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SW 9533

Short Note

Production and Identification of heavy Ni isotopes: Evidence for the doubly magic nucleus $^{78}_{28}$Ni

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Abstract. We report the first observation of the doubly magic nucleus ^{78}Ni$_{50}$ and the heavy isotopes ^{77}Ni, ^{73,74,75}Co, ^{80}Cu. The isotopes were produced by nuclear fission in collisions of 750 A·MeV projectiles of ^{238}U on Be target nuclei. The fully-stripped fission products were separated in-flight by the fragment separator FRS and identified event-by-event by measuring the magnetic rigidity, the trajectory, the energy deposit, and the time of flight. Production cross-sections and fission yields for the new Ni-isotopes are given.

PACS: 21.60.Cs; 27.50+e; 25.85-w

Doubly-closed shell-nuclei and the neighboring isotopes are intensively investigated as the nuclear shell-model residual interaction is calculated from excitation energies and quantum numbers of their well-characterized levels. ^{78}Ni is the heaviest of three doubly magic Ni isotopes: ^{48}Ni$_{20}$, ^{56}Ni$_{28}$ and ^{78}Ni$_{50}$ and, with ^{100}Sn, the second doubly closed-shell nucleus among the N=50 isotones. Neutron-capture and β-decay properties around Z=28 and N=50 are of great importance with respect to the stellar r-process needed to explain the relative abundances of nuclei in the solar system.

It has been a long standing challenge to observe ^{78}Ni because of its very large A/Z-ratio of 2.79. As refractive elements are extracted with low efficiency by ISOL-methods until now, recoil separators are better suited to investigate these elements. The most neutron-rich Ni isotopes were produced either by low-energy fission or by projectile fragmentation. The isotopes of $^{70-74}$Ni were discovered [1], and their half-lives were measured [2] in very asymmetric thermal-neutron induced fission of ^{235}U. Production of $^{75-76}$Ni was investigated by ^{86}Kr projectile-fragmentation at 500 A·MeV, and their half-lives were determined [3, 4]. By extrapolating the production cross-section for ^{86}Kr fragmentation along the line N=50 or Z=28, a value of 0.5 pb is expected for the production of ^{78}Ni. A count rate of 0.5 ^{78}Ni/day follows for an effective luminosity of 10^{31}cm^{-2}s^{-1}. The discovery of very n-rich fission fragments in the reaction of 750 A·MeV ^{238}U on a Pb target [5], the production cross sections of 190 μb for Ni isotopes and the higher luminosity in case of a Be target suggested to use the fission process for searching for ^{78}Ni [6].

Projectile fission at relativistic energies leads to forward-focussed fully-ionized fragments. Within the 30 mrad angular aperture and the 2% momentum acceptance of the FRS [7] only fragments emitted forward or backward in the U-frame of reference can be transmitted. The consequences are a clean selection of forward-emitted fission fragments at rigidities Bρ larger than the projectile value $(B\rho)_0$, but a transmission of fission fragments through the FRS of a few percent only [6].

^{238}U ions delivered by a Penning-source were accelerated in the UNILAC and the heavy-ion synchrotron SIS (GSI) to an energy of 750 A·MeV. Spills with a duration of 1 s and an average number of
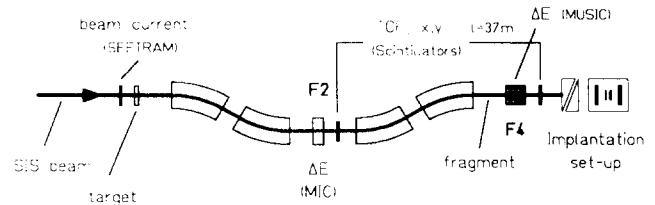

Fig. 1. Experimental setup for the separation and identification of ^{78}Ni and other fission fragments at the fragment separator FRS.

10^8 U-ions were extracted every 5 s and directed onto a 1 g/cm^2 Be target. Reaction products were analyzed with the FRS operated in the achromatic mode [7]. The identification was done event-by-event by the $B\rho$-ΔE-ToF method. Energy loss measurements (ΔE) were performed at the dispersive focal plane F2 (see Fig.1) by a Mini-Ionization Chamber (MIC) and at F4 by the ionization chamber MUSIC [8]. The MUSIC Z-resolving power reached 130. There is a gap in the detected nuclear charges between U ions and the heaviest elements from fission. In order to bridge the Z calibration between the known fission pattern and the projectile atomic number, fragmentation products with $62 \leq Z \leq 92$ were measured by the MUSIC chamber.

