ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E7-95-552

Yu.A.Lazarev, Yu.V.Lobanov, Yu.Ts.Oganessian,
V.K.Utyonkov, F.Sh.Abdullin, A.N.Polyakov,
J.Rigol, I.V.Shirokovsky, Yu.S.Tsyganov, S.Iliev,
V.G.Subbotin, A.M.Sukhov, G.V.Buklanov,
B.N.Gikal, V.B.Kutner, A.N.Mezentsev, K.Subotic,
J.F.Wild*, R.W.Lougheed*, K.J.Moody*

ALPHA DECAY OF ^{273}110: SHELL CLOSURE AT N = 162

Submitted to «Physical Review C»

*University of California, Lawrence Livermore National Laboratory, Livermore, California 94551, USA

1995

The stability of heavy nuclei is governed by nuclear shell structure whose influence is dramatically amplified near closed proton and neutron shells. Beyond the spherical shells Z=82 and N=126, the stability of nuclei diminishes rapidly with increasing Z until the transuranium region, where the influence of deformed-shell gaps in single-particle level spectra near Z=100 and N=152 alters the trend. Since the mid-1960's, nuclear theory has been predicting with increasing confidence that the next spherical shells be located at Z=114 and N$\simeq$178–184 (see, e.g., review [1]). More recently, it was realized that this region of spherical superheavy nuclides might be connected by a "peninsula" of stability to the edge of the known heaviest elements. This far-reaching conclusion was based on the predicted existence of the deformed proton and neutron shell closures near Z$\simeq$108 and N$\simeq$162 [1–4]. Direct experimental evidence for the new shell closures was first provided by the decay properties of the recently discovered N=158–160 nuclides $^{262}104$, $^{265,266}106$, and $^{267}108$ [5,6] as a large enhancement in their stability compared to that of nuclides with *lower* Z or N values.

A critical test of the theory could be the observation of a decrease in stability for nuclides with Z, N *beyond* the predicted magic numbers Z$\simeq$108 and N$\simeq$162. Thus, the determination of whether the neutron closure is exactly at N=162 or at a higher N value can be made by measuring α-decay properties of a nuclide with N=163 or 164. As known from α-decay studies around the N=126 shell, the α-decay energy, Q_α, becomes considerably larger if the shell is crossed and breaks the trend of the Q_α values decreasing with increasing N for isotopes of a given Z.

The choice of feasible reactions to produce a neutron-rich nuclide with N>162 is strongly limited. "Cold fusion" reactions with ^{208}Pb or ^{209}Bi

targets allow this to be achieved only at Z=112. With actinide-target-based fusion-evaporation reactions, the N>162 region is achievable at Z=110. The main decay mode for Z=110 nuclides with N=163–164 is expected to be α emission rather than spontaneous fission (SF) [2–4]. If the neutron shell closure were, indeed, at N=162, $^{273}110$ should have $Q_\alpha \sim 11.2$ MeV or even higher and a sub-ms half-life [4]. However, if the shell closure were at N=164, $^{273}110$ should have a Q_α value at least 0.6 MeV lower and a $T_{1/2}$ of tens of ms.

During the period from September 10 to December 30, 1994, we carried out experiments at the Dubna U400 cyclotron to produce neutron-rich Z=110 nuclides by the $^{244}Pu+^{34}S$ reaction at the bombarding energy $E(^{34}S)=190$ MeV, some 6 MeV above the Bass fusion barrier [7], resulting in an excitation energy for the compound nucleus $^{278}110$ of ≈ 50 MeV. This bombarding energy is expected to provide the maximum yield of $^{273}110$, the 5n evaporation product, although the 4n and 6n channels leading to $^{274}110$ and $^{272}110$ are also open. Three plutonium targets (98.6% ^{244}Pu, 1.1% ^{242}Pu, and 0.3% ^{240}Pu) with average areal densities of 0.41 mg cm^{-2} ^{244}Pu and a total area of 11.7 cm^2 were arranged on a wheel whose rotation was synchronized to the 150 Hz frequency of the cyclotron so that a target was exposed to an $\sim$2.2 ms beam macropulse during each 6.7 ms beam cycle. The targets were electrodeposited on 0.70 mg cm^{-2} Ti substrates and covered with a 30 μg cm^{-2} carbon layer. In 57 days of actual bombardment with an average intensity of 5×10^{12} particles/s of ^{34}S, the targets received a total beam dose of 2.5×10^{19} particles.

