Laser ionization of ^{124}Ag and its decay to levels of ^{124}Cd

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Gamma-rays following the decay of the neutron-rich isotope ^{124}Ag have been studied at the ISOLDE facility using a chemically selective laser ion source. Excited structures beyond the first 2^+ level in ^{124}Cd have been identified for the first time, and are discussed in terms of a recent anharmonic vibration model. [S0556-2813(96)50612-6]

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The structure and decay of neutron-rich $_{45}$Rh to $_{50}$Sn isotopes play a crucial role in the development of a description of the $A \simeq 120-130$ region of the astrophysical r process by which about half of the nuclear species in nature heavier than iron are synthesized. Stable nuclides produced by this nucleosynthesis process show enhanced solar-system r abundances ($N_{r,\odot}$) near mass $A \simeq 80$, 130, and 195 [1,2] that have been attributed to the nuclear-structure properties of their r process progenitors lying on and near the closed neutron shells at $N=50$, 82, and 126. In particular, the identification and study of neutron-magic nuclides, such as ^{79}Cu$_{50}$, ^{80}Zn$_{50}$, and ^{130}Cd$_{82}$, has made possible quantitative calculations of these $N_{r,\odot}$ enhancements [3].

A number of extensive calculations for the structure and decay properties of the nuclides with $110 \leqslant A \leqslant 125$ were unable to reproduce the observed $N_{r,\odot}$ pattern [4,5]. However, recent efforts that utilize a weakening of the strength of the $N=82$ closed shell below $Z=50$ have proved more successful [6].

Looking for experimental fingerprints of this effect, we have embarked on a series of spectroscopic measurements in order to determine the structure and decay properties of neutron-rich nuclides with $Z<50$ and $N \simeq 82$. The goal of these studies at CERN-ISOLDE is to investigate structure and decay properties of the neutron-rich Ag and Cd isotopes by taking advantage of the chemical selectivity of laser ionization [7] to enhance Ag production relative to the isobaric background usually obtained with conventional plasma ion sources. The new data for the neutron-rich Ag nuclides and their Cd daughters can then be compared to theoretical models in which the strength of the $N=82$ closed shell becomes a variable.

Extensive data for the structure of the even-even Cd nuclides has been provided by in-beam spectroscopy, radioactive decay studies and, more recently, by fission-fragment γ-ray spectroscopy [8]. However, these approaches have only been able to provide information as far as ^{122}Cd. The only literature data for ^{124}Ag has been a 540(80) ms half-life derived from β-delayed neutron (βdn) measurements [9], and the identification of a single γ line at 613 keV that exhibited a 170(30) ms half-life [10]. In both studies, the Ag was produced in a conventional on-line mass separator setup.

In a recent note [11], we reported the use of a laser ion source (LIS) at the new PS-Booster ISOLDE facility to enhance the ionization of Ag relative to other isobaric activities that permitted the first βdn measurements of the half-lives of $^{125-127}$Ag. The half-life of ^{124}Ag was remeasured and found to be 172(5) ms.

In the present experiment, an improved version of the LIS described in detail in Ref. [7] has been used. This laser setup installed at the ISOLDE facility consists of three copper vapor tubes, one of them working as an oscillator and two as amplifiers at a pulse repetition rate of 10 kHz ($P_{\text{total}}=55$ W), and two dye lasers equipped with microprocessor controlling of the wavelengths. Ultraviolet radiation was generated by frequency doubling with a nonlinear barium-beta-borate (BBO) crystal. The laser beams were focused over a distance of 20 m through a window in the separator magnet into a hole ($d_{\text{hole}}=2$ mm) of the ion source.

