The ALTO facility at IPN Orsay and study of neutron rich nuclei in the vicinity of $^{78}$Ni

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The ALTO facility at IPN Orsay is based on a linear electron accelerator (50 MeV, $10\mu$A) dedicated to the production of neutron rich radiactive beams by photofission of a thick uranium carbide target paced on an ISOL line. The construction of the facility has ended in december 2005 and the first on-line tests have been carried out in mid-2006. The production of fission fragments after separation have been measured and are similar to the calculated predictions. Previously, using the same ISOL line, neutron rich nuclei in the vicinity of $^{78}$Ni have been produced and studied using the deuteron beam available at the Tandem accelerator in Orsay. First results on excited states in $^{83}_{32}$Ge$_{51}$ and $^{81}_{31}$Ga$_{50}$ have been obtained and discussed in the frame of the shell model.

1. The ALTO facility for the production of radioactive beams

The availability of intense neutron rich ion beams will open new perspectives in the study of nuclei very far away from the valley of stability. It would allow to apprehend the behaviour of the nuclear matter under extreme conditions. Several laboratories are focussing on studies aimed at producing high enough intensities to warrant a new generation of experiments. Facilities are planned to provide these radioactive beams, e.g., the SPIRAL2 project at GANIL or the EURISOL project in Europe. Fission is a very powerful mechanism to produce a number of such beams. A large effort is done to investigate the production of neutron rich isotopes in fission reaction or photofission. We have developped at IPN Orsay a program to optimize the production of radioactive beams from $^{238}$U fission using in a first time the deuteron beam of the Tandem and finally the electron beam of the new facility : ALTO.

1.1. The ALTO facility

Taking into account the studies performed at the Tandem using the deuteron beam and the succes of an experiment at CERN using photofission [1] it has been decided to start a conceptual project for the installation at IPN-Orsay of 50 MeV electron accelerator : The ALTO project (Accélérateur Linéaire auprès du Tandem d’ Orsay). The accelerator has been installed in the experimental area of the Tandem (see figure 2), to deliver beams mainly to the PARRNe ISOL device. After the photo-fission experiment success [1], the
CERN scientists authorities interested in the ALTO project have decided to offer the LIL (injector of the LEP) front end to the IPN Orsay. The linac is composed of thermionic gun, a bunching system and a matching section to the linac. The gun is a thermionic source held to 90 kV, it is designed to provide beam pulses up to 2 sec in length and peak current of 50 mA. The operating frequency is 100 Hz. The pre-buncher is a RF cavity 15 mm long working in standing waves mode at 3 GHz. It is mounted at 100 mm from the buncher. For the transverse focusing of the beam, three solenoids are installed downstream the gun. The buncher is a tri-periodical RF structure cavity working in standing waves mode at 3 GHz. The cavity structure is surrounded by a solenoid producing a 0.2 T magnetic field. The buncher provides an output energy of about 4 MeV. The accelerating section is a 4.5 m long RF cavity operating in travelling waves mode at 3 GHz. The section output energy is of 46 MeV. In order to match the beam from the buncher exit to the accelerating section entrance we use one solenoid and one quadrupole triplet. The whole RF structure (pre-buncher, buncher and accelerating section) is powered by only one 35 MW klystron TH 2100. The operating of the accelerator at 50 MeV needs a HF power less than 20 MW. The transport beam line consists of two 65 dipole magnets (R=0.4 m) and seven magnetic quadrupoles. The first Q-triplet placed behind the accelerating section allows the control

Figure 1. Schematic view of the implantation of ALTO in the experimental area of the Tandem
of the beam envelop at the entrance of the first magnet. To make the achromatism in the deviation, a quadrupole will be placed between the two magnets. The spot beam dimension is adjusted on the PARRNe target by using the last Q-triplet. The expected energy resolution is less than $5 \times 10^{-3}$. The beam line is equipped by instruments for the beam diagnostic: measurement of current, beam position, energy and energy dispersion. With this new accelerator operating at 50 MeV and 10 $\mu$A the production inside the target will be $10^{11}$ fissions per second i.e. an increase by a factor 100 in comparison with the use of the deuteron beam of the Tandem (26 MeV 1 $\mu$A).