Evaporation residues (EVRs) recoiling from the ^{244}Pu targets were separated in flight from beam particles and transfer-reaction products by the Dubna Gas-filled Recoil Separator described in Ref. [8]. To set the

field B of the separator's dipole magnet for Z=110 EVRs, we used prior measurements [5,6,8] of the average charge states for EVRs with Z=84 through 108 moving in 1 Torr of hydrogen, cf. Fig.1 in Ref. [6]. The separated EVRs passed through a time-of-flight (TOF) measurement system composed of two (start and stop) multiwire proportional chambers in a 1.5-Torr pentane-filled module and were implanted in a position-sensitive detector (PSD) array composed of three 40×40 mm^2 silicon *Canberra Semiconductor* detectors, each with four 40-mm high $\times$ 9.7-mm wide strips. We obtained horizontal (x) positions for the reaction products from the 12 strips and vertical (y) positions from the 40-mm high resistive layer of the detectors. Top and bottom or y-position signals from each strip were each divided into a signal for α/implant events ($\sim$2–14 MeV) and a signal for SF events ($\sim$20–250 MeV). We also recorded the energy sum of the α/implant events; we determined the energy of SF events by off-line summing of their y-position signals. With each detected energy event, we also recorded the strip number, TOF information, the time in μs from the beginning of each beam pulse to either α/implant or SF events, and the running time in 0.1-ms intervals. The dead time of the electronics system was ≈ 7 μs.

Alpha-energy calibrations were performed periodically using α emitters from the $^{nat}W+^{34}S$ reaction. Most of the strips had initial α-energy peak FWHMs of ≈ 40 keV, but, due to radiation damage, their performance was degraded during the bombardment to a FWHM of ≈ 120 keV, at which time a detector was replaced. By using known event sequences from the calibration reactions, we measured the FWHM y-position deviation Δpos to be 1.2 mm (3% of the strip height) for α-α sequences. The FWHM Δpos value for Z=110 EVR-α correlations was estimated to be 1.7 mm. These Δpos criteria were applied in searching for correlated Z=110 event sequences. A signature for $^{273}110$ was expected to be the observation of its α decay [2–4] followed by α decay of the unknown nuclide $^{269}108$ and of the known nuclides $^{265}106$ ($T_{1/2}\approx$2–30 s, $b_\alpha \gtrsim 50\%$, $E_\alpha \approx 8.71$ to 8.91 MeV [5]), $^{261}104$ ($T_{1/2}=78^{+11}_{-6}$ s [9], $b_\alpha \gtrsim 80\%$, $E_\alpha \approx 8.22$ to 8.41 MeV, $b_{EC} \leq 10\%$, $b_{sf} < 10\%$ [9–11]), and $^{257}102$ ($T_{1/2}=25\pm2$ s, $b_\alpha > 99\%$, $E_\alpha \approx 8.19$ to 8.40 MeV [10,11]). From systematics and predictions [4], $^{269}108$ was expected to be an α emitter with $E_\alpha \sim 9.3$ MeV and a $T_{1/2}$ of 1 to 10 s.

We carried out an extended off-line search for $^{273}110$ event sequences in which implantation events of Z=110 EVRs with the expected measured energy of 6.5±2.7 (2σ) MeV were followed with $|\Delta pos| \leq 1.44$ mm (2σ) by an in-beam or out-of-beam $^{273}110$-like α-decay event and then followed by at least one *out-of-beam* α-decay event from the $^{273}110$ descendants: $^{269}108$, $^{265}106$, $^{261}104$, or $^{257}102$. The in-beam period was determined from a consecutive set of 10-μs intervals of time from the beginning of each beam pulse, in each of which more than one EVR was detected per data file. Any event detected outside this time interval was considered to be out of beam. The EVR-$\alpha 1$ correlations were considered as candidates for further analyses. In selecting these EVR-$\alpha 1$ pairs, the time window Δt_1 between the EVR and $\alpha 1$ was opened up to 300 ms and 100 ms for E_α ranges of 10.0 to 10.6 MeV and 10.6 to 12.0 MeV, respectively. During the entire measurement time we detected in all 12 strips a total of 19664 such candidate EVR-$\alpha 1$ pairs. Then we selected all subsequent α-decay events following each one of these 19664 EVR-$\alpha 1$ pairs within the α-energy, time, and y-position windows specified below. The E_α windows were set to be 9.0 to 10.0 MeV for $^{269}108$, 8.5 to 9.0 MeV for $^{265}106$, and 8.15 to 8.45 MeV for each of both $^{261}104$ and $^{257}102$. In the search for $^{265}106$-like

α-events and $^{261}104$- or $^{257}102$-like α-events, the time distances from the $\alpha 1$ particle were extended to 360 s and 1100 s, respectively; in the search for $^{269}108$-like α-events, the time windows were 120 s and 20 s for the E_α ranges 9.0 to 9.3 MeV and 9.3 to 10.0 MeV, respectively. The y-position deviations between all α's in a candidate chain were required to be within the $\pm 2\sigma$ range of 1.04 mm; except for the $\alpha 1$ particle, all other α's in a given chain were allowed to have a y-position deviation of ±2.48 mm from the y-position of the EVR of this chain. With the ≈33% duty cycle of the U400 cyclotron, the probability that one (or more) of the four α decays will occur between beam pulses is 98.8%. The probability of *detecting* out of beam one (or more) of the four α's is 80% for our 2π PSD array, provided all of the four descendants of $^{273}110$ have 100% α branches.

As a result of the above-described selection, 14 candidate chains of the $^{273}110$ type were observed in detector strips 1 through 6, and one four-member sequence, with $E_{\alpha 1}$=11.35 MeV, was detected in strip 7. This last sequence fit best the expected pattern of implantation in the PSD array and subsequent α decay of the new nuclide $^{273}110$ and was produced after 43 days of actual bombardment (see Table I).