In its current configuration, Ag nuclides are produced at ISOLDE through the spallation of uranium in a thick (44 g/cm^2) UC$_2$-C target using a 1 GeV beam of protons. The proton beam is produced in 2.4 μs bursts, separated by multiples of 1.2 s. These sudden short bombardments stimulate a fast release of the reaction products from the target material giving rise to moderate decay losses of short-lived isotopes. After diffusing towards a heated niobium cavity, to which the laser light is focused, the Ag atoms are ionized and are accelerated and mass separated. In addition to laser ionization of Ag, surface ionization of elements with low ionization potential, such as In and Cs, cannot be avoided in the hot cavity. In fact, for $A=124$ the actual spallation production of the two In isomers is about 30 times stronger than that of ^{124}Ag, and Cs is produced approximately 200 times stronger. However, by choosing optimum temperature conditions (ionizer temperature 2000 K) surface ionization of In could be reduced to 0.7%. Note that due to its high ionization potential, the Cd isotopes are not ionized at all. For the same conditions, the LIS efficiency for Ag was determined to 10.8%. Hence, when operating the ion source *without* laser, we only observe the decay of surface-ionized In and Cs. On

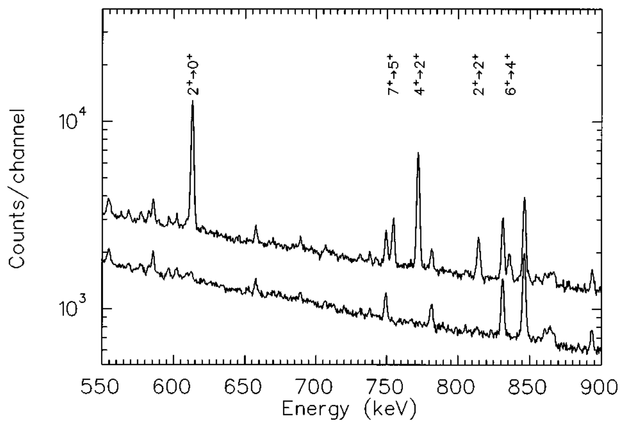

FIG. 1. Partial γ-ray spectra for two ion-source conditions. With the lasers off, only γ lines of surface ionized In and Cs isotopes are observed (lower spectrum). With the lasers on, γ lines of Ag can clearly be observed in addition (upper spectrum).

the other hand, when operating the ion source *with* the laser on, the Ag yield is enhanced to the point that Ag and its daughter Cd are observed with β-intensities approximately equal to those of the surface ionized In nuclides (see Fig. 1).

The ion beam was implanted on a tape which was moved periodically to minimize buildup of daughter and granddaughter activities and to remove long-lived isobaric contaminations. Two large HpGe detectors were placed at 90° relative to each other and were at 3- and 8-cm distances from the collection point. Due to severe electronic noise produced by the 10 kHz pulsing of the lasers, the $\gamma\gamma$-coincidence measurements were strongly disturbed. Therefore, γ-singles data were collected in multispectrum mode in several 100-ms intervals, which were started at different times after the implantation of the beam. Hence, the assignment of γ lines was mainly performed by comparing laser-on/laser-off spectra, and by analysis of the γ-ray half-lives.

In Fig. 1, we show two spectra of γ rays in the energy range from 550 keV to 900 keV, accumulated for a 200-ms period starting 40 ms after closing the beam gate, with the laser on, and also with the laser off. In Table I are listed the energies and intensities of the γ rays that were found both to show a half-life of approximately 170 ms and to be absent in the spectra with the laser off.

In Fig. 2, we show a proposed level scheme that incorporates a number of the more intense γ transitions. The levels below 2 MeV are supported either by the intensity balance or by identification of two transitions from each level. The levels above 2 MeV whose energies are shown in parentheses reflect the systematics for the lighter even-even Cd nuclides that are shown in Fig. 3. Two other possible levels that decay by two transitions are listed in Table I and enclosed in parentheses, but not shown in Fig. 2.

Several features of these structures and decay are of importance. The decay of ^{124}Ag to levels in ^{124}Cd is quite similar to that proposed by Zamfir *et al.* for the decay of the one neutron-pair lighter isotope ^{122}Ag to levels in ^{122}Cd [12]. In their study, two levels were assigned spin and parity 0^+ on the basis of angular correlation measurements. At the same time, the γ rays identified as the 8^+ to 6^+ transition in ^{122}Cd in two different fission-gamma studies were also ob-

TABLE I. Energies, intensities, and placements of γ rays observed following the decay of 172-ms ^{124}Ag to levels in ^{124}Cd. The placements shown in brackets are not included in the level scheme shown in Fig. 2.