1.2. Production yields measurements at ALTO

In june 2006, first tests have been allowed by the safety authorities. The electron beam limited to an intensity of 100 nA and an energy of 50MeV hits the target containing 60g of $^{238}$U. We first have confirmed that the radioprotection measurements fits with our calculation performed. The calculated predictions were done by extrapolating the gain in the yields of all the fission fragments to the yields for the nobles gases obtained during our photofission experiment [1]. Measurements of fission fragments production have then be performed during the first ALTO experiment after separation from the mass 78 to the mass 145. Figure 3 represent the production measured during this experiment and extrapolated to 10$\mu$A beam current. The productions of the refractory elements could not be measured. These measurements are in total agreement with the calculated prediction, and $2 \times 10^5$ $^{132}$Sn and $1.4 \times 10^3$ $^{78}$Zn per second have been obtained with a 100 nA electron beam current.

![Figure 2. Production of fission fragments obtained at ALTO using a 100 nA electron beam and extrapolated to 10 $\mu$A.](image-url)
2. Study of the N=50 major shell effect at PARRNe

Recently considerable evidence has been pointed out for the existence of shell gap reinforcements and disappearances far off stability, leading in certain cases to the statement that some well known magic numbers would vanish while new ones would raise. Among the Mayer and Jensen "historical" magic numbers, 50 is known to retain its magic character for protons (Sn isotopes) from \( N = 50 \) to \( N = 82 \). On the other hand, probing the stiffness of the 50 neutron shell gap from \( Z = 50 \) down to \( Z = 28 \) still represents a vivid and extremely active field of investigation in present nuclear structure research (see [2–4] and references therein). The conclusions of Refs [2] and [3] on a possible \( N = 50 \) shell-effect weakening are contradictory. if we consider for instance one of the most direct (but certainly not unique) pieces of evidence that a shell closure dominates the nuclear structure: the evolution in energy of the first \( 2^+ \) excited state of the even-even nuclei at the crossing of the corresponding magic number of nucleons. we can see that the \( N = 50 \) shell closure has definitely a strong influence, but the constant decrease of the \( 2^+ \) energy for the \( N = 50 \) isotones from \( Z = 40 \) to \( Z = 32 \) i.e. as they become more and more proton deficient, is somewhat surprising. The question of knowing what it remains from this influence in the vicinity of the expected double shell closure \( Z = 28 \ N = 50 \) is still open and obtaining more data on the structure of these hard-to-reach nuclei is certainly mandatory.