This event sequence occurred in the center of the PSD array (5 mm off the vertical-middle of strip 7), where a 6.39-MeV EVR implantation event detected in coincidence with a characteristic TOF signal was followed in 394 μs by an α-decay event with $E_{\alpha 1}$=11.35 MeV; then, following this by 158 s, an out-of-beam α-decay event with $E_{\alpha 2}$ = 8.63 MeV was detected, followed 384 s later by a third α-decay event with $E_{\alpha 3}$=8.22 MeV. The y-position signals registered for each member of the sequence revealed a close correlation of the four events on strip 7.

Table I. The measured parameters of the correlated event sequences which were considered as candidates for $^{273}110$.

Particle	Particle energy[e] (MeV)	Strip no.	Δt[f]	Δpos[g] (mm)	Assignment	N_b
EVR[a]	6.39	7			$^{273}110$	
α	11.35	7	394 μs	-1.1	$^{273}110$	
α[b]	8.63	7	158 s	-1.6	$^{265}106$	
α	8.22	7	384 s	-1.5	$^{257}102$	0.006
EVR[c]	3.81	1			$^{273}110$	
α	11.72	1	13.2 ms	-1.4	$^{273}110$	
α[b]	8.86	1	43 s	-2.3	$^{265}106$	0.064
EVR	5.65	4			$^{273}110$	
α	10.57	4	94.4 ms	+0.6	$^{273}110$	
α[b]	8.71	4	31 s	+0.1	$^{265}106$	0.32
EVR[d]	4.78	2		+0.72		
α	10.72	2	125 μs			
α[b]	6.72	2	532 s	-1.04		
α[b]	8.27	2	442 μs	-1.00		0.023[h]
EVR	3.72	10			$^{273}110$	
α	10.85	10	1.3 ms	-1.7	$^{273}110$	
α	9.81	10	1.7 s	-0.7	$^{269}108$	
α	8.51	10	73 s	-1.2	$^{265}106$	
α	8.20	10	117 s	-1.2	$^{261}104$	
α	8.29	10	146 s	-0.8	$^{257}102$	0.0014[i]

[a] This sequence was detected at 4:49 a.m. on 10 December 1994 after 1041 h of actual bombardment at a total beam dose of 1.9×10^{19} particles of ^{34}S. The FWHM of the α-particle energy peaks in strip 7 were measured as 120 keV near this time.

[b]Event occurred between cyclotron beam pulses.

[c] This sequence was detected at 5:35 a.m. on 14 September 1994 after 56 h of actual bombardment at a total beam dose of 1.1×10^{18} particles of ^{34}S. The FWHM of the α-particle energy peaks in strip 1 were measured as 75 keV near this time.

[d]The bottom position signal was not detected for this implantation event; the y-position deviations indicated for the two out-of-beam α's of this chain are given with respect to the y-position of the 10.72-MeV α1, while the y-deviation of the EVR from the α1 was reconstructed by using the energy sum signals of the EVR and α1.

[e]The quoted EVR energies are measured values. No estimate was included for the pulse-height defect.

[f]The indicated Δt values are time distances to the preceding event of a given correlation chain.

[g]The y-position deviations are given with respect to the EVR implantation site; as expected, the y-deviations between the α's are smaller.

[h]This N_b value is obtained without including the 6.72-MeV α in the N_b calculation.

[i]This N_b value is obtained if the 9.81-MeV α is supposedly assigned to the *unknown* descendant $^{269}108$ and included in the N_b calculation; otherwise N_b=7.1 for this chain. The 8.51-MeV α event was not included in these N_b calculations, since this α energy seems too low for $^{265}106$.

A unique feature of this observed event sequence is the high $E_{\alpha 1}$ value of 11.35±0.06 MeV for the mother α decay with the 394 μs lifetime. Only a nuclide at the upper edge of the nuclide chart could create the observed pattern of these three consecutive α decays. Considering the neutron-rich composition of the ^{244}Pu+^{34}S reaction system used near the fusion barrier energy, we can eliminate Z<110 candidates, because such parent nuclides and their descendants are expected to have much lower α decay energies and much longer lifetimes. The event chains originating from even-even Z=110 candidates should end with SF decay with a 100% probability, which is not the case for the observed sequence. Therefore we interpret this sequence as the α decay of ^{273}110 followed by two detected α decays of its descendants, ^{265}106 and ^{257}102 (or ^{261}104). While the E_α energies of ^{261}104 and ^{257}102 are rather similar, the 384-s correlation time conforms better to the decay of ^{257}102; the probability density P(t)=dN/d(lnt) for the ^{257}102 to decay at t=384 s is 0.17, 34% of the maximum P(t) value. Alpha decay of the unknown nuclide ^{269}108 and that of ^{261}104 were not observed. Thus, we detected three of five short-lived members of the α-decay chain starting at ^{273}110, in agreement with the 50% probability for detecting α decays by the PSD array.