Energy (keV)	Intensity	from level	to level
297.9	5.0		
301.1	5.3	1729	1428
461.1	43.1	1846	1386
534.2	6.6	1963	1428
538.8	17.6	2385	1846
612.9	100.0	613	0
616.4	1.6		
620.2	2.3	2841	2221
742.2	2.7		
754.6	15.0	[2718]	1963
772.1	59.4	1385	613
814.5	11.4	1428	613
835.7	8.7	2221	1386
876.2	1.4	3097	2221
924.5	2.5	[2771]	1846
1193.6	1.3		
1312.1	3.0		
1332.2	6.4	[2718]	1385
1428.2	2.7	1428	0
1729.4	2.1	1729	0
1912.7	3.2		
1963.4	2.5	1963	0
2158.3	1.5	[2771]	613
2453.8	4.8		
2458.8	1.7		
2514.2	0.7		

served [8,13]. These data supported the presence of two β isomers in ^{122}Ag, similar to its isotone ^{124}In which has two isomers with half-lives of 3.2 s and 2.4 s, and spins and parities tentatively assigned as 3^+ and 8^-, respectively [14]. During our earlier Ag experiment [11], we remeasured the half-life of delayed neutrons at $A=122$ and obtained only a single component with 520(14) ms, in agreement with literature values. Isomers with indistinguishable half-lives and tentatively assigned spins and parities of 3^+ and 8^- have also been reported for ^{126}In (1.6 s) and ^{128}In (0.9 s) [14].

With our considerably improved Ag enhancements, it was possible to reduce the uncertainty in the half-life of ^{124}Ag in the βdn measurements and now deduce a value of 172(5) ms with no evidence for a second component in the 500-ms range [9]. Within the given uncertainties, this βdn value does not significantly differ from the 160(9) ms half-life value we obtain for the intense 613-keV 2^+ to 0^+ transition, nor from the 166(20) ms and 185(71) ms half-lives that we obtain for the weaker 461- and 814-keV transitions. These latter transitions would reflect enhanced population from the high- and low-spin Ag isomers, respectively.

The spread in spin population in the decay of ^{124}Ag to levels of ^{124}Cd, appears comparable to that observed for ^{122}Ag decay to levels of ^{122}Cd, although we have not established any 0^+ levels. The unplaced γ rays in the 2 MeV to 2.5 MeV range are likely to be transitions to the ground state

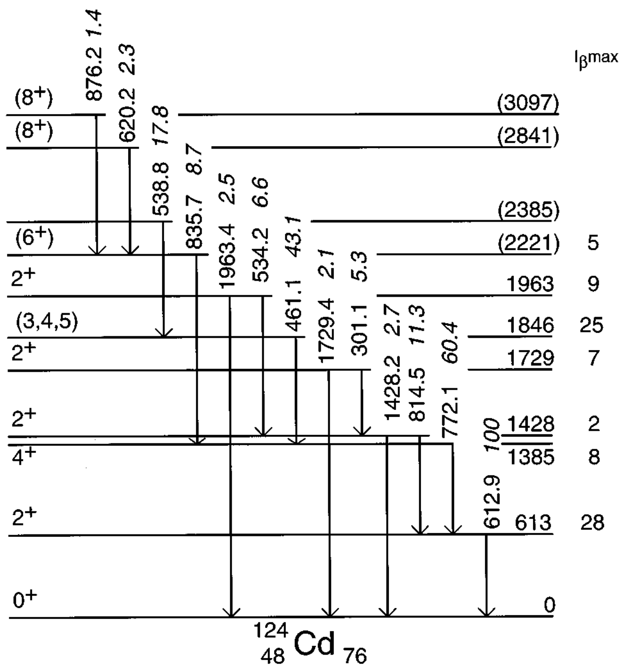

FIG. 2. Levels in ^{124}Cd populated by the decay of the ^{124}Ag ground state and a possible isomer produced in the proton spallation of an uranium target with a 1-GeV proton beam.

