ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E7-95-100

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NEW NUCLIDE $^{267}108$ PRODUCED BY THE $^{238}U+^{34}S$ REACTION

Submitted to «Physical Review Letters»

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1995

The ground-state decay properties of two recently discovered Z=106 nuclides, $^{265}106$ ($T_{1/2} \approx 2$-30 s) and $^{266}106$ ($T_{1/2} \approx 10$-30 s, $b_{sf} \lesssim 50\%$) [1], revealed a large enhancement in their stability as compared to that of nuclides with *lower* Z and N values. For example, at N=160 the transition from $^{262}102$ ($T_{1/2} \approx T_{sf}$=5 ms [2]) to $^{266}106$, an increase of four protons, increases the stability against spontaneous fission (SF) by a factor of $\gtrsim 4\times10^3$. Similarly, in going from $^{260}106$ ($T_{1/2}$=3.6 ms, $b_{sf}=b_\alpha$=50% [3,4]) to $^{266}106$, the stability increases by factors of $\gtrsim 3\times10^3$ for SF decay and $\sim 3\times10^3$ for α decay. Thus, the ground-state decay properties of $^{266}106$ provide a strong indication of the existence of deformed shell closures near N=162 and Z=108 that were predicted by macroscopic-microscopic calculations (see, e.g., Refs. [5–10]). The discovery of significantly increased nuclear stability near N=162 and Z=108 creates new opportunities for extending the nuclear domain at its upper edge.

We report here on experiments designed to explore further the nuclear stability near N=162 and Z=108 by producing new heavy isotopes of element 108 with N=159 and N=160 in the complete fusion reaction $^{238}U+^{34}S$. Another goal of our experiments was to probe cross section values for the actinide-target-based fusion-evaporation reactions leading to the Z=108 nuclides. Preliminary results from these experiments carried out in March-April 1994 were included in Ref. [11]. Prior to our work, two isotopes of element 108 had been produced in "cold fusion" reactions [12,13]. These are the even-even isotope $^{264}108$ with $T_{1/2}\approx 0.08$ ms, identified by one correlated decay sequence [12], and the odd-A α emitter $^{265}108$ with $T_{1/2}$=1.8 ms, for which three correlated α-decay sequences were observed [12].

According to the predictions made in Refs. [7–9], the even-even nuclide $^{268}108$ is expected to be an α emitter with $T_{1/2}\sim 0.1$ s. Its partial SF half-life was predicted to be of the order of 10^2 s [9]. Thus, a signature for $^{268}108$ would be the observation of α decay with the α-particle energy $E_\alpha\sim 9.7$ MeV [7] followed by SF decay of the unknown daughter $^{264}106$, or eventually by SF decay of the short-lived grand-daughter $^{260}104$, if $^{264}106$ undergoes α decay. Considering decay properties observed for $^{264,265}108$ [12] as well as those predicted for $^{266,268}108$ [7–9], we expect a signature for $^{267}108$ to be the observation of the α decay with $E_\alpha\sim 10$ MeV, followed by α decays of the known nuclides $^{263}106$ ($T_{1/2}$=0.9 s, E_α=8.95 to 9.10, 9.25 MeV [14,15]), $^{259}104$ ($T_{1/2}$=3.1 s, b_α=93%, E_α=8.77, 8.87 MeV, b_{sf}=7% [16]), and $^{255}102$ ($T_{1/2}$=3.1 min, b_α=61.4%, E_α=7.62 to 8.31 MeV, b_{EC}=38.6% [16]).

In the present work we used a ^{34}S bombarding energy of 186 MeV to produce Z=108 compound nuclei with an excitation energy of ≈50 MeV, sufficient for the evaporation of 4 or 5 neutrons. The laboratory fusion barrier energy for the ^{238}U+^{34}S system is 181 MeV as calculated by the Bass prescription [17]. Beams of ^{34}S projectiles were delivered by the U400 cyclotron of the Joint Institute for Nuclear Research. The SO_2 gas, with sulfur enriched in ^{34}S to ≈80%, was used to feed the discharge chamber of a PIG ion source with an indirectly heated cathode, which made it possible to obtain intense ^{34}S beams at a reasonably low consumption of the ^{34}S (≈30 mg h^{-1} pμA^{-1}).

