First Observation of the $T_z = -7/2$ Nuclei ^{45}Fe and ^{49}Ni

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A primary beam of ^{58}Ni at 600 MeV/nucleon from the SIS synchrotron at GSI was used to produce proton-rich isotopes in the titanium-to-nickel region by projectile fragmention on a beryllium target. The fragments were separated by a projectile-fragement separator and unambiguously identified. We report here the first observation of the $T_z = -7/2$ nuclei ^{45}Fe and ^{49}Ni, the most proton-rich nuclei ever synthesized with an excess of seven protons. In addition, the new isotope ^{42}Cr ($T_z = -3$) was identified. According to commonly used mass predictions, these isotopes are all unbound with respect to two-proton emission from their ground states. From the nonobservation of ^{38}Ti ($T_z = -3$) in this experiment, an upper limit of 120 ns is deduced for the half-life of this isotope. [S0031-9007(96)01355-5]

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One of the most exciting, yet unobserved phenomena at the proton drip line is probably the occurrence of the two-proton ground-state $(2p)$ radioactivity which was predicted about 30 years ago [1]. A two-proton decay may proceed either via ^{2}He emission or by a simultaneous emission of two protons which are uncorrelated in space. For the nuclei considered as candidates for the $2p$ radioactivity, one-proton emission is energetically forbidden.

A $2p$ decay mode has been observed for ^{6}Be [2,3] and for ^{12}O [4]. In these cases, however, the Q value for $2p$ decay is much larger than the Coulomb barrier, so that no radioactive process characterized by a long half-life can take place and, correspondingly, half-lives of the order of 10^{-21} s are observed. Furthermore, the data measured for these nuclei indicate a sequential emission of two protons in a two-step process.

Although considerable experimental efforts have been made in order to observe the $2p$ radioactivity [5–7], no evidence for this disintegration mode was found up to now. According to theoretical predictions of Goldanskii [8], the nuclei ^{22}Si, ^{31}Ar, ^{39}Ti, and ^{42}Cr are possible candidates for this radioactivity, although the uncertainties of the mass predictions also allow for these nuclei to be bound or to have a rather long half-life for $2p$ decay ($T_{1/2}^{2p}$). Indeed, for three of them (^{39}Ti, [5], ^{31}Ar [9], and ^{22}Si [10]), β decay has been measured to be the dominant decay mode.

New theoretical predictions by Brown [11] identified ^{39}Ti, ^{45}Fe, and ^{48}Ni as the best candidates with $T_{1/2}^{2p}$ predicted to be in the 1 μs–150 ms range. A recent theoretical work [12] also proposed ^{38}Ti as a possible candidate, although its $T_{1/2}^{2p}$ value seems to be too small to be observable by the technique used in the present work. Besides ^{39}Ti, none of the isotopes regarded as possible candidates for the $2p$ radioactivity by recent theoretical predictions [11,12] have been observed prior to the present work.

A possible Thomas-Ehrman effect (see, e.g., [5,13]) adds even more uncertainty to the theoretical mass predictions at the proton drip line. However, recent spectroscopic studies [14,15] demonstrated that the isobaric-multiplet mass equation is a reliable tool for mass predictions in the region studied in this work.

It has been one of the sucesses of heavy-ion fragmentation to extend the knowledge of the proton drip line from $Z = 13$ to 22. Particularly striking was the production of ^{22}Si, the first observed $T_z = -3$ nucleus [16]. This region at the limit of nuclear binding allows for a stringent test of mass predictions. It also opens large energy windows on a variety of β-decay modes such as $\beta 2p$, $\beta 3p$, $\beta 4p$, and $\beta 5p$ emission. An additional important motivation for the exploration of the *fp*-shell nuclei is that, for this region, shell-model calculations have recently been extended [12].

