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OBSERVATION OF THE NEW NEUTRON-RICH NUCLEI ^{29}F, ^{35,36}Mg, ^{38,39}Al, ^{40,41}Si, ^{43,44}P, ^{45,46,47}S, ^{46,47,48,49}Cl, AND ^{49,50,51}Ar BY MEANS OF A 55 MeV/u ^{48}Ca BEAM

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1. INTRODUCTION

It has been shown /1/ that the isotopic distributions of the production cross-sections of projectile-like fragments at an intermediate energy is strongly dependent on the N/Z ratio of the projectile. Experiments aiming at the production and identification of new nuclei have been performed at GANIL, so far with ^{40}Ar and ^{86}Kr beams.

The production of new neutron-rich isotopes from the argon beam /2,3/ went up to ^{30}Ne corresponding to the maximum neutron number available in the projectile. On the other hand, the fragments from the krypton beam at GANIL energies, albeit allowing the identification of numerous new isotopes /4,5/ in the range $18 \leq Z \leq 28$ are characterized by a fairly high excitation energy /6/ increasing with their mass difference from the projectile. The most recent information on the neutron-rich isotopes of the third period of the Mendeleev system, however, comes from the pioneering experiment which was performed at the Bevalac nine years ago /7/ using the fragmentation of ^{48}Ca at a relativistic energy.

Since the beam intensity at GANIL is several orders of magnitude higher compared to the Bevalac, one may expect an overall gain of about a factor of 100 accounting for the thinner targets which have to be used at lower energies. This gain factor should correspond to an extension of, say, two more isotopes per element. Also much progress has been made recently /8/ in the production of metallic beams from ECR ion sources. Therefore, it was most tempting to investigate the fragments from a ^{48}Ca beam at GANIL.

2. EXPERIMENTAL PROCEDURE

The ^{48}Ca beam has been produced using the ECR Minimafios source of GANIL. The ^{48}Ca oxide from the Laboratory of Nuclear Reactions, Dubna was mixed with aluminium powder. This mixture compressed in a cylindrical shape, was loaded into a tantalum crucible fixed at the end of a tantalum rod. The rod was approached from outside to the hot plasma of He support gas burning in the core of the ECR source. This procedure allows to optimize the production of the high-intensity beams of $^{48}Ca^{+18}$. The rod position with respect to the plasma and thus the reduction rate was monitored by the intensity signal of ^{48}Ca at the site of the injector cyclotron.

With this method a rather stable $^{48}Ca^{18+}$ beam current of some 250 nA was obtained at the exit of the experimental station at an energy of 55 MeV/u. One filling of the crucible lasted two days at an hourly consumption of 1.8 mg of pure calcium.

Tantalum (^{181}Ta) targets were used with thicknesses of 166 mg/cm^2 and 250 mg/cm^2 for producing isotopes in the regions of $12 \leq Z \leq 18$ and $8 \leq Z \leq 10$, respectively. The choice of a neutron-rich tantalum target rather than a light target, which in principle is more advantageous in terms of the number of interactions and the kinematic properties of the isotopes, was motivated by a strong enhancement for the production of the most neutron-rich fragments, which had been observed earlier /9/.

The projectile-like fragments were collected at 0° by the triple-focussing magnetic analyser LISE /10/. The LISE facility is a double achromatic spectrometer consisting of two dipole magnets D and the associated quadrupole Q focussing elements, as shown in fig. 1. It has two focal planes, the first F_1 being the momentum-dispersive one on which particles with different $B\rho$-values focus at different positions, and the second F_2 the achromatic one where all the particles are collected into the same position. It is possible to collect all the fragments in a rather small spot and to install 4π-detectors of a reasonable size for the decay studies.

For the detection of fragments a four-stage semiconductor telescope consisting of two 300 μ ΔE_1, ΔE_2, one 1000 μ surface barrier detectors ΔE_3 and a 5.5 mm Si(Li) residual energy detector E_R were mounted inside a small vacuum chamber connected to the exit of LISE.