Two scintillation detectors of 20×5 cm^2 area and 5 mm thickness were positioned in the focal planes at F2 and F4 to measure the ToF and the position [9]. To reconstruct the flight path, the angle α of the trajectory in F4 was calculated from the x-positions in the first and fourth stage of the MUSIC chamber. A mass resolving power A/ΔA of 250 was achieved on-line. The mass calibration of several hundred different fission fragments, separated simultaneously, was corroborated by reproducing the A/q value of the projectile.

To separate ^{78}Ni, the field setting of the FRS was calculated with the velocity β_f = 0.054 deduced from the mean fission kinetic energy measured in ^{235}U(n_{th}, f) [10]. The resulting velocity in the laboratory frame for ^{78}Ni and the corrections for the differences in energy-loss in the target between U and Ni led to $B\rho$ = $1.16(B\rho)_0$. Energy losses in the detectors located in F2, determined with the primary beam, were taken into account to calculate the rigidity in the second half of the spectrometer. The 1 g/cm^2 Be target introduced an energy broadening depending on the target depth where the fission takes place. The related momentum width of Ni fragments reached 4%, due to the large difference in stopping power between U and Ni. In spite of the 2% momentum acceptance of the FRS, we observe a maximum transmission, 1.6% in case of Ni, for three masses. An effective luminosity of $2 \cdot 10^{28}$cm^{-2}s^{-1} for

our research of [78]Ni follows. Detailed simulations were performed with the code MOCADI to achieve the transmission curve for each isotope as a function of $B\rho$.

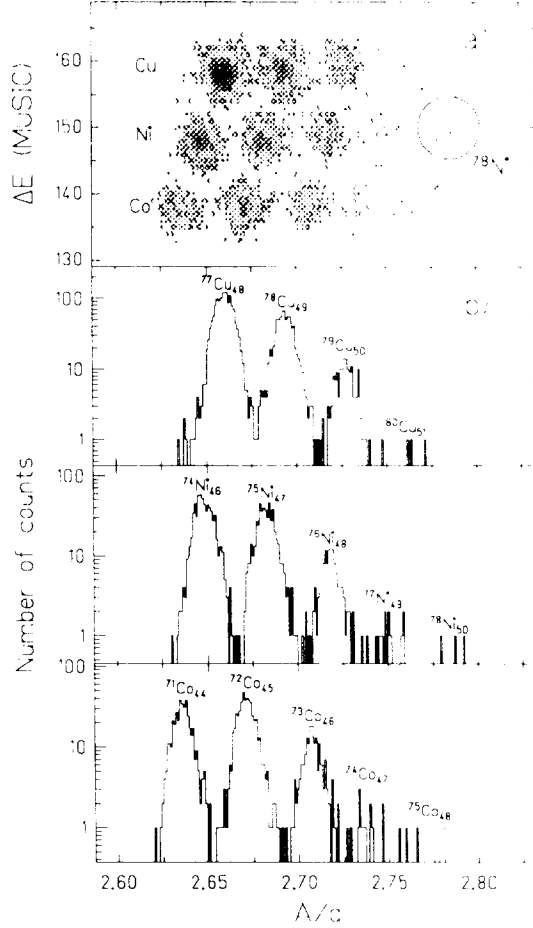
Fig. 2. a) ΔE versus A/q scatter plot at $B\rho = 1.16(B\rho)_0$ and b) A/q-projections of the Cu, Ni, and Co isotopes.