In the last quarter of the experiment, besides TOF information from regular start and stop signals, ΔE signals from the stop chamber alone (processed by an additional amplifier with highly increased gain) were recorded during *out-of-beam* periods, provided the actual TOF information was zero. The 8.63-MeV α event in the Z=110 sequence coincides within 5 μs with such a low-amplitude ΔE signal, which accompanies ~60% of the events in the small peak at 8.65 MeV (see Fig.1), as well as 5 to 35% of other α peaks and α events not contained in recognizable peaks. A sub-

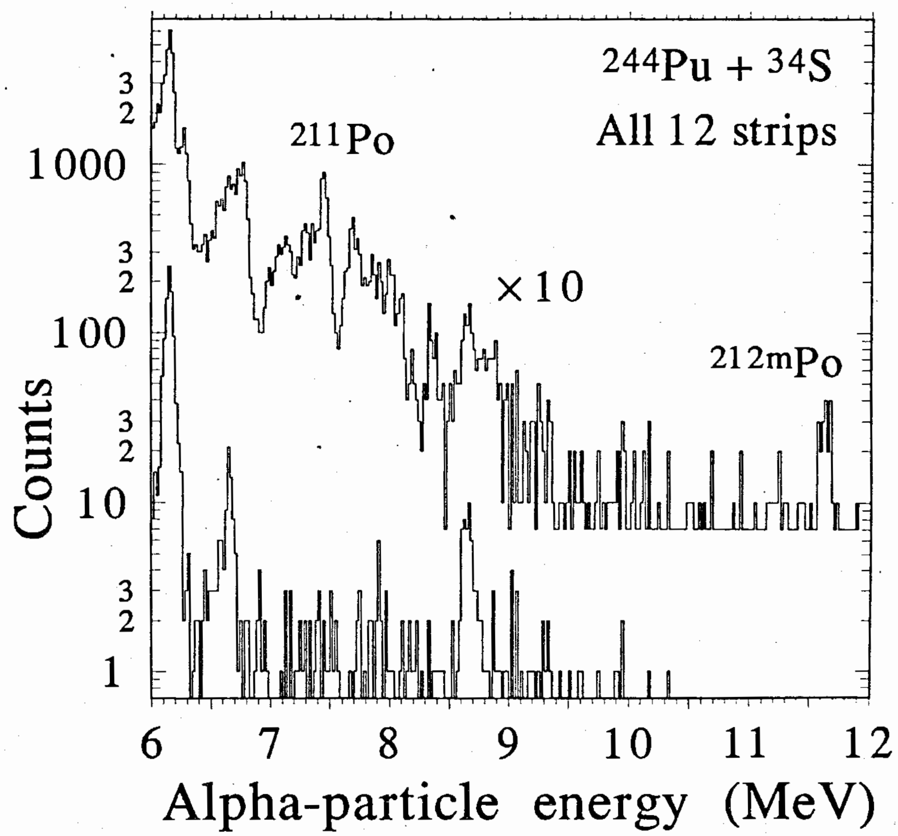

Fig.1. Gross energy spectrum of out-of-beam α particles detected in all 12 strips in the last quarter of the experiment (0.6×10^{19} particles ^{34}S); the lower spectrum shows α events accompanied by ΔE signals. The gross spectrum for the entire experiment is similar. Most α activities (including ^{212m}Po) are probably from deep inelastic collisions of ^{244}Pu and ^{34}S; traces of α emitters from ^{nat}W+^{34}S calibrations are possible. A bombardment of a 0.52 mg cm^{-2} ^{nat}Pb target with 5.4×10^{16} particles of 190-MeV ^{34}S (carried out at the Z=110 B value of the dipole magnet) showed only 14 out-of-beam α counts in the E_α range of 8.0 to 10.5 MeV and *zero* in the range of E_α=10.5 to 12.0 MeV.

sequent ^{244}Pu+^{22}Ne experiment [11] has shown that conversion electrons accompanying the α decay of ^{261}104 and ^{257}102 are detected by the stop chamber in coincidence with the α's and give rise to such a signal 10±5% of the time. Thus, the detection of a conversion electron from ^{261}104 is a likely source of the ΔE signal accompanying the 8.63-MeV α in the Z=110 sequence, since odd-A ^{265}106 decays preferably to excited states of ^{261}104. The higher percentage association of the ΔE signals with a few specific α groups in Fig.1 implies the existence of additional causes for these ΔE signals. However, while the bulk of 8.65-MeV α's was shown to be uncorrelated to any other preceding or subsequent events, the one 8.63-MeV α event involved in the four-member Z=110 sequence is strongly correlated to the other members of this chain.