The time structure of the pulsed ^{34}S beam was determined by the cyclotron modulating frequency of 150 Hz and a duty factor of ≈40%, which corresponds to a beam cycle of 6.7 ms and a beam pulse duration of ≈2.7 ms. Six uranium targets electrodeposited on 0.70-mg cm^{-2} Ti substrates with average areal densities of 0.54 mg cm^{-2} of ^{238}U (99.9%) and a total area of 36 cm^2 were arranged on a wheel rotating at 3000 rpm. In an 860-h bombardment, with an average intensity of 6×10^{12} particles/s of ^{34}S, the targets received a total beam dose of 1.7×10^{19} particles. For calibration purposes, we performed bombardments of ^{nat}W and ^{207}Pb with ^{34}S, as well as bombardments of ^{206}Pb with ^{48}Ca and ^{nat}Pt with ^{26}Mg.

Evaporation residues (EVRs) recoiling out of the ^{238}U targets were separated in flight from beam particles and various transfer-reaction products by the Dubna gas-filled recoil separator described in Ref. [18]. The separator was filled with hydrogen at a pressure of 1.0 Torr. The magnetic rigidity of the separator's dipole magnet, Bρ, was adjusted to center the quasi-Gaussian distribution of EVRs on the focal-plane detector in the horizontal direction. To set the Bρ value for the Z=108 EVRs with the expected average velocity $<v/v_0>\approx 1.7$ ($v_0=2.2\times 10^6$ m s^{-1} is the Bohr velocity), we used prior measurements [1,18] of the average charge states $<q>$ for the EVRs with Z=89 through 106, as well as new $<q>$ data from various calibration bombardments performed in the present work (see Fig. 1). The separated EVRs passed through a time-of-flight (TOF) measurement system composed of two multiwire proportional chambers in a 1.5-Torr pentane-filled module and were finally implanted in a 120×40 mm^2 position-sensitive detector (PSD) array.

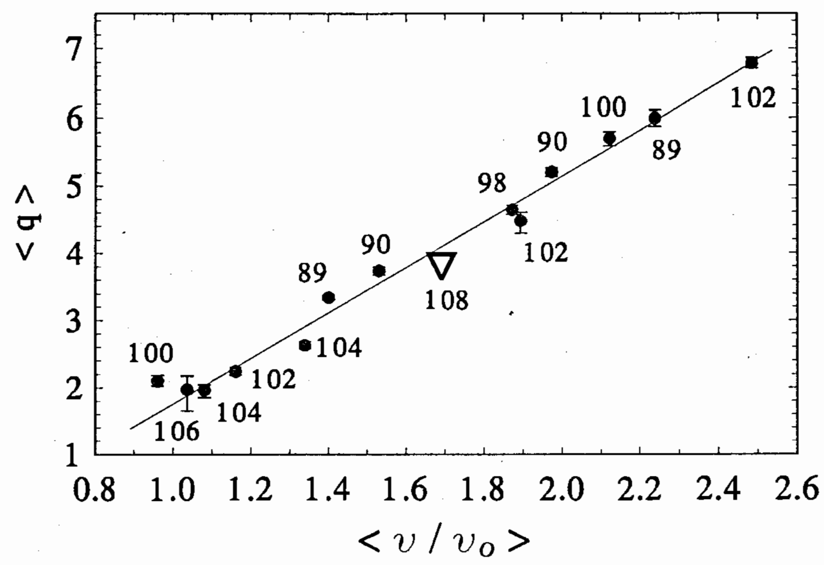

Fig. 1. The velocity dependence of the average charge states <q> of very heavy atoms traversing 1 Torr of hydrogen. Z values for atoms are given near the data points. The systematics is based on both previous data [1,18] and <q> measurements performed in this work. The triangle shows the <q> value for Z=108. The line is included to guide the eye.

The PSD array consisted of three 40×40 mm^2 passivated boron implanted silicon detectors produced by *Canberra Semiconductor NV*, with each detector having four 40-mm high × 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 fully depleted detectors. Top and bottom signals from each strip on the resistive detector back were split into three channels to provide y-position signals for α/implant events and SF events, as well as an energy sum signal for α/implant events. We determined

total fission energies by summing the 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 fission events, and the time since the beginning of the data acquisition cycle in 0.1-ms intervals. The data were acquired in list mode in a PC AT/386 and periodically transferred to a SUN SPARCstation IPX for storage and analysis.