The purpose of the present study is to search for the remaining candidates for $2p$ radioactivity, i.e., ^{38}Ti, ^{42}Cr, ^{45}Fe, and ^{48,49}Ni. In a first step, we tried to identify these isotopes among the fragments of a relativistic ^{58}Ni beam, thus extending our previous work [17] which allowed us to observe ^{50}Ni.

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In an experiment preformed at the projectile-fragment separator FRS of GSI [18], we used a primary beam of ^{58}Ni at 600 MeV/nucleon impinging on a 4 g/cm^2 beryllium target. The projectile fragments of interest were separated from the bulk of less exotic fragments by means of the FRS with an intermediate degrader of aluminum (1.87 g/cm^2 for the ^{45}Fe setting and 4.00 g/cm^2 for the ^{38}Ti setting) and identified in flight using its standard detection setup. The latter consists of two plastic scintillators for position and time-of-flight (TOF) measurements, two multiwire proportional chambers (MWPC) for a position measurement, and a multisampling ionization chamber (MUSIC) for an energy-loss (ΔE) measurement (see [17] for a schematic representation of the detector setup). These detectors, together with a precise measurement of the magnetic fields in the dipoles of the FRS, allowed us to perform a TOF-ΔE-$B\rho$ analysis. All detectors were calibrated by means of the primary beam transmitted with a reduced counting rate at different energies to the exit focus of the FRS.

Two different settings were used to search for the proton-rich isotopes of interest. The first one (counting time about 72 h) was optimized for the transmission of ^{45}Fe ($B\rho_1 = 6.018$ T m, $B\rho_2 = 5.513$ T m) and aimed at the observation of ^{42}Cr, ^{45}Fe, ^{48}Ni, and ^{49}Ni. The second setting (counting time about 24 h) was chosen to identify ^{38}Ti ($B\rho_1 = 6.134$ T m, $B\rho_2 = 5.177$ T m).

Figure 1 shows the identification plot resulting from the setting for ^{45}Fe. Events present in this plot have to fulfill the following conditions: (i) The energy-loss signals from the four anodes of the MUSIC and the energy-loss signals from the two scintillators have to be consistent, (ii) the TOF values determined from the right-hand-side and left-hand-side photomultipliers of the scintillators have to agree within the limits of the respective time resolutions, and (iii) the position as determined with the MWPCs has to be consistent with the one determined by means of the scintillator at the exit focus of the FRS. In addition, the position, determined with the MWPCs at the final focal plane, of events fulfilling the above mentioned conditions was compared to model predictions. These model predictions have been checked and slightly corrected for a setting to transmit ^{48}Fe and neighboring nuclei with the same isospin projection T_z. The measurements yielded position distributions with a standard deviation of $\sigma = 11$ mm. In order to finally accept an event, its position had to be within two standard deviations from the expected average position. Under these conditions, the nuclear charge Z and the mass-to-charge ratio A/Z (at relativistic energies, isotopes in the nickel region are fully stripped) are determined by means of the MUSIC energy-loss signal, the TOF from the two scintillators, and the $B\rho$ as calculated from the positions in the intermediate and final focal planes as well as from the respective magnetic fields.

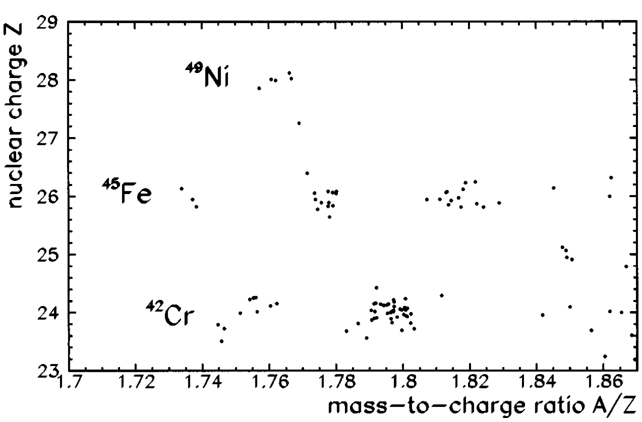

FIG. 1. Two-dimensional plot of the nuclear charge Z versus the mass-to-charge ratio A/Z for the setting optimized for ^{45}Fe. Ten counts of ^{42}Cr, three counts of ^{45}Fe, and five counts of ^{49}Ni are observed.