Other measured parameters of the correlated EVR-α-α-α sequence also support its assignment to ^{273}110. The 6.4-MeV energy of the EVR fits closely with our estimate of 6.5±2.7 (2σ) MeV for energies of Z=110 EVRs that are expected to be measured by the PSD. The $E_{\alpha 2}$ energy of 8.63 ± 0.06 MeV is in agreement with the reported α-particle energies of 8.71 to 8.91 MeV for four decays of ^{265}106 [5]. The time interval of 158 s indicates that the half-life of ^{265}106, which was estimated in Ref. [5] from the measured α-decay energies as 2 to 30 s, is tens of seconds rather than seconds, assuming that this time interval is dominated by the lifetime of ^{265}106 and not ^{269}108. Thus, the average hindrance factor could be considerably more than the value of 3 used in Ref. [5] to estimate the upper bound of the ^{265}106 half-life. Several high-spin neutron orbitals are predicted [1,2,12] to occur below N=164, so that α decays of some odd nuclides here should have large hindrance factors; this expectation holds for ^{273}110 in view of the predicted N=163 level with spin and parity $\frac{13^-}{2}$. We note that re-

cent GSI experiments [13] gave a preliminary half-life value of 7^{+13}_{-5} s (68% confidence interval) for ^{265}106, in good agreement with the $T_{1/2}$ estimate made in Ref. [5].

A high statistical significance for the observed EVR-α-α-α chain is provided by the short correlation time between the 6.4-MeV EVR and 11.35-MeV α particle and by the inclusion of the out-of-beam 8.63-MeV α event. During the 57-day bombardment we observed a total of 257 (only 14 in strip 7) EVR-α correlations for EVR energies from 3.8 to 9.2 MeV and α energies from 10 to 12 MeV with correlation times of $\leq$0.4 ms and $|\Delta pos| \leq 1.44$ mm (2σ). As seen in Fig. 1, the average rate of out-of-beam α events in the E_α range of 8.1 to 9.5 MeV expected for the ^{273}110 descendants was extremely low, two events per day per strip (the in-beam rate is about two events per minute per strip). From our data we calculate the chance of finding an out-of-beam ^{265}106-like α event of E_α=8.5 to 9.0 MeV following an EVR-α sequence within 158 s with $|\Delta pos| \leq 1.04$ mm (2σ) to be only 1 in 10500. The probability of finding an in-beam α event with E_α=8.15 to 8.45 MeV and $|\Delta pos| \leq 1.04$ mm within 542 s is 0.23. Thus, our *conservative* estimate of the expected number N_b of random four-fold correlations with similar properties is 6×10^{-3} for the whole PSD array and entire measurement time T=1375 h. This very small yet non-zero N_b value gives a probability for the observed event sequence to be of random origin.

We also examined the statistical significance of the aforementioned 14 candidate chains containing at least one descendant α event out of beam by performing N_b calculations, for the whole PSD array and the entire measurement time, similar to those described above for the ^{273}110 sequence with $E_{\alpha 1}$=11.35 MeV. As shown in Table I, only two of these 14 chains had N_b<0.1, while the other 12 chains had N_b values in the range 0.3

to 5.0; as an example, we included in Table I the N_b=0.3 chain with $E_{\alpha 1}$=10.57 MeV. In considering the $E_{\alpha 1}$=10.72-MeV event sequence, we found that the ^{261}104/^{257}102-like 8.27-MeV out-of-beam α-event is strongly correlated in time and position to a preceding out-of-beam 6.72-MeV α-event. Despite the very short correlation time Δt_1=125 μs, the loss of the bottom position signal of the 4.78-MeV EVR makes it difficult to decide whether this EVR-α1 pair is related to the tight out-of-beam α-α correlation at a statistically significant level. We included this chain in Table I as an interesting observation calling for further examination and explanation.

The three-member event sequence in Table I with $E_{\alpha 1}$=11.72 MeV, which was detected after 56 h of actual bombardment, also shows the ^{273}110 implantation/decay pattern. The observation of the out-of-beam 8.86-MeV α event 43 s after the occurrence of the α1 event lends a great deal of significance to this chain, but there are a number of less perfect features as well. It occurred in strip 1, where the background is some 3 times higher as compared to the center of the PSD array; the measured EVR energy of 3.81 MeV was at the lower edge of the expected $\pm 2\sigma$ range of Z=110 EVR energies, and the measured Δpos values were close to their higher limits. The $E_{\alpha 1}$ of 11.72 MeV gives a $Q_{\alpha 1}$ value for this transition of 11.90 MeV, some 0.7 MeV higher than is expected from theoretical predictions [4]. This $E_{\alpha 1}$ corresponds to an unhindered $T_{1/2}$ value of 1.5 μs [2], which requires a hindrance factor of $\sim$6000 to achieve a $T_{1/2}$ of 9 ms, as the value of Δt_1 indicates; such a transition would likely have a low abundance. We should expect the odd-A nuclide ^{273}110 with $N=N_{shell}+1$ to have a broad and complex α spectrum, as it is the case, e.g., for the five known even-Z α emitters with N=153, ^{251}Cf through ^{259}106 [10]. Different versions of macroscopic-microscopic calculations [1,2,12] definitely predict

a striking *bunching* of single-particle levels with spins and parities ($J\pi$) of $\frac{1^+}{2}$, $\frac{3^+}{2}$, $\frac{7^+}{2}$, $\frac{9^+}{2}$ and $\frac{11^-}{2}$ of the N=157, 159, and 161 nuclei, as well as a *large*, $\approx$1-MeV *gap* up to the next, clearly isolated N=163 level with $\frac{13^-}{2}$. Although the corresponding $\frac{13^-}{2}$ analog state in ^{269}108 is not predicted to be available to the decay of ^{273}110, the hindrance of a transition to the possible $\frac{11^-}{2}$ bandhead or its first rotational state at $J\pi=\frac{13^-}{2}$ should not preclude the observation of this decay mode.