Alpha-energy calibrations were periodically performed for each strip using the α peaks from nuclides produced in the ^{nat}W+^{34}S reaction. Most of the strips had α-energy peak FWHMs of about 70 keV (an average value for the 36-day bombardment during which there was degradation of the detector performance due to radiation damage). An approximate fission-energy calibration was obtained by extrapolating the α-energy calibration, as well as by detecting the known SF activities 2.3-s ^{252}102 [16] and 21-ms ^{238}Cf [19] produced in the ^{206}Pb+^{48}Ca and ^{207}Pb+^{34}S reactions, respectively. These reactions were also used to estimate the collection efficiency of the Z=108 EVRs and the range of their energies measured by the PSD. By using known α-decay sequences from the calibration reactions, we estimated the FWHM y-position deviation Δpos to be 1.2 mm (3% of the strip height) for α-α correlations. For EVR-α and EVR-SF correlations, Δpos depends significantly on EVR energies measured by the PSD. A comparison of the EVR-α data for ^{217}Th produced in the ^{nat}W+^{34}S and ^{nat}Pt+^{26}Mg reactions shows an increase in Δpos from 1.2 to 3.5 mm with a decrease in the average measured EVR energy from ≈8 to ≈3 MeV. For the ^{238}U+^{34}S reaction, the Gaussian-like distribution of measured Z=108 EVR energies is expected to have an average of 6 MeV and a FWHM of 3 MeV.

In the off-line analyses we searched for event sequences in which EVRs within the expected energy range were correlated in time and (x,y)-position with subsequent α and/or SF decays. Table I lists the correlated event sequences that we attribute to Z=108 implantation events followed by the detected α decays of $^{267}108$. The out-of-beam α-particle energy spectrum is shown in Fig. 2 for all strips for the entire bombardment; in Fig. 3 we show, for each strip, the number of out-of-beam α decays in the energy range of interest, 7.6 to 10.4 MeV, an average rate of about 4 events per day per strip, resulting in a high statistical significance for event sequences with one or two α particles detected between cyclotron beam pulses. We examined the statistical significance of each observed correlation by calculating from our data the number of random EVR-α-α sequences with similar properties, N_b, that are expected to occur for the whole PSD array during the entire measurement time T=860 h. For example, in considering the event sequence with $E_{\alpha 1}$=9.87 MeV, we calculated N_b for implantation events with measured EVR energies of 3.5 to 8.5 MeV that are followed within the time interval Δt_1=20 ms by an in-beam α decay with $E_{\alpha 1}$=9.4 to 10.4 MeV and then, within the time interval Δt_2=2.0 s, by an out-of-beam α decay with $E_{\alpha 2}$=8.6 to 9.0 MeV. Using the y-position window $|\Delta pos|$=0.4 mm, we determined N_b<0.0002 for this case. Similar N_b calculations, with corresponding changes in energy, time and position windows, were also performed for the EVR-α-α sequences with $E_{\alpha 1}$=9.74 and 9.86 MeV, which resulted in N_b<0.02 and <0.003, respectively.

Table I. The measured parameters of the correlated $^{267}108$ event sequences observed in the $^{238}U+^{34}S$ reaction. All α-decay events are out-of-beam except for those two indicated. The accuracy of the measured α-particle energies is estimated to be ±60 keV.

Particle	Particle energy *MeV*	Strip No.	Time interval	Δpos^c *mm*
EVR[a]	4.1	11		
α	9.74	11	29 ms	−1.0
α	7:75	11	9.1 min	−2.1
EVR	6.2	6		
α	9.86	6	32 ms	−0.6
α^b	8.80	6	3.6 s	−0.6
EVR	4.4	9		
α^b	9.87	9	20 ms	+0.2
α	8.80	9	2.0 s	+0.4

[a]The quoted EVR energies are measured values. No estimate was included for the pulse-height defect.
[b]Event occurred during the beam pulse.
[c]The y-position deviations are given with respect to the EVR implantation site.