We observed ten events of ^{42}Cr, three events of ^{45}Fe, and five events of ^{49}Ni. These three isotopes have been identified for the first time in the present experiment. As the production cross sections decrease by about a factor of 20 per mass unit in the neutron-deficient tail of the isotopic yield distribution [17], we do not expect any count for the doubly magic nucleus ^{48}Ni. Less exotic isotopes of nickel and cobalt are absent in the spectrum, because their expected positions are beyond the FRS focal plane detectors.

The conditions used to accept an event, as discussed above, reduce the background from secondary reactions or from any other contamination to a very low level. This is demonstrated by the odd-Z isotopes which are known to be unbound (the most proton-rich isotopes known for manganese and cobalt are ^{46}Mn [19] and ^{50}Co [17], respectively). In the entire Z versus A/Z plot shown in Fig. 1, only one background event can be identified close to the position of ^{48}Co ($Z = 27$, $A/Z = 1.778$). This high background suppression enables us to conclude even with only three and five events on the first observation of ^{45}Fe and ^{49}Ni, respectively.

In a similar measurement, we searched for ^{38}Ti. For this purpose, the FRS was tuned in its first half on an intermediate value between the optimum settings for masses 38 and 39 of titanium isotopes, and in its second half on ^{38}Ti. Such a setting yields a comparable and close-to-maximum transmission for both ^{38}Ti and ^{39}Ti. In the analysis, the data were treated in the same way as for the setting on ^{45}Fe.

The resulting spectrum is shown in Fig. 2. We clearly observe ^{39}Ti with 166 events, whereas we cannot attribute a single count to ^{38}Ti. As already discussed in the previous paragraph, the position at the final focus of the FRS of chromium isotopes for this tuning is beyond the acceptance of the detectors. Again, the quality of the background rejection can be judged by means of isotopes known to be unbound (e.g., the most proton-rich bound scandium isotope is ^{40}Sc with $Z = 21$ and $A/Z = 1.905$).

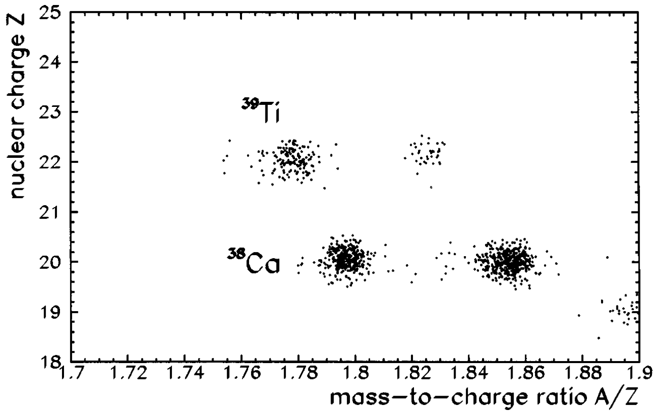

FIG. 2. Nuclear charge Z versus the mass-to-charge ratio A/Z from the setting for ^{38}Ti. In the spectrum, we observe 166 counts for ^{39}Ti, however, no count for ^{38}Ti.

In Table I, we list the candidates for the $2p$ radioactivity together with their half-lives predicted according to different models. These model predictions will be used as a basis for the discussion with follows.

^{45}Fe and ^{49}Ni are the first $T_z = -7/2$ nuclei experimentally identified. It is very likely that they are the only nuclei of the $T_z = -7/2$ series which are experimentally accessible. The lighter members (^{41}Cr, etc.) as well as the heavier ones (^{53}Zn, etc.) are expected to be unbound with half-lives shorter than 10^{-13} s.

