± 0.09	48 ± 6	555-0
585.6 ± 0.5	9 ± 3	586-0
653.08 ± 0.19	12 ± 4	unplaced
688.23 ± 0.10	59 ± 4	688-0

[a] γ intensities normalized to 1000 for the 260-keV γ ray.

[b] Values obtained from spectrum in coincidence with the 103-keV γ ray.

[c] Values obtained from spectrum in coincidence with the 260-keV γ ray.

the part labeled (c) is the ^{126}Cd enhanced spectrum, and the part labeled (d) is the ^{126}In enhanced spectrum. Spectra up to 7 MeV were obtained, but no γ rays above the one at 688 keV have been assigned to ^{126}Cd. Hence only the Ge(Li) spectra from 100–700 keV are displayed. ^{126}Cd peaks are labeled with asterisks and the energies are given in keV.

Standard sources of ^{22}Na, ^{56}Co, ^{133}Ba, ^{182}Ta, and ^{226}Ra were used to provide energy and intensity calibration and map the nonlinearities of the systems. The centroids and areas of the peaks were determined by a nonlinear least-squares method in which the fitting function was a skewed Gaussian. The energies and intensities of all but two (277 and 325 keV) of the 11 γ rays assigned to ^{126}Cd were obtained from the singles spectra. Background peaks mask the 277- and 325-keV peaks in the singles spectra. Hence the energies and intensities of these γ rays were obtained from gated coincidence spectra, using the energies of known ^{126}Cd and ^{126}In γ rays to determine the energy calibration. Table I is a listing of the energies, intensities, and placements of the γ rays which have been assigned to the decay of ^{126}Cd.

Two Ge(Li) detectors in 180° geometry were used for the coincidence measurements. A standard arrangement of apparatus was used with constant fraction timing and an acceptance window of 60 ns. Beam deposition and counting occurred simultaneously, and the tape was moved periodically to inhibit interference from long-lived products. Coincidence events were stored in a buffered memory with a 4096 × 4096 channel array and transferred to magnetic tape whenever the buffer was filled. Spectra in coincidence with selected peak and background gates were obtained by computer sorting. A visual comparison of peak and background gated spectra was made to determine the coincidence relationships. Sample gated spectra for the 260- and 428-keV γ rays are shown in Fig. 3, where the part labeled (a) is the 260-keV gate and that labeled (b) is the 428-keV gate. The energies are again given in keV. Table II is a summary of the coincidence results.

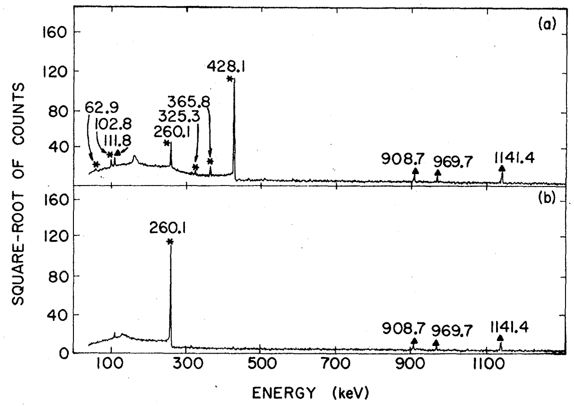

FIG. 3. Spectra in coincidence with γ rays from ^{126}Cd at (a) 260 and (b) 428 keV. The symbol * indicates ^{126}Cd, and ▲ indicates ^{126}In.

III. DECAY SCHEME AND DISCUSSION

The γ measurements described above were used to construct the first available decay scheme for ^{126}Cd. Our value for the ^{126}Cd half-life of 0.506 ±0.015 sec is considerably smaller and outside of the range of values from about 2 to 200 sec predicted by the gross theory of β decay.[14] The half-lives for ^{120}Cd, ^{122}Cd, and ^{124}Cd are also considerably less than the predictions of the gross theory.

The ^{126}In level scheme based on our γ-ray singles and coincidence data is shown in Fig. 4. It is difficult to precisely determine J^{π}'s for levels in ^{126}In since the strength of β feeding to the ^{126}In ground

TABLE II. $\gamma\gamma$ coincidences observed in ^{126}Cd decay.

Gating energy (keV)	Definite coincidences (keV)	Possible coincidences (keV)
63	366	260
103	277, 325, 586	260
260	63, 103, 325, 366, 428	586[a]
277	103	
325	103,260	
366	63, 260	
428	260	
586	103	260[a]

[a] Not consistent with placement proposed in this work.