We interpret the three correlated event sequences with $E_{\alpha 1}$=9.74, 9.86, and 9.87 MeV as the α decay of the new isotope $^{267}108$ followed by α decay of one of the descendant nuclides, $^{255}102$ in the first sequence, and $^{259}104$ in the two other sequences. We also observed two out-of-beam α-α correlations with N_b<0.03 linking α decays of $^{263}106$, $^{259}104$, and $^{255}102$. It is possible that these correlations orig-

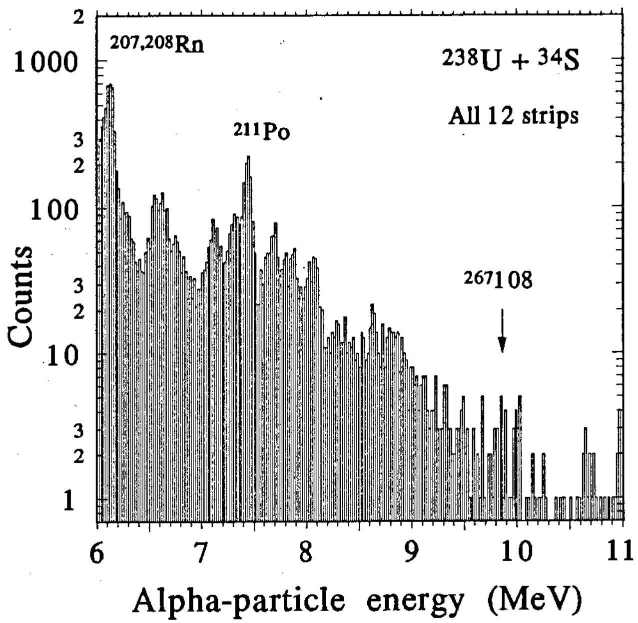

Fig. 2. Energy spectrum of out-of-beam α particles detected in all 12 strips in the 36-day bombardment of ^{238}U with 1.7×10^{19} particles of ^{34}S. Most α-activities seen in the spectrum are due to $Z\geq84$ nuclides produced in deep inelastic collisions between ^{238}U and ^{34}S, with possible traces of some α emitters from ^{nat}W+^{34}S calibrations.

inate from the decays of ^{267}108 where the ^{267}108 α particles escaped the PSD array.

The measured parameters of the correlated EVR-α-α sequences listed in Table I fully support the assignment of these sequences to the implantation in the PSD array and subsequent α decay of the ^{267}108 EVRs. The 9.74- to 9.87-MeV α-particle energies are in good agreement with both predictions [7] and systematics (see, e.g., Fig. 5 in Ref. [12]). The measured $E_{\alpha2}$ values, as well as the measured time

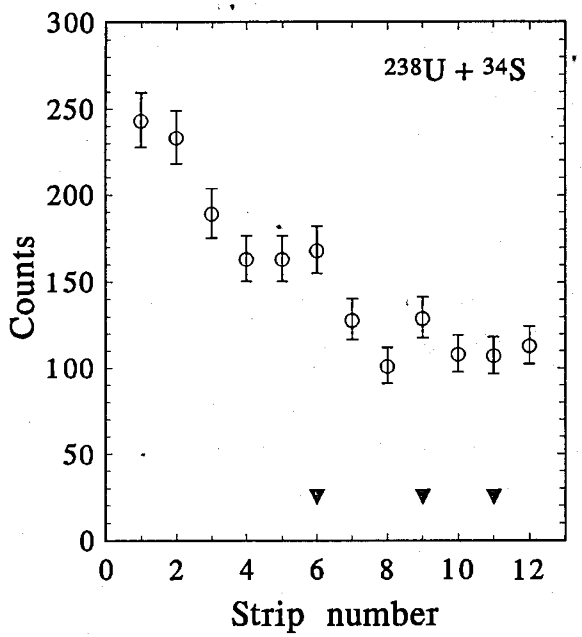

Fig. 3. The distribution across detector strips for all out-of-beam α-decay events with E_α=7.6 to 10.4 MeV detected in the ^{238}U+^{34}S bombardment. The triangles show the location of the three Z=108 event sequences.

intervals between the correlated α decays, agree with the α-particle energy and half-life values for ^{255}102 and ^{259}104 [16]. The measured EVR energies of 4.1 to 6.2 MeV are in the range of 6.0±2.5 (2σ) MeV that is expected for Z=108 EVRs on the basis of calibration measurements. For all three correlations, the detection of the EVRs by the PSD array was accompanied by TOF signals consistent with expectations for a compound nucleus. From our data, we estimated the average charge state <q> of the Z=108 EVRs in hydrogen to be

3.8±0.2 at <v/v_0>=1.7. This value is in good agreement with the <q> systematics shown in Fig. 1.