We also considered as a ^{273}110 candidate sequence the six-member chain shown in Table I with $E_{\alpha 1}$=10.85 MeV. This chain, by our definition, is essentially all in beam, except that the 9.81-MeV α event was at the edge of the beam pulse, where the background is $\sim$0.1 of the completely in-beam rate, but still about a factor of 10^2 of the out-of-beam rate. Hence, it was not one of the 14 chains which contained at least one clearly out-of-beam α decay. The statistical significance of this chain rests on the inclusion in the N_b calculation of the 9.81-MeV α which might be assumed to represent the decay of the *unknown* ^{269}108 daughter. The main difficulty with this assumption is that the 9.81-MeV α energy is $\sim$0.5 MeV too high for ^{269}108, based on both experimental systematics and theoretical predictions [4]. Also, the EVR energy and its Δpos value to α1 of 1.7 mm were outside of their expected $\pm\ 2\sigma$ range, and the probability of detecting all of these events in beam is only 0.001 in our case.

Thus, our detailed analysis of the ^{244}Pu + ^{34}S data confirms the uniqueness and the high statistical significance of the 11.35-MeV event sequence belonging to ^{273}110, which was first reported in Refs.[14,15]. The complete analysis reveals other event sequences which deserve further consideration, including those with $E_{\alpha 1}$=11.72 MeV and $E_{\alpha 1}$=10.85 MeV, but their significance is lower than the 11.35-MeV chain, and the following discussion will be based so far on that sequence.

The $\simeq$0.4-ms interval between implantation and α decay of the $^{273}110$ EVR results in a maximum likelihood $T_{1/2}$ value of $0.3^{+1.3}_{-0.2}$ ms (68% confidence interval). Based on one detected chain, the production cross section of $^{273}110$ at E(^{34}S) = 190 MeV is roughly 0.4 pb, close to expectations when extrapolated from the 2.5 pb cross section measured for the ^{238}U(^{34}S, 5n) reaction [6]. The cross section estimate for $^{273}110$ could be higher if we assume an EC branching in the decay of $^{261}104$, $^{265}106$, or $^{269}108$.

The α-particle energy E_α=11.35 MeV measured for $^{273}110$ gives a Q_α of 11.52 MeV when corrected for recoil energy of the daughter nucleus. Such a high Q_α value for the Z=110 nuclide with N=163 provides direct and convincing evidence that a neutron shell closure indeed exists and is located at N=162 and not at a higher value of N. The Q_α value for $^{273}110$ would have been about 1 MeV lower if the shell closure had occurred at N>162. We illustrate this in Fig. 2 with a plot of Q_α *vs* N for isotopes of even-Z elements Cf through 110, including $Q_\alpha\simeq$11.3 and $\simeq$10.9 MeV for the isotopes $^{269}110$ and $^{271}110$ that were identified in ^{208}Pb+^{62,64}Ni experiments conducted at GSI/Darmstadt [16] in the same time period as the present experiment; we also show the point $Q_\alpha\sim$11.8 MeV from a report [17] on the possible production of $^{267}110$ in ^{209}Bi + ^{59}Co bombardments at LBL/Berkeley. The measured E_α energies for Z=110 were assumed to correspond to the ground-state to ground-state transition. Although the odd-A Z=110 nuclides are not expected to decay to the ground state, they would have to decay to daughter energy levels unrealistically different to alter the Q_α *vs* N pattern in Fig. 2.

In Fig. 2 one can clearly see the reversal in Q_α *vs* N behaviour for $^{273}110$ as compared with the trend for the lighter Z=110 isotopes. This observa-