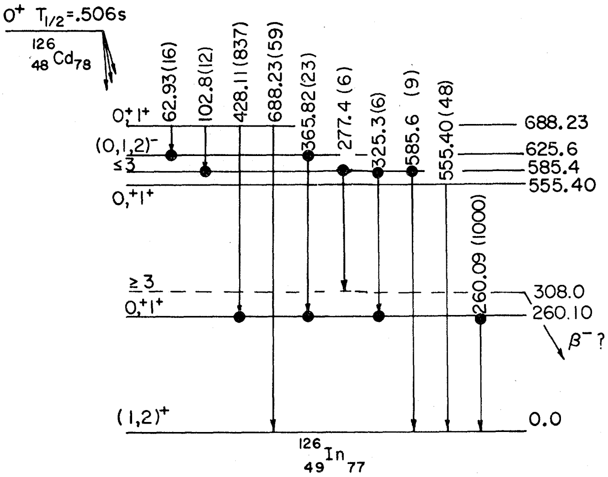

FIG. 4. Decay scheme of ^{126}Cd from this work.

state is not known and difficult to measure. Some J^π information can be obtained by assuming a ground state β feeding and calculating the corresponding $\log ft$. A Q_β of 4.6 MeV from the mass tables of Garvey *et al.*[15] was used. A discussion of the individual ^{126}In levels follows.

Ground state: The ^{126}Cd ground state is 0^+. Odd-odd In isotopes from ^{112}In through ^{122}In all have 1^+ ground states. These states are described as $(\pi g_{9/2}{}^{-1}, \nu g_{7/2}{}^{-1})_{J=1^+}$ The J^π for the ^{124}In ground state has been postulated to be 2^+ based on the decay characteristics of both ^{124}Cd and ^{124}In. This 2^+ state may also be a member of the above multiplet. The strong γ strength associated with ^{124}Cd decay was taken as additional evidence for $J > 1$. This case is a sharp contrast to that of ^{120}Cd and ^{122}Cd where no γ strength was observed.[6] For these cases the 1^+ for the In ground state allows the β decay from the corresponding even-even Cd nucleus to proceed through the In ground state with greater than 94% of the total strength. The case of ^{126}Cd decay is similar to that for ^{124}Cd in that the associated γ strength is quite large (comparable to that of the ^{126}In daughter). Thus a first-forbidden or higher β transition between the ^{126}Cd and ^{126}In ground states is most plausible. Assuming a $\log ft > 5.9$ (a β transition with $\log ft < 5.9$ must be allowed[16]) then implies that the β feeding to the ground state is less than 1%. We favor a J^π of 2^+ for the ^{126}In ground state. Higher spins are improbable due to the absence of β feeding from ^{126}In to the lowest-lying 4^+ state in ^{126}Sn determined in a parallel study in this laboratory. A negative parity for the ^{126}In ground state is unlikely from systematics and observation of an allowed β transition to the lowest-lying 2^+ state in ^{126}Sn. A less plausible but possible interpretation is that J^π for the ^{126}In ground state is 1^+ (0^+ is rejected on shell-model grounds.)

260.10±0.08-keV level. The strongest γ ray and the one with the richest γ-coincidence spectrum was at 260 keV. We thus postulate the first excited state to be at 260 keV. For a ground state β feeding less than 93% the $\log ft$ for the 260-keV level is less than 5.9. The γ strength of the ^{126}Cd decay is probably inconsistent with β feeding to the ground state of greater than 90%, therefore we favor a J^π of 0^+ or 1^+ for the 260-keV level.

308.0±0.6-keV level. The existence of this level is based on the 585- and 688-keV levels discussed below and the definite coincidence between the 277- and 103-keV γ rays. Because of the lack of coincidence between the 277- and the strong 428- and 688-keV rays, the 277-keV transition cannot feed the 688-keV level. The other possibility is that it depopulates the 585-keV level to a new level at 308 keV. No γ ray is observed between this level and either the ground state or 260-keV level, and no coincidence is observed between the 277- and 260-keV γ rays. A possible explanation is that the 277-keV γ ray populates an intermediate spin ^{126}In isomer which then β decays to levels in ^{126}Sn. Similar isomers have been seen in other In nuclei.[8] The existence of this level is uncertain, thus it is indicated by a dashed line in Fig. 4.