The scatter plot ΔE versus A/q for isotopes of Co, Ni, and Cu, separated at the FRS with a setting calculated for [78]Ni, is shown in Fig.2a, where the individual isotopes are clearly resolved. For a total dose of 10^{13} U ions delivered in 132 h on the target three events can be assigned to the isotope [78]Ni. Other new nuclei, [77]Ni, [73,74,75]Co and [80]Cu can be identified. the low count rate requires a background-free measurement. The correlation ellipse between x-position and the angle α measured in F4 allowed to reject 3% of the events. All parameters of the three events of [78]Ni were checked to be compatible with the values obtained for the other isotopes. In particular the MIC signals in F2 of the three events correspond to Ni fragments. The number of counts. deduced from Fig. 2b, for the isotopes of maximum transmission are given in Table 1. A neutron odd-even effect is obvious from these numbers. The striking drop between [79]Cu$_{50}$ and [80]Cu$_{51}$ points to the shell closure at N=50.

Production cross sections are given (Table 1). independent yields $\eta_{(A,Z)}$ and fractional independent yields $\eta_{(A,Z)}/\eta_{(Z)}$ are calculated from the measured fission cross section of 115 mb on a Be-target and from the elemental yields $\eta_{(Z)}$: $4.6 \cdot 10^{-3}, 1.6 \cdot 10^{-3}$, and $0.4 \cdot 10^{-3}$ for Cu, Ni, and Co, respectively [6]. A systematic uncertainty of 20% due to the FRS transmission and the beam intensity measurement has to be added to the large statistical error.

In collisions with Be, [238]U is excited to energies larger than 20 MeV [6] by nuclear interactions. In Table 2 we compare our production parameters of [78]Ni with the values extrapolated from the

Isotope	$\left(\frac{A}{q}\right)_{exp}$	N	σ	$\eta_{(A,Z)}$	$\frac{\eta_{(A,Z)}}{\eta_{(Z)}}$
	[u/e]		[nb]	$\cdot 10^{-9}$	$\cdot 10^{-6}$
[78]Cu$_{49}$	2.70	739	77	642	140
[79]Cu$_{50}$	2.73	145	15	130	28.3
[80]Cu$_{51}$	2.75	4	0.4	3.5	0.8
[76]Ni$_{48}$	2.72	132	14	120	75
[77]Ni$_{49}$	2.75	13	1.3	11	6.9
[78]Ni$_{50}$	2.79	3	0.3	2.6	1.6
[73]Co$_{46}$	2.71	165	17	140	350
[74]Co$_{47}$	2.74	15	1.6	14	35
[75]Co$_{48}$	2.77	5	0.6	5	12.5

Table 1. Production cross sections and fission yields for the n-rich isotopes of Cu, Ni, and Co.

measurement of $^{235}U(n_{th}, f)$ [10]. The independent yield distribution is assumed to be Gaussian. The parameters are the element yields $\eta_{(Z)}$, the width σ_A and the difference $A - A_p$ between the mass of the selected isotope and the mean mass. The enhancement of $\eta_{(A,Z)}$ by a factor of 50 as compared to $^{235}U(n_{th}, f)$ is due to the larger elemental yield for very asymmetric fission at increased exitation energies [6]. Since σ_A is found to be unchanged (σ_A=1.6), the reduction in $\eta_{(A,Z)}/\eta_{(Z)}$ is a result of the shift of the mean mass A_p.

	A_p	$\eta_{(Z)}$	$\eta_{(A,Z)}$	$\frac{\eta_{(A,Z)}}{\eta_{(Z)}}$	σ_{tot}[b]	$\sigma_{78_{Ni}}$[nb]
[235]U + n_{th}	71.2	4.3 $\cdot 10^{-7}$	6.0 $\cdot 10^{-11}$	1.2 $\cdot 10^{-4}$	584	35
[238]U + Be	70.0 ±0.5	1.0 $\cdot 10^{-3}$	2.6 $\cdot 10^{-9}$	1.6 $\cdot 10^{-6}$	0.115	0.3 ± 0.2

Table 2. Comparison of the [78]Ni production parameters in $^{235}U(n_{th}, f)$ [10] and $^9Be(^{238}U,f)$ at 750 A MeV [6].

In this experiment the doubly magic nucleus [78]Ni was identified for the first time. The production rate of 0.5 atoms/day is presently too low for ion-β time correlation measurements [11] to determine the β-decay half-life. At high energies slowing down in matter leads to large losses due to secondary reactions, whereas at lower energies the FRS-transmission breaks down. Parallel to the efforts to increase the U-beam intensity new setups aiming at nuclear structure studies are to be anticipated.

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