The flight time of the collected fragments is measured between the initial (at the target) and final foci of LISE (telescope position). The time of flight is determined from the time signal of the E_R detector and the radio-frequency (R.F.) signal of the last cyclotron. The detectors are connected to charge and voltage sensitive preamplifiers in order to derive the ΔE,E and timing signals. Using the timing signal as "START" and a signal derived from the R.F. as "STOP" of a time-to-amplitude converter, the time of flight through the spectrometer is acquired. This R.F. being typically 10 MHz, the start and stop signals are reversed in order to prevent unnecessary triggering. Thus, the isotopes with a higher value of A/Z are found to be on the lower end of the time-of-flight scale in fig. 2. The constancy of the correlation between the R.F. and the time of impact

on the target is monitored by a neutron detector mounted close to the primary beam catcher at the exit of the first dipole magnet. The time resolution obtained for the beam used in this experiment is 1% of the

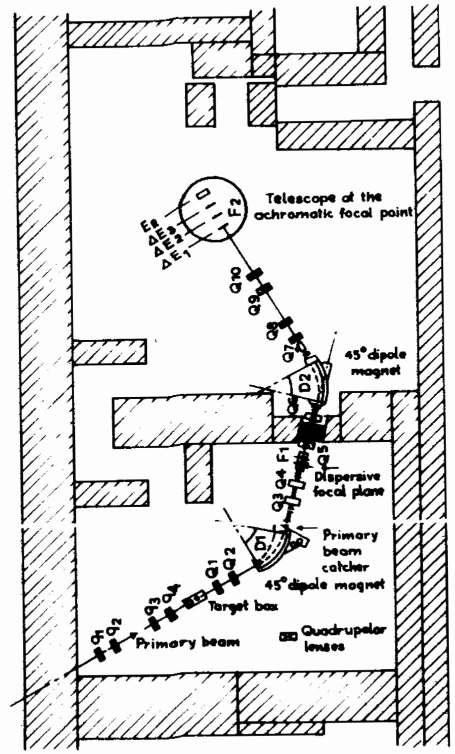

Fig. 1. Configuration of the analysing magnetic line QDQDQ (spectrometer LISE). q_1-q_4 are quadrupole lenses of the transportation channel for the ^{48}Ca projectiles. Q_1-Q_{10} are quadrupole lenses of the spectrometer LISE. D_1 and D_2 are the LISE magnetic dipoles. F_1 and F_2 are dispersive and achromatic planes. ΔE_i, E_R are a semiconductor detector telescope

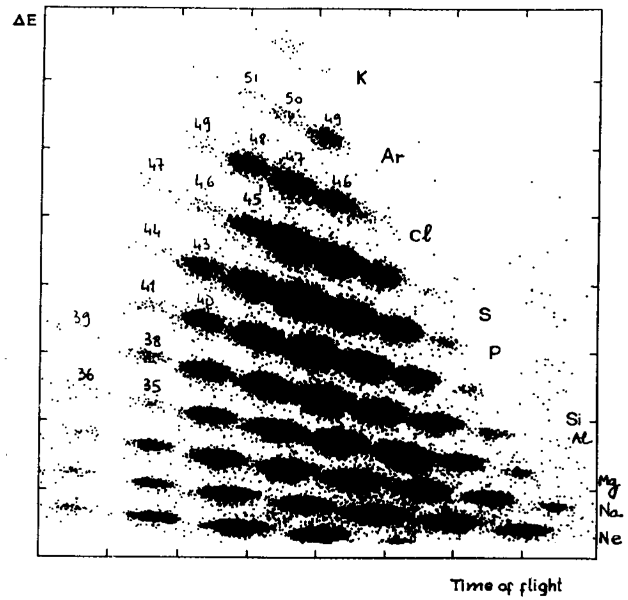

Fig. 2. Bidimensional representation of the particle identification in the mass A and atomic number Z, obtained by means of the surface barrier detector ΔE and by TOF measurements at the magnetic rigidity $B\rho$ = 2.768 T.M of the spectrometer LISE. The numbers indicate the mass numbers A of the new neutron-rich isotopes synthesized. The exposure time is 40 hours

