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FIRST OBSERVATION OF THE DOUBLY MAGIC NUCLEUS $^{78}\text{Ni}_{50}$

M. Bernas¹, F. Ameil^{1,2}, P. Armbruster², S. Czajkowski³, Ph. Dessagne⁴,
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C. Kozhuharov², Ch. Miehé⁴, G. Münzenberg², M. Pfützner⁵, C. Röhl⁶,
W. Schwab², C. Stéphan¹, K. Sümmerer², L. Tassan-got¹ and B. Voss².

¹IPN Orsay, IN2P3, ²GSI, Darmstadt, ³CENBG Bordeaux-Gradignan, IN2P3,
⁴CRN Strasbourg, IN2P3, ⁵Warsaw University, ⁶TH Darmstadt.

Enhanced shell effects at double closure far off stability have been a long standing question. Doubly magic nuclei have been searched for intensively during the last decade. Binding energy, shape, decay-mode and simple excited configurations in this class of nuclei provide characteristic data from where residual interactions can be established and shell-model calculations extended to new areas of the chart of nuclides. Regarding the nucleosynthesis, the ^{78}Ni isotope is the first N=50 isotope encountered in the rapid neutron capture. For this waiting point nucleus, β -decay half-life and n-capture cross section are to be known in order to improve our understanding of the r-process and to reproduce the mass abundances as they have been measured in the solar system.

Neutron-rich nuclei can be reached only by projectile fragmentation, in case the expected nucleus stays close to the projectile, and by fission. In very asymmetric thermal neutron induced fission of ^{235}U , new isotopes of $^{70-74}\text{Ni}$ were separated and identified, and their β -decay halflives were

determined from time correlations between the implantation of the ion of interest and the detection of the subsequent β particle [1]. Production of n-rich Ni isotopes was investigated with ^{86}Kr fragmentation at 500 A.MeV [2] and ^{75}Ni was observed. More recently ^{76}Ni was identified in the same reaction and both Ni half-lives were measured [3]. However, the production cross section for ^{78}Ni with projectile fragmentation of ^{86}Kr was extrapolated to be 0.5 pb. The actual value can be even lower since the ^{86}Kr projectile would lose exclusively 8 protons in the collision without neutron evaporation which is extremely unlikely.

The recent discovery of more than 50 n-rich isotopes separated with the FRagment Separator FRS [4] in projectile-fission of ^{238}U at relativistic energies [5] and the characteristics of the element yield distribution observed on Pb and Be targets [6] have suggested that projectile fission of 750 A.MeV ^{238}U on a Be target could be the best way to produce the ^{78}Ni isotope. In relativistic collisions fission fragments are stripped and forward emitted. Within the 30 mr angular acceptance of the FRS only fission fragments emitted forward or backward in the U frame can be transmitted. Consequences are a clean separation of fission fragments at rigidities larger than the projectile rigidity $(B\rho)_0$ and a transmission through the FRS of a few % only.

The U ions were accelerated with the heavy ion synchrotron SIS at GSI-Darmstadt- and delivered with an intensity of $2 \cdot 10^7/\text{s}$. They were directed on a 1 gr/cm^2 Be target. The fragments were separated by the FRS operated in the achromatic mode [4] and identified event-by-event by the Bp- ΔE -ToF method. Energy losses were measured in the dispersive focal plane F2 with an Ionization chamber MIC and after the FRS, in F4, with the Multi Sampling Ionization Chamber (MUSIC) [7]. Two scintillation detectors [8] were positioned in the focal planes at F2 and F4 to determine the time of flight and the coordinates of the trajectory of the fragment as shown on Fig. 1. To resolve the masses, an accuracy of 10^{-3} is required on the determination of the physical parameters: the ToF and the length of the flight pass to obtain the velocity β , the magnetic field B and the radius ρ . In this experiment a timing precision of 0.2 ns over a ToF of 150 ns leads to a resolving power $A/\Delta A = 250$.

Fig.1 Experimental set-up

The velocity of Ni fission fragments due to the fission process is assumed to be the same as found in $^{235}\text{U}(n_{\text{th}},f)$ [9]. It is combined with the projectile velocity in order to calculate the proper setting of the FRS. The increment in A/Z versus the U projectile and the gain in velocity given by fission drive B_p to $1.16(B_p)_0$.