2.1. Low energy states of \( ^{83}_{32}\text{Ge}_{51} \)

The Ga isotopes were obtained from the fission of \( ^{238}\text{U} \) nuclei at the PARRNe mass separator, installed at the Orsay Tandem accelerator. The 26 MeV deuteron beam delivered by the MP-Tandem hit a 5 mm thick graphite converter placed 110 mm upstream from the centre of the target. The fast incident neutrons produced in the break up of the deuterons irradiated an UC\(_x\) target heated up to 2200°C [5,6]. The fission fragments released from the target were ionized with a MK5 ISOLDE-type ion source [7]. The ions were extracted at 30 kV, then magnetically mass separated and finally collected on a movable aluminized Mylar tape (see Figure 3). The \( \beta \)-detection system consisted of a 4\( \pi \) plastic scintillator surrounding the tape, providing an angular acceptance of \( \approx 4\pi \) sr, and 2 large volume Ge detectors placed in a compact geometry. With this set-up both \( \beta-\gamma \) and \( \gamma-\gamma \) coincidence events could be detected. The longer-lived isobar activities were cyclically evacuated by moving the tape every 2 seconds (1 second of build-up plus 1 second of decay). An absolute time-stamping of every \( \beta \) or \( \gamma \) event was performed on an absolute time scale by use of a six fold peak sensing ADC COMET-6X associated with the OASIS data acquisition system. This allowed to choose any time window from 400 ps up to the whole 2 s-duration of the build-up/decay time or any time binning in the off-line analysis. In our analysis, this window was set to 70 ns for prompt \( \beta-\gamma \) coincidences. The \( Z \) identification was provided by the analysis of the evolution in time of the \( \gamma \)-lines during the decay period. Most of the peaks present in the \( A = 83 \) \( \gamma \)-spectra have been attributed to the activities of \( ^{83}\text{Br} \ (T_{1/2} = 2h40) \), \( ^{83}\text{Se} \ (T_{1/2} = 22.3\ \text{min}) \), \( ^{83m}\text{Se} \ (T_{1/2} = 70.1\ \text{s}) \), \( ^{83}\text{As} \ (T_{1/2} = 13.4\ \text{s}) \), \( ^{83}\text{Ge} \ (T_{1/2} = 1.85\ \text{s}) \). Besides, in this mass region, \( \gamma \)-transitions belonging to the \( A-1 \) nuclei are likely to be present in the \( \gamma \)-spectra recorded for a given mass \( A \) due to \( \beta \)-n decay. Excited levels of \( ^{83}\text{Ge} \) are populated from \( \beta \)-decay and excited levels of \( ^{82}\text{Ge} \) from \( \beta \)-n decay. The \( \gamma \)-rays observed in this work and not reported prior
Figure 3. Experimental set up at the Tandem accelerator at Orsay. The two halls are separated with 1.5 m thick concrete wall to isolate the production place (with $^{238}$U target and ion source), from the separation and detection place and therefore reduce the background. A more detailed scheme of the counting point is shown in the insert.

to the present experiment, nor in the $A = 83$ activities nor in the $^{82}$Ga $\rightarrow$ $^{82}$Ge decay, are candidates to belong to the $^{83}$Ga $\rightarrow$ $^{83}$Ge decay. Two such $\gamma$-lines have been found: one at 867.4(8) keV and the other at 1238.2(5) keV. More detailed discussion for the attribution of these two lines to the decay of $^{83}$Ga can be found in reference [8]. The simplest hypothesis concerning the nature of the two states which were observed in this experiment can be made by comparison with the neighbour less exotic $N = 51$ odd-nuclei. Selected parts of their level schemes are shown in Figure 4 and compared to our proposed level scheme. The positive parity levels in $^{89}$Sr$_{51}$ were soon understood as originating from the positive-parity neutron single-particle orbitals $2d_{\frac{5}{2}}$, $3s_{\frac{1}{2}}$, $2d_{\frac{3}{2}}$ and $1g_{\frac{7}{2}}$ situated above the $N = 50$ closed shell and their coupling to the $2^+_1$ quadrupole first excited state of $^{88}$Sr$_{50}$. Such a structure is characteristic of the behaviour of a nucleus situated next to an effective strong shell closure. In particular the coupling of the 51$^{st}$ neutron placed in the lowest lying neutron orbital $2d_{\frac{5}{2}}$ to the $2^+_1$ of the $^{88}$Sr core gives rise to a multiplet of states $\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+$ and $\frac{9}{2}^+$. In a situation of weak coupling, the energy splitting of
the multiplet is governed by a simple $6 - j$ symbol \( \{ J_c, j, J_e, k \} \) where \( J_c \) stands for the core angular momentum, \( j \) that for the odd particle and \( J \) is the total angular momentum. Assuming a quadrupole residual interaction between the core and the particle then we take \( k = 2 \) leading to a relative order \( \begin{pmatrix} 7^+ \end{pmatrix}, \begin{pmatrix} 5^+ \end{pmatrix}, \begin{pmatrix} 3^+ \end{pmatrix}, \begin{pmatrix} 1^+ \end{pmatrix} \), a doublet \( \begin{pmatrix} 3^+ / 9^+ \end{pmatrix} \) and the \( \begin{pmatrix} 1^+ \end{pmatrix} \) pushed up. This is qualitatively what is observed in \(^{89}\)Sr where the members of the \( 2^+ \otimes \nu 2d_{5/2} \) multiplet were the most securely identified. The discrepancy observed for the \( \begin{pmatrix} 3^+ \end{pmatrix} \) state is well understood as due to an interaction with the neutron single