typical flight time of 170 ns through LISE. To avoid pile-up effects for ensuring a good energy and time resolution the counting rate on the detectors was limited to some 10^3 events per second. This was done by restricting the momentum acceptance of the LISE spectrometer by means of movable slits in the intermediate focal plane. A thin Al foil of 5.3 mg/cm^2 was installed at this place in order to suppress the low-intensity components of incimpletely stripped fragments.

The fragments were identified in a redundant way: the two first detectors independently allowed double Z determinations, the mass was

derived from the total energy and the time of flight as well as from magnetic rigidity and the time of flight. This method delivered clean spectra of high signal-to-noise ratios.

3. RESULTS AND DISCUSSION

Two different settings of the magnetic rigidity of the spectrometer were used in order to study the stability of nuclei in two regions. The first aim of the experiment was to explore the stability of new isotopes in the region $12 \leq Z \leq 18$ which had been studied at the Bevalac /7/. For this purpose, a 166 mg/cm^2 Ta target corresponding to an energy loss of about ten per cent had been chosen. The spectrometer was set to magnetic rigidity $B\rho$ = 2.768 T.m. optimized for nuclei around ^{44}S. This was also motivated by the astrophysical interest of this isotope /11/. Figure 2 represents the two-dimensional plot (energy loss versus time of flight) obtained under these conditions after 40 hours integration with an average current of 150 nA. The new species ^{35,36}Mg, ^{38,39}Al, ^{40,41}Si, ^{43,44}P, ^{45,46,47}S, ^{46,47,48,49}Cl, ^{49,50,51}Ar are clearly visible. Figure 3 shows, as an example, the projection for the series of silicon isotopes. Comparison of these results with the ones obtained at relativistic energies at Berkeley /7/ shows the progress of typically two isotopes. This corresponds to the expected gain and is essentially due to the intensity at GANIL. Nevertheless one should note that we are still away from the neutron drip-line by about four masses (see figure 4). Furthermore, in terms of the reaction mechanism, it is interesting to note the presence of strong transfer reaction channels at an intermediate energy. Indeed, a part of the new "fragments" are more neutron-rich than the projectile. This feature was already observed in a production experiment of new proton-rich nuclei /12/ as well as in reaction mechanism studies /13/. This indicates that transfer reactions also provide a very efficient tool for the production of nuclei far from stability, complementary to projectile fragmentation at intermediate energies.

In the second case, the spectrometer was set at its maximum rigidity of 3.23 T.m. Still, due to the given energy of 55 MeV/u from the GANIL accelerator, the use of a rather thick target (250 mg/cm^2 of tantalum) was required to transmit such exotic nuclei as ^{29}F, ^{26}O, ^{32}Ne. The thick target, however, creates very large velocity

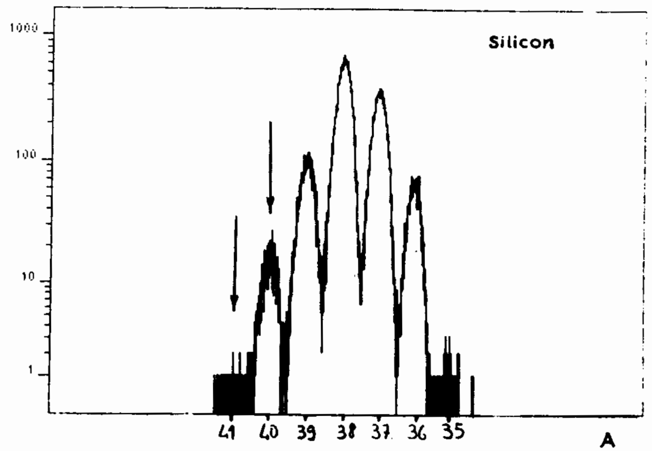

Fig. 3. The intensity distribution of the events due to the Si isotopes, which have been detected during 40 hours at the magnetic rigidity $B\rho = 2.768$ T.m. Arrows indicate the mass numbers A for the new neutron-rich Si isotopes