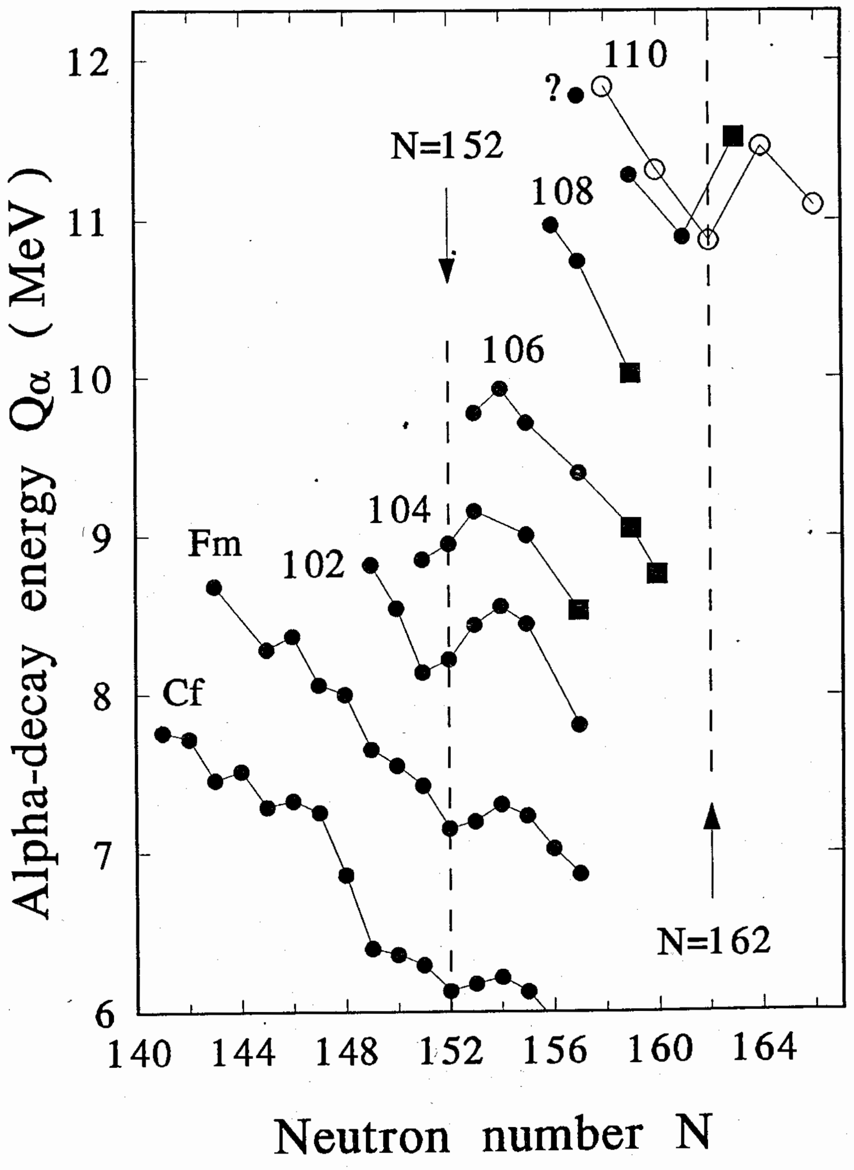

Fig.2. Alpha-decay energy Q_α *vs* neutron number N for isotopes of even-Z elements Cf through 110 [5,6,10,11,14–17]. Squares show data from Refs. [5,6,11], as well as Q_α for $^{273}110$ from this work. Open circles show theoretical Q_α values [4] for even-even Z=110 isotopes.

tion is in good agreement with the recent theoretical Q_α predictions [4] shown in Fig.2. The 0.6-MeV increase in Q_α between N=161 and N=163 reflects the strength of the shell closure at N=162 and can be contrasted with a Q_α increase of 0.1–0.3 MeV between N=151 and N=153 in the region of Fm to Z=104, or, alternatively, with that of 1.8–2.6 MeV between N=125 and N=127 in the Po–Th region. The N=162 shell closure appears much weaker than the spherical shell N=126, but seems at least comparable in strength to the deformed shell N=152.

In conclusion, the production and identification of the nuclide $^{273}110$ signifies the observation of the element 110. The principal result of the present work is the direct experimental evidence for a strong shell closure at N=162 as determined by the measured α-decay properties of $^{273}110$, the only N=163 nuclide known at this time.

We wish to thank Ts. Vylov and V.G. Kadyshevsky for the support of the present work. We thank the U400 cyclotron staff for providing the intense ^{34}S beams. We are grateful to P. Burger, F. Hanappe, E.K. Hulet, M. Keters, E. Liatard, B. Martin, and A. Sobiczewski for their various contributions to the success of this experiment. We thank V.I. Krashonkin, V.Ya. Lebedev, E.A. Shchukina, S.V. Shishkin, V.I. Tomin, A.B. Yakushev, and A.M. Zubareva for their essential help. The ^{244}Pu target material was provided by the U.S. DOE through ORNL. Much of the support for the LLNL authors was provided through the U.S. DOE under Contract No.W-7405-Eng-48. Some of the Dubna authors acknowledge the individual financial support by Grants RFN000 and RFN300 from the International Science Foundation and the Government of the Russian Federation. These studies were performed in the framework of the Russian Federation/US Joint Coordinating Committee for Research on Fundamental Properties of Matter.

References

[1] P. Möller and J.R. Nix, J. Phys. G **20**, 1681 (1994).

[2] Z. Patyk and A. Sobiczewski, Nucl. Phys. **A533**, 132 (1991).

[3] R. Smolańczuk, J. Skalski, and A. Sobiczewski, Phys. Rev. C **52**, 1871 (1995).

[4] R. Smolańczuk and A. Sobiczewski, in *Low Energy Nuclear Dynamics* (World Scientific, Singapore, 1995) p. 313.