The isotope ^{45}Fe was not observed in an experiment performed some years ago at GANIL [19]. However, the counting rate expected in this experiment was only 1–2 counts. The observation of ^{45}Fe in the present work is of prime interest for the search for $2p$ radioactivity. According to recent mass predictions [11,12], it is the best candidate for the $2p$ radioactivity because it is within experimental reach, and its $T_{1/2}^{2p}$ value is predicted to be short as compared to its β-decay half-life, but long with respect to its flight time through a spectrometer (see Table I). The mass values from the 1986–1987 atomic mass predictions [21] vary widely from one prediction to the next, but show that this nucleus, on average, is less bound than ^{42}Cr and ^{49}Ni (see below). The two-proton decay energies range from 1.08 to 2.12 MeV, yielding barrier-penetration half-lives between 0.1 ms and 2 ps. According to the mass prediction of Audi and Wapstra [20], the half-life should be in the interval of 400 ns and 10^6 ms.

The identification of ^{45}Fe in the present work allows us to only give a lower limit for its half-life. Compared to the number of counts observed for ^{46}Fe, we expect 3–4 counts for ^{45}Fe, if we take into account a drop of the cross section by a factor of 20 and a transmission of ^{46}Fe which is a factor of 5 lower than that of ^{45}Fe. This is in perfect agreement with the experimental observation and lets us conclude that the half-life of ^{45}Fe is comparable to, or longer than, the flight time through the FRS of about 350 ns.

Similarly to ^{45}Fe, ^{49}Ni is predicted to be $2p$ unbound by all commonly used mass models, however, the latest mass predictions [21] give it unbound only by a few hundred keV, so that its decay should be dominated by β decay. In the case of ^{49}Ni, the mass models predict decay energies in the range from 0.19 to 2.09 MeV, which results in tunneling half-lives between 10^{39} s and 100 ps (see also Table I). In spite of this large half-life range, an experimental observation of its decay properties or a measurement of its mass excess is highly desirable. The presence of ^{49}Ni in the experimental spectrum with a counting rate well within the limits of expectation allows us to exclude mass models which predict half-lives much smaller than the flight time through the FRS.

With the identification of ^{42}Cr in the present work, a fourth member of the $T_z = -3$ series (in addition to ^{22}Si [16], ^{46}Fe [19], and ^{50}Ni [17]) has been observed. This series probably ends with ^{50}Ni. As mentioned earlier in this Letter, ^{42}Cr is predicted to be $2p$ unbound by all commonly used mass predictions [21]. However, the energy available for the emission of two protons varies between 0.18 MeV and 1.34 MeV. From barrier-penetration calculations assuming spectroscopic factors of unity, this energy range yields $T_{1/2}^{2p}$ values ranging from 5 ns to 5×10^{30} s. The latest mass evaluation [20] predicts a two-proton decay energy of $E_{2p} = 0.26 \pm 0.34$ MeV which results in a half-life of $T_{1/2}^{2p} > 10^7$ s (see also Table I). This long half-life is in agreement with the conclusion drawn by Brown [11] that ^{42}Cr has only a very small and probably unmeasurable $2p$ branch.

The experimental observation of ^{42}Cr with a number of counts which compares well with systematics [17] indicates that its half-life is at least as long as the flight time through the FRS which is of the order of 350 ns. This allows us to reject models predicting a half-life shorter than this value if one assumes that the spectroscopic

TABLE I. Predicted $2p$-decay half-lives $T_{1/2}^{2p}$ (in ms) from different calculations. The mass evaluation from Audi and Wapstra [20] has been used in barrier-penetration calculations to determine the $T_{1/2}^{2p}$ values given in the third line.