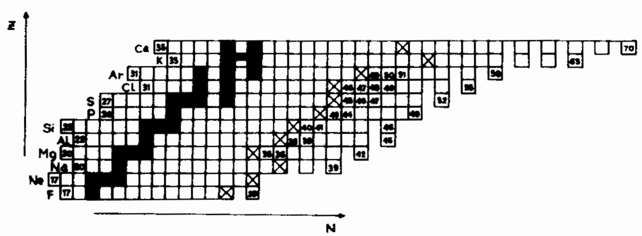

Fig. 4. Part of the isotope chart for the light elements with $9 \leqslant Z \leqslant 20$. Crosses show the last known neutron-rich isotopes. The numbers (near crosses) show the new neutron-rich isotopes produced in the present experiment. The numbers along the boarders (left-hand and right-hand) indicate the isotopes which are predicted by Garvey-Kelson /15/ to be the last nuclear stability nuclides

distributions. They are very inconvenient because the transmission of the spectrometer for the wanted isotopes is reduced and, furthermore, the velocity tails of very light isotopes are transmitted. This, in turn, requires the momentum acceptance slits of the spectrometer to be set at $\Delta\rho/\rho = 1\%$ which further reduces the counting rate of the wanted isotopes. Thus, due to the fact that the momentum acceptance of the spectrometer becomes mismatched to the velocity distributions of the fragments, the gain in production proportional to the target thickness and the loss in transmission, are balanced.

Figure 5 shows a part of a two-dimensional ΔE versus time-of-flight plot (i.e. A/Z) after 15 hours of integration with an average beam current of 200 nA. The known nitrogen isotopes ^{20}N, ^{21}N, ^{22}N, ^{23}N as well as ^{23}O, ^{24}O and the new isotope ^{29}F (4 counts) are clearly observed. The unstable isotope ^{25}O is obviously absent but no counts of ^{26}O are seen. Nevertheless, taking into account the observed counting rate of the above-mentioned isotopes and using the fit of Sümmerer et al. /14/ for cross-section estimation we should have observed only 2 or 3 counts. Therefore, it is impossible to conclude on the particle stability or non-stability of ^{26}O at the level of

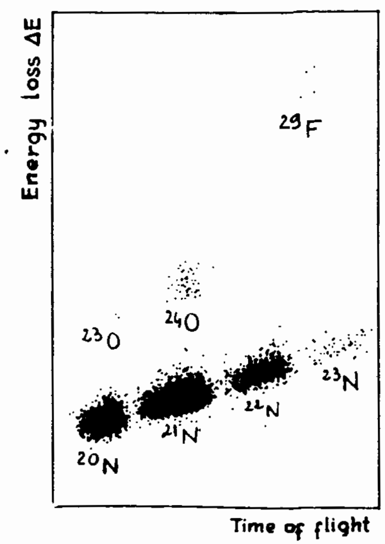

Fig. 5. Bidimensional distribution of the events (ΔE res. TOF) due to the N,O and F isotopes which were accumulated for 15 hours of exposure at the magnetic rigidity $B\rho = 3.23$ T.m. of the spectrometer LISE. Four counts due to the new isotope ^{29}F are observed for the first time. The corresponding counting rates for the other nuclei are ^{20}N (1897), ^{21}N (4907), ^{22}N (829), ^{23}N (53), ^{23}O (2), ^{24}O (54)