555.40±0.1-keV level. This level is based on the lack of a coincidence between the 555-keV γ ray and any other γ transition. We consider the intensity of the 555-keV γ ray large enough to merit placement directly feeding the ^{126}In ground state. A ground state β feeding of 90% gives $\log ft = 6.0$ for the above level. Since such strong β feeding is unlikely, as discussed above, we favor a J^π of 0^+ or 1^+ for this level.

585.4±0.2-keV level. This well established level is based on coincidences between the 260- and 325-keV γ rays and a good energy match with the 586-keV crossover γ ray. The β feeding to this level cannot be shown to be nonzero within our γ-intensity uncertainties if internal conversion of the 103-keV transition is considered. Depopulation of this level to the 260-keV level implies $J \leq 3$.

625.6±0.3-keV level. This level is established by coincidence between the 260-, 366-, and 63-keV γ rays. A consideration of possible conversion coefficients for the 63-keV transition indicates that only $E1$ is possible. Assumption of $M1$ for the 63-keV transition gives an intensity into the 625-keV level that is over 50% greater than the depopulating intensity. The level thus has negative parity.

688.23±0.08-keV level. Most of the ^{126}Cd β strength populates this level. It is well established by coincidences and a good energy match

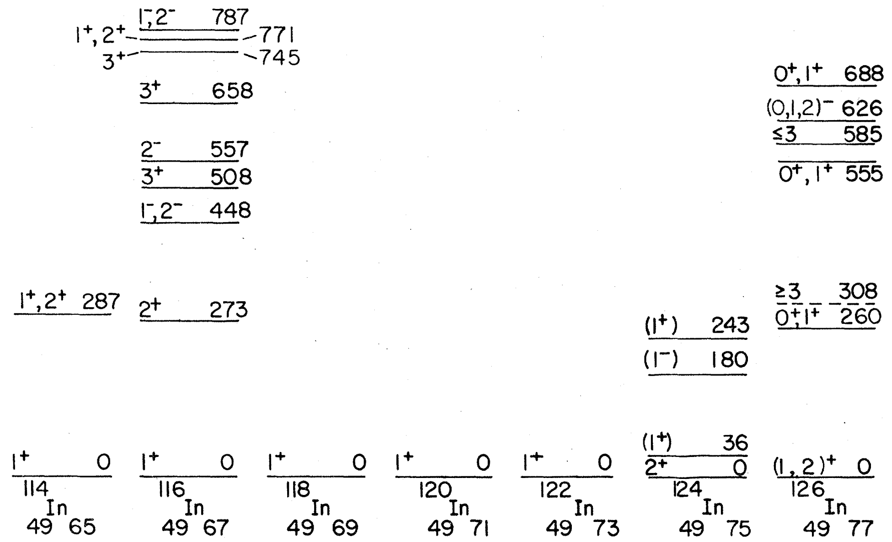

FIG. 5. Systematics of low-spin levels in neutron-rich odd-odd In nuclei.

between the various depopulating cascades. In order for the logft of this level to be greater than 5.9 the ground state β feeding must be greater than 99.5%. Since this is highly unlikely, the J^π assignment for this level is 0^+ or 1^+. A 90% ground state β feeding gives a logft of 4.6 for the 688-keV level. One explanation for such a low logft is that a $g_{7/2}$ neutron in ^{126}Cd decays to a $g_{9/2}$ proton in ^{126}In.

The only γ ray not placed is the one at 653 keV. It was not observed in any coincidence spectrum but is too weak to place directly populating the ^{126}In ground state with any degree of confidence.

It is informative to compare the level structure obtained for ^{126}In with that of other odd-odd In nuclides. Low-spin level structures from ^{114}In through ^{126}In are compared in Fig. 5. The level schemes for ^{114}In, ^{116}In, and ^{124}In are taken from $(p, n\gamma)$,[9] (n,γ) and (d,p),[11] and ^{124}Cd decay,[2] respectively. Levels in Fig. 5 go up to 800 keV and only levels with $J \leq 3$ are included.