The above observations and arguments provide strong evidence for the identification of ^{267}108. From measured time intervals between implantation and α decay events of the ^{267}108 nuclides, we calculate a maximum likelihood half-life value of 19^{+29}_{-10} ms (see also Ref. [20]). The production cross section of the new isotope at the ^{34}S bombarding energy of 186 MeV is 2.5 pb, with an estimated accuracy of a factor of ~3. We note, however, that the *upper* confidence limit of the reported cross section value could be higher if we include an uncertainty in the collection efficiency due to the small number of observed Z=108 events which are used to estimate how precisely the Z=108 EVR distribution is centered in the horizontal direction at the focal plane.

We detected nine correlated EVR-SF event pairs, with time intervals of 0.08 to 5.6 ms between the pair members (we note that the dead time of the electronics system was about 55 μs in this experiment). We found no time and position correlations of both out-of-beam and in-beam SF events to preceding Z=108 α decays. The probability density distribution of the time intervals in the observed EVR-SF correlations does not contradict the assumption of a single SF activity with a maximum likelihood half-life of $1.0^{+0.8}_{-0.3}$ ms, although a ≈20% contribution from longer-lived SF species cannot be excluded. The apparent cross section corresponding to the 1-ms SF activity is of the order of 1 pb. We consider the most probable origin of the observed SF events to be the 0.9-ms spontaneously

fissioning isomer ^{240mf}Am, with possible smaller contributions from 14-ms ^{242mf}Am and 1.0-ms ^{244mf}Am, which are produced by transfer reactions with cross sections of the order of 10 to 100 nb (see Ref. [21]). Such transfer products are expected to be suppressed by the gas-filled separator by a factor of $\sim10^4$–10^5 [18].

From the absence of α-SF correlations that we can attribute to the production of ^{268}108, we calculated that the 68% confidence level upper limit for its production cross section is 1.3 to 1.9 pb, assuming for the unknown ^{264}106 b_{sf} values between 0 and 100%, respectively. The non-observation of ^{268}108 can be readily explained, since for fusion-evaporation reactions induced by ^{18}O, ^{22}Ne, and heavier projectiles on actinide targets, cross sections for the 4n-evaporation channel are 3 to 5 times smaller than for the 5n channel (see, e.g., Refs. [1,18,22]). Finally, the non-observation of any SF events following the three detected α decays of ^{267}108 allows us to calculate straightforwardly an upper limit for the SF branch of ^{263}106. Taking into account the 100% probability of detecting SF events, we obtain $b_{sf}<30\%$ at the 68% confidence level, in contrast to $b_{sf}\approx70\%$ suggested for ^{263}106 in Ref. [23] on the basis of indirect arguments.

An important result of the present work is the measurement of the 2.5 pb cross section for the ^{238}U(^{34}S,5n) reaction, which is 10^5 times lower than that of the reaction ^{238}U(^{22}Ne,5n) [22]. As will be discussed in a future publication, this dramatic cross section decrease reveals a fusion limitation mechanism different from that associated with the overcritical Coulomb-to-nuclear force ratio in the entrance reaction channel.

To conclude, we have produced and positively identified the new N=159 isotope of element 108. The decay properties that we established for $^{267}108$ offer further evidence for significantly increased nuclear stability near the predicted deformed shells N=162 and Z=108.

We take pleasure in thanking Ts.Vylov and V.G.Kadyshevsky for the effective support of the present work. We wish to thank the U400 cyclotron staff for providing the intense ^{34}S beams. Our thanks are due to Yu.D.Shipilov and co-workers for producing the highly enriched ^{34}S material, to V.Ya.Lebedev and A.B.Yakushev for preparing the $^{34}SO_2$ used in the cyclotron ion sources, and to V.I.Chepigin for technical assistance. We are grateful to P.Burger and M.Keters of *Canberra Semiconductor NV* (Olen, Belgium) for the fruitful cooperation. Our thanks go to V.I.Tomin, V.E.Zhuchko, and A.M.Zubareva for their help in the development of the new electronics and data acquisition system used in these experiments, and to V.I.Krashonkin for the efficient maintenance of the gas-filled separator. The Livermore collaborators thank their Russian hosts for their hospitality during the experiment. Much of the support for the LLNL authors was provided through the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No.W-7405-Eng-48. Some of the Dubna authors acknowledge the individual financial support by Grant No. RFN000 from the International Science Foundation. These studies were performed in the framework of the Russian Federation/US Joint Coordinating Committee for Research on Fundamental Properties of Matter.

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Received by Publishing Department
on March 6, 1995