	^{38}Ti	^{39}Ti	^{42}Cr	^{45}Fe	^{48}Ni	^{49}Ni
Brown [11]	⋯	2–140	10^7–10^9	0.002–0.3	0.001–0.2	$>10^{20}$
Ormand [12]	$(0.4–2.3) \times 10^{-12}$	0.4–2000	10^5–10^{19}	10^{-5}–10^{-1}	0.01–3660	⋯
Audi *et al.* [20]	2×10^{-6}–6	∞	10^7–∞	4×10^{-4}–10^6	⋯	⋯

factors are in the order of unity. However, in order to exclude ^{42}Cr from the list of possible $2p$ candidates, a direct mass measurement or the observation of its β decay is needed.

The absence of ^{38}Ti in the spectrum shown in Fig. 2 allows one to obtain a half-life limit for this isotope: From the counting rate observed for ^{39}Ti, we can calculate an expected counting rate for ^{38}Ti. As mentioned above, the proton-rich tail of the production cross-section distribution decreases by about a factor of 20 per mass unit on average [17]. However, an odd-even effect occurs in this distribution corresponding to a "slope factor" of about 40–60 between an odd-mass isotope and its neighbor and about 7–10 between an even-mass nucleus and its more neutron-deficient neighbor. From the 166 events observed for ^{39}Ti, and taking into account the slightly different transmissions of ^{38}Ti and ^{39}Ti (31% and 23%, respectively), we would expect about 4–6 counts for ^{38}Ti.

From the nonobservation of ^{38}Ti in the present work, we cannot definitively conclude that this isotope is unbound and unobservable in this kind of experiment. Although, even at the proton drip line, large fluctuations in the fragment production cross sections for ^{58}Ni fragmentation have not been observed [17], a cross section for ^{38}Ti lower by a factor of 5 as compared to systematics cannot be excluded. However, such a behavior is unlikely. The present work thus favors the hypothesis that ^{38}Ti is unbound and that its half-life is short compared to the flight time of 350 ns. Assuming that the production cross section of ^{38}Ti follows the systematic trend observed for other ^{58}Ni fragments, we can give an upper limit for the half-life of 120 ns. Barrier-penetration calculations then yield a two-proton decay energy of $E_{2p} > 1$ MeV. Using the ground-state mass of ^{36}Ca from Audi and Wapstra [20], a lower limit for the mass excess of 9.14 MeV for ^{38}Ti can be deduced.

To summarize, the fragmentation of a relativistic ^{58}Ni beam has allowed for the first observation of the two $T_z = -7/2$ nuclei ^{45}Fe and ^{49}Ni, the most proton-rich nuclei ever identified with an excess of seven protons. These nuclei, together with the new $T_z = -3$ nucleus ^{42}Cr, are all predicted to be two-proton unbound, ^{45}Fe being probably the best candidate for $2p$ radioactivity. Decay studies of these isotopes which are possible even with low counting rates should give valuable spectroscopic information, especially concerning the question of whether their decay is dominated by β decay or by $2p$ radioactivity. A $2p$ decay could be identified by a short half-life ($<$3 ms) and a decay energy of about 1.1 MeV. In addition, an observation of the decay of the $2p$ daughter nuclei—both are most likely β-delayed proton emitters—may greatly ease the identification of a $2p$ decay.

Even if $2p$ decay could not be observed for the isotopes under discussion, the study of β-delayed decay modes should provide valuable spectroscopic information. The isobaric analog states of ^{45}Fe and ^{49}Ni fed by superallowed Fermi transitions, e.g., can decay by a large variety of different decay modes, including the up-to-now unobserved $\beta 4p$, $\beta 5p$, $\beta p\alpha$, and $\beta 2p\alpha$ decay modes. Another important motivation for pursuing these studies is the conclusion from this work that the doubly magic nucleus ^{48}Ni is reachable in fragmentation experiments. This nucleus would be the only doubly magic isotope whose mirror nucleus (^{48}Ca) is bound, a fact which would allow for an interesting mirror-symmetry investigation.

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