The ground states for ^{114}In through ^{122}In are 1^+. The only simple explanation for this J^π is the configuration $(\pi g_{9/2}{}^{-1}, \nu g_{7/2}{}^{-1})_{1^+}$. A J^π of 2^+ has been postulated[2] for the ^{124}In ground state which is probably mostly the same configuration. Most of the levels in ^{126}In can be described in terms of two-hole configurations. Four of the seven levels could be described as $(\pi g_{9/2}{}^{-1}, \nu g_{7/2}{}^{-1})_J$. The negative parity level at 626 keV could be $(\pi p_{1/2}{}^{-1}, \nu s_{1/2}{}^{-1})_J$. We have three levels at 260, 555, and 688 keV that are probably 0^+ or 1^+. A two-hole description can produce only one 1^+ and no 0^+ levels. Such levels could be described in terms of three-hole neutron states or particle states coupled to collective vibrations. Levels in odd A In isotopes have been described[17] in terms of a Nilsson model representation.

The density of low-spin states in ^{126}In is quite similar to that for ^{114}In and ^{116}In. In contrast ^{124}In has a strikingly higher density of low-spin levels below 300 keV. Description of this higher level density would require contributions from three-hole neutron or collective states at energies considerably below those necessary for other odd-odd In nuclei. It is not clear why such a sudden state density increase appears, although it may be associated with the fact that ^{124}In has two more neutron holes than ^{126}In. In this regard it would be of interest to obtain more information on low-spin states in ^{118}In, ^{120}In, and ^{122}In. Detailed decay studies of ^{118}Cd, ^{120}Cd, and ^{122}Cd would be enlightening but would require high intensity sources since most of the β feeding is to the corresponding In ground states which all have $J^\pi = 1^+$.

ACKNOWLEDGMENTS

This work was supported by the U. S. Department of Energy, Division of Basic Energy Sciences. We owe a special appreciation to W. L. Talbert, Jr., who was primarily responsible for the design of the in-beam ion source. We also acknowledge the efforts of A. R. Landin, R. L. Gill, and M. A. Cullison who effectively maintained the TRISTAN system while this work was in progress.

[1] B. Grapengiesser, The Swedish Research Council's Laboratory, Research Report No. LF-59, 1974 (unpublished).

[2] B. Fogelberg, T. Nagarajan, and B. Grapengiesser, Nucl. Phys. A230, 214 (1974).

[3] S. N. Kiselev and V. R. Burmistrov, Yad. Fiz. 11, 244 (1970) [Sov. J. Nucl. Phys. 11, 137 (1970)].

[4] D. D. Bogdanov, I. Bacho, V. A. Karnaukhov, and L. A. Petrov, Yad. Fiz. 6, 1113 (1967) [Sov. J. Nucl. Phys. 6, 807 (1968)].

[5] E. Schwarzbach and H. Munzel, Radiochem. Acta 10, 20 (1968).

[6] O. Scheidemann and E. Hagebo, J. Inorg. Nucl. Chem. 35, 3055 (1973).

[7] M. Eibert, A. K. Gaigalas, and N. I. Greenberg, J. Phys. G 2, L203 (1976).

[8] M. Ionescu-Bujor, E. A. Ivanov, A. Iordochescu, D. Plostinaru, and G. Pascovici, Nucl. Phys. A272, 1 (1976).

[9] D. A. Hutcheon and D. R. Gill, Nucl. Phys. A248, 397 (1975).

[10] S. A. Hjorth and L. H. Allen, Ark. Fys. 33, 121 (1966).

[11] V. L. Alexeev, B. A. Emelianov, D. M. Kaminker, Yu. L. Khazov, I. A. Kondurov, Yu. E. Loginov, V. L. Rumiantsev, S. L. Sakharov, and A. I. Smirnov, Nucl. Phys. A262, 19 (1976).

[12] J. R. McConnell and W. L. Talbert, Jr., Nucl. Instrum. Methods 128, 227 (1975).

[13] G. Rudstam, Nucl. Instrum. Methods 139, 239 (1976).

[14] K. Takahashi, M. Yamada, and T. Kondoh, At. Data Nucl. Data Tables 12, 101 (1973).

[15] G. T. Garvey, W. J. Gerace, R. L. Jaffe, I. Talmi, and I. Kelson, Rev. Mod. Phys. 41, 51 (1969).

[16] S. Raman and N. B. Gove, Phys. Rev. C 7, 1955 (1973).

[17] K. Heyde, M. Waroquier, P. Van Isacker, and H. Vincx, Nucl. Phys. A292, 237 (1977).