or 2_1^+ state coming from levels that would be populated in decay of a low-spin isomer. At the same time, the considerable number of γ rays in the 500 keV to 1500 keV range would appear to originate in higher-spin levels cascading to the yrast levels as the nucleus undergoes deexcitation. Thus, it is likely that the level scheme of ^{124}Cd we present originates from the decay of a low-spin isomer, probably 2^+ or 3^+, and a high-spin isomer, probably 7^- or 8^-. Either of these isomers have relatively similar half-lives as is found for the ^{126}In isotone and suggested by the time behavior of the 461- and 814-keV transitions, or—in the case of different half-lives—one of the isomers has an extremely low βdn branch (P_n) as only one component was found in the neutron time spectrum. And indeed, our QRPA calculations using the code of Möller and Randrup [15] predict half-lives of 103 ms for the $[\pi g_{9/2};\nu d_{3/2}]$ low-spin isomer and 133 ms for the $[\pi g_{9/2};\nu h_{11/2}]$ high-spin isomer, however with identical P_n values of 1.1%. Within this shell-model approach, we have no possibility to form a βdn-emitting 500 ms 2-quasiparticle isomer in ^{124}Ag [9]. When, furthermore, assuming equal production of both isomers in 1-GeV spallation, we must conclude that they are indistinguishable from their gross β-decay properties $T_{1/2}$ and P_n.

These new data for ^{124}Cd now permit some insight into the changes in collective structure in the heavy Cd nuclides as the $N=82$ closed shell is approached. Structures for $^{118-124}$Cd nuclides are shown in Fig. 3. It is useful to recall that ^{118}Cd has been considered the outstanding example of a nearly pure vibrational nuclide, one that also showed some levels from particle-hole intruder states that reach a minimum in energy at $N=66$ (mid shell) [16,17]. For both ^{118}Cd and ^{120}Cd, the low-energy structure is characterized by a nearly degenerate vibrational 0^+, 2^+, 4^+ triplet. In moving from ^{118}Cd to ^{124}Cd, six-neutron holes have been filled, most likely in the $h_{11/2}$ orbitals. Hence, the collective structure of ^{124}Cd should be governed by the interactions between the two $g_{9/2}$ proton holes, and the six remaining neutron holes, divided among the $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$ orbitals. Because the high-spin orbitals are both over half full, the interaction should be a strong hole-hole interaction, and relatively symmetrical vibrational structure should dominate. We note that the other valence orbitals, the $d_{3/2}$ and $s_{1/2}$ neutron orbitals, and $p_{1/2}$ proton orbitals can only play a limited role in forming collective structures. Indeed, what is observed is a narrowing of the 4^+-2^+ gap, and a drift upward in the position of the second 0^+ state.

Casten, Zamfir, and Brenner have shown that for many nuclides the analysis of collectivity can be carried out using a model for anharmonic vibrational nuclides, and, that for nuclides where the E_{4^+}/E_{2^+} ratio lies between 2.05 and 3.15, E_{4^+} is approximately equal to 2 $E_{2^+} + \epsilon_4$ [18]. In Fig. 3, the E_{4^+}/E_{2^+} ratio is shown in brackets for all of the Te and Cd nuclides, and ϵ_4 is shown in parentheses. Rather universal values have been found for ϵ_4 that depend on Z. For nuclides below $Z=50$, that value is 190 ± 24 keV. Zamfir *et al.* ana-