statistics. In the table are given the one- and two-neutron separation energies for the four isotopes of fluorine, namely ^{28}F, ^{29}F, ^{30}F and ^{31}F calculated with the four different Garvey-Kelson /15/, Moeller and Nix /16/ and the Uno-Yamada /17/ mass-formulae. In agreement with the result of the experiment, ^{29}F is predicted to be bound with the four formulae. The odd-even effect on the stability of nuclei is clearly seen for ^{28}F which is particle unstable and for ^{30}F also predicted to be particle unstable. Except for the constant-shell mass formula of Uno-Yamada, it seems that ^{29}F is the last stable isotope of fluorine and, therefore, that the predicted neutron drip-line has been reached in this experiment for Z=9.

4. CONCLUSION

The present experiment using a high intensity ^{48}Ca beam, has allowed one to map the neutron drip-line for Z=9 with the discovery of ^{29}F and to approach it for larger atomic numbers with the observation of eighteen new nuclei in the range $12 \leq Z \leq 18$. The high counting rates observed for exotic nuclei in this region certainly will permit the study of their β-delayed neutron emission in a similar way, as described in a previous paper /18/.

Table

Prediction for one-neutron and two-neutron separation energies for ^{28}F, ^{28}F, ^{29}F, ^{30}F, ^{31}F, using four different mass-formulae: Garvey-Kelson /15/, Moeller-Nix /16/, Uno-Yamada /17/ (constant shell CS and linear shell LS mass formulae)

Nuclide	J.G.K		Möller-Nix		Uno-Yamada C.S.		L.S.	
	S(1n)	S(2n)	S(1n)	S(2n)	S(1n)	S(2n)	S(1n)	S(2n)
^{28}F	-0.7	2.03	0.45	2.75	0.28	3.42	-0.78	+3.42
^{29}F	1.33	0.63	2.25	2.7	2.79	2.97	3.13	2.34
^{30}F	-2.81	-1.48	-0.79	1.45	-1.53	1.16	-2.85	0.28
^{31}F	-0.24	-3.05	-0.65	-1.44	1.59	0.057	-0.63	-3.48

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Гильмо-Мюллер Д. и др. E7-88-650
Наблюдение новых нейтроноизбыточных ядер ^{29}F, $^{35,36}Mg$, $^{38,39}Al$, $^{40,41}Si$, $^{43,44}P$, $^{45,46,47}S$, $^{46,47,48,49}Cl$ и $^{49,50}Ar$ в реакции с ионами 55 МэВ/А ^{48}Ca

В реакции Ta + ^{48}Ca (55 МэВ/А) впервые синтезированы новые ядра ^{29}F, $^{35,36}Mg$, $^{38,39}Al$, $^{40,41}Si$, $^{43,44}P$, $^{45,46,47}S$, $^{46,47,48,49}Cl$ и $^{49,50,51}Ar$. Для идентификации изотопов использовались магнитный спектрометр, измерение времени пролета и $\Delta E,E$-техника. Эксперимент выполнен в Французском национальном центре ГАНИЛ.

Сообщение Объединенного института ядерных исследований. Дубна 1988

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Observation of the New Neutron-Rich Nuclei ^{29}F, $^{35,36}Mg$, $^{38,39}Al$, $^{40,41}Si$, $^{43,44}P$, $^{45,46,47}S$, $^{46,47,48,49}Cl$, and $^{49,50,51}Ar$ by Means of a 55 MeV/u ^{48}Ca Beam

Using magnetic separation and identification through time of flight and $\Delta E,E$ measurements, the new nuclei, ^{29}F, $^{35,36}Mg$, $^{38,39}Al$, $^{40,41}Si$, $^{43,44}P$, $^{45,46,47}S$, $^{46,47,48,49}Cl$, $^{49,50,51}Ar$ have been observed from interactions of a ^{48}Ca beam of 55 MeV/u with tantalum targets. This experiment was performed at the French National Facility GANIL.

Communication of the Joint Institute for Nuclear Research. Dubna 1988