[5] Yu.A. Lazarev, Yu.V. Lobanov, Yu.Ts. Oganessian, V.K. Utyonkov, F.Sh. Abdullin, G.V. Buklanov, B.N. Gikal, S. Iliev, A.N. Mezentsev, A.N. Polyakov, I.M. Sedykh, I.V. Shirokovsky, V.G. Subbotin, A.M. Sukhov, Yu.S. Tsyganov, V.E. Zhuchko, R.W. Lougheed, K.J. Moody, J.F. Wild, E.K. Hulet, and J.H. McQuaid, Phys. Rev. Lett. **73**, 624 (1994).

[6] Yu.A. Lazarev, Yu.V. Lobanov, Yu.Ts. Oganessian, Yu.S. Tsyganov, V.K. Utyonkov, F.Sh. Abdullin, S. Iliev, A.N. Polyakov, J. Rigol, I.V. Shirokovsky, V.G. Subbotin, A.M. Sukhov, G.V. Buklanov, B.N. Gikal, V.B. Kutner, A.N. Mezentsev, I.M. Sedykh, D.V. Vakatov, R.W. Lougheed, J.F. Wild, K.J. Moody, and E.K. Hulet, Phys. Rev. Lett. **75**, 1903 (1995).

[7] R. Bass, Lecture Notes in Physics **117**, 281 (1980).

[8] Yu.A. Lazarev, Yu.V. Lobanov, A.N. Mezentsev, Yu.Ts. Oganessian, V.G. Subbotin, V.K. Utyonkov, F.Sh. Abdullin, V.V. Bekhterev, S. Iliev, I.V. Kolesov, A.N. Polyakov, I.M. Sedykh, I.V. Shirokovsky, A.M. Sukhov, Yu.S. Tsyganov, and V.E. Zhuchko, in *Heavy Ion Physics, Scientific Report* 1991-1992 (JINR Report No. E7-93-57, Dubna, 1993), p.203; in *Proceedings of the International School-Seminar on Heavy Ion Physics*, Dubna, 1993 (JINR Report No. E7-93-274, Dubna, 1993) Vol.2, p.497.

[9] B. Kadkhodayan, A. Türler, K.E. Gregorich, P.A. Baisden, K.R. Czerwinski, B. Eichler, H.W. Gäggeler, T.M. Hamilton, D.T. Jost, C.D. Kacher, A. Kovacs, S.A. Kreek, M.R. Lane, M.F. Mohar, M.P. Neu, N.J. Stoyer, E.R. Sylwester, D.M. Lee, M.J. Nurmia, G.T. Seaborg, and D.C. Hoffman, Radiochim. Acta, in print.

[10] M.R. Schmorak, Nucl. Data Sheets **59**, 507 (1990).

[11] The indicated decay properties reflect in part results from our recent $^{244}Pu+^{22}Ne$ bombardment in which we detected 69 α-α correlation chains formed by genetically linked α-decay events of $^{261}104$ and $^{257}102$. To be submitted to Phys. Rev. C.

[12] S. Ćwiok, S. Hofmann, and W. Nazarewicz, Nucl. Phys. **A573**, 356 (1994).

[13] J.V. Kratz, presented at the Pacifichem'95 Conference (Amer. Chem. Soc.), Honolulu, HI, December 17-22, 1995.

[14] Yu.A. Lazarev, in *Low Energy Nuclear Dynamics* (World Scientific, Singapore, 1995) p. 293.

[15] Yu.A. Lazarev, Yu.V. Lobanov, Yu.Ts. Oganessian, V.K. Utyonkov, F.Sh. Abdullin, A.N. Polyakov, J. Rigol, I.V.Shirokovsky, Yu.S.Tsyganov, S. Iliev, V.G. Subbotin, A.M. Sukhov, G.V. Buklanov, B.N. Gikal, V.B. Kutner, A.N. Mezentsev, I.M. Sedykh, K. Subotic, R.W. Lougheed, J.F. Wild, K.J. Moody, and E.K. Hulet, in *Heavy Ion Physics, Scientific Report* 1993-1994 (JINR Report No. E7-95-227, Dubna, 1995) p.29.

[16] S. Hofmann, V. Ninov, F.P. Hessberger, P. Armbruster, H. Folger, G. Münzenberg, H.J. Schött, A.G. Popeko, A.V. Yeremin, A.N. Andreyev, S. Saro, R. Janik, and M. Leino, Z. Phys. **A350**, 277 (1995); GSI Nachrichten 02–95, 4 (Darmstadt 1995).

[17] A. Ghiorso, D. Lee, L.P. Somerville, W. Loveland, J.M. Nitschke, W. Ghiorso, G.T. Seaborg, P. Wilmarth, R. Leres, A. Wydler, M. Nurmia, K. Gregorich, K. Czerwinski, R. Gaylord, T. Hamilton, N.J. Hannink, D.C. Hoffman, C. Jarzynski, C. Kacher, B. Kadkhodayan, S. Kreek, M. Lane, A. Lyon, M.A. McMahan, M. Neu, T. Sikkeland, W.J. Swiatecki, A. Türler, J.T. Walton, and S. Yashita, Phys. Rev. C **51**, R2293 (1995).

Received by Publishing Department
on December **29**, 1995