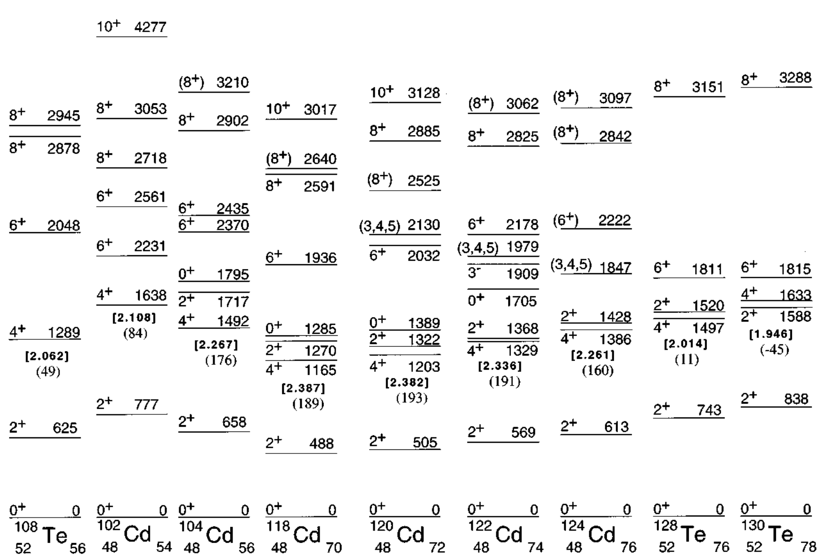

FIG. 3. Structure of the even-even Cd and Te nuclides. The 8^+ and 10^+ levels shown in $^{118-122}$Cd nucleides have been observed in fission-fragment γ-ray coincidence studies. The other possible 8^+ levels (those with spin in parentheses) as well as the levels shown with spin (3,4,5) have been observed in Ag decay studies. The numbers in brackets just below the 4^+ levels are the energy ratio E_{4^+}/E_{2^+}. The numbers in parentheses below the 4^+ levels are the ϵ_4 values.

lyzed the structure of ^{122}Cd in this means, and were able to indicate that the 6^+ level at 2178 keV is a good candidate for the 6^+ vibrational level, and that the 8^+ level at 3062 keV could be a candidate for the 8^+ vibrational level [5]. For comparison, we have also shown the structure for ^{104}Cd$_{56}$ the even-even Cd nucleus with six neutrons beyond the $N=50$ closed shell. Both the E_{4^+}/E_{2^+} and ϵ_4 are seen to be quite comparable to those values for the heavy Cd nuclides.

In Fig. 3, we have also shown the structure of the six-neutron particle and hole Te nuclides, ^{108}Te and ^{128}Te, along with their E_{4^+}/E_{2^+} ratio and ϵ_4. While they differ somewhat from the Cd nuclides, the values for both the six-particle and six-hole nuclides are close to each other and consistent with the anharmonic vibrator picture.

We have also included in Fig. 3 the even-even Te nuclide, ^{130}Te with only four neutron holes in the $N=82$ closed neutron shell, and the even-even Cd nuclide, ^{102}Cd which has only four neutrons beyond the $N=50$ closed neutron shell. In both cases, significant departures from both the E_{4^+}/E_{2^+} ratio and ϵ_4 value are found when compared with the adjacent nuclide, and in both cases, the values are lower.

Hence, these new data reported for ^{124}Cd in this paper are fully consistent with the notion that the Cd nuclides from six-particle ^{104}Cd through six-hole ^{124}Cd, as well as their isotonic Te nuclides, show what might be termed ''consistent vibrational structure'' and, that the shift away from collective structure begins for both Cd and Te nuclides when either the holes or particles are less than six.

We noted at the outset that one approach to nuclear structure and decay in the heavy Cd nuclides that could account for the observed r-process abundances included a weakened shell structure for the $N=82$ closed neutron shell below $Z=50$. Therefore, it will be the structure of ^{126}Cd$_{78}$ where the first experimental indication of weakened shell strength could be found. That is, the degree to which the E_{4^+}/E_{2^+} ratio and ϵ_4 value are found to shift toward lower values should be a test of the degree to which the $N=82$ shell strength is comparable to both the $N=82$ shell strength above $Z=50$ and the $N=50$ shell strength in the light Cd nuclides. These same laser-enhanced ionization techniques, when combined with high resolution mass separation, should make investigation of the decay of the heavier, even-mass Ag decay possible and bring observation of the structure of even-even Cd nuclides as far as ''closed-shell'' ^{130}Cd$_{82}$ within reach.

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