The 1 gr/cm^2 target of Be introduces a location straggling effect on the energy of the Ni fragments. The corresponding momentum broadening reaches 4% due to the large difference in stopping power for U and Ni. Therefore, in spite of the 2% momentum aperture of the FRS, four Ni isotopes are transmitted optimally out of the six observed at each B_p setting. This transmission is 1.6% in case of Ni.

A ΔE -ToF scatter-plot of Cu, Ni and Co isotopes measured for the ^{78}Ni tuning of the FRS is shown in Fig.2. The individual isotopes are clearly resolved. For a total dose of 10^{13} U ions delivered in 132 h on the target 3 events can be assigned to ^{78}Ni . Dealing with small numbers of events demands a back-ground free measurement. For the rare isotopes, the correlation ellipse between the angle of the trajectory and the x coordinate in S4 was plotted and 3% of the events randomly distributed were eliminated. All parameters of the three ^{78}Ni events, in particular the MIC signals, were tested to be compatible with the other Ni events. Other new isotopes ^{77}Ni , $^{73,74,75}\text{Co}$ and ^{80}Cu are seen in the plot. During the search for ^{78}Ni , 22 new isotopes were identified between the elements V and Ga, not reported in our first measurement [5].

Fig. 2: Scatter-plot and A/q projections of very n-rich Cu, Ni and Co isotopes separated at $Bp = 1.16 (Bp)_0$.

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

Table 1: Production cross sections and yields.

The corresponding numbers of counts (Fig. 2) are given in Table 1. A neutron odd-even effect is obvious from these numbers. The striking drop

between $^{79}\text{Cu}_{50}$ and $^{80}\text{Cu}_{51}$ points to the shell closure at $N=50$. 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 for ^{238}U fission 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]. The preliminary distribution of the Ni yields is given on Fig.3.

Fig.3: Comparison of experimental yields measured for production of Ni.

The results obtained on the 1.2 gr/cm^2 Pb target are indicated as well as the isotopic distribution measured in $^{235}\text{U}(n_{\text{th}}, f)$ [9]. On a Be target ^{238}U projectile is excited to energies larger than 20 MeV by nuclear interaction. The factors which enter in the calculation of the independent yield, assumed to be a Gaussian, are the element yield $\eta(Z)$, the width σ_A and the difference $(A-A_p)$ between the mass of the selected isotope and the mean mass value. Since σ_A is found unchanged ($\sigma_A = 1.6$) and $\eta(Z)$ is much larger than with $^{235}\text{U}(n_{\text{th}}, f)$, the reduction in fractional independent yield $\eta(A,Z) / \eta(Z)$ results from the shift in the mean mass value A_p . The larger value of $\eta(A,Z)$ presently found does

not compensate the much larger thermal neutron fission cross section of 584 b. The cross section to produce ^{78}Ni is smaller by two orders of magnitude than the extrapolated value for $^{235}\text{U}(n_{\text{th}},f)$.

	A_p	$\eta(Z)$	$\eta(A,Z)$	$\eta(A,Z)/\eta(Z)$	σ_{tot}	$\sigma^{78}\text{Ni}$ nb
$^{235}\text{U}(n_{\text{th}},f)$	71.2	$4.3 \cdot 10^{-7}$	$6.0 \cdot 10^{-11}$	$1.2 \cdot 10^{-4}$	584	35
$^{238}\text{U} + \text{Be}$	70 ± 0.5	$1 \cdot 10^{-3}$	$2.6 \cdot 10^{-9}$	$1.6 \cdot 10^{-6}$	0.115	0.3 ± 0.2

The doubly magic nucleus of ^{78}Ni has been identified for the first time and the associated production yield was measured. The counting rate of 0.5 atom/day is presently too low to consider a measurement of the half-life by ion- β time correlations [10]. At present energy the slowing-down process in matter leads to losses of roughly 80% from secondary reactions whereas at lower incident energy the FRS transmission breaks down for projectile fission. Parallel to the effort of the SIS accelerator crew to improve the U beam intensity, we anticipate other methods to obtain first spectroscopic informations on very rare key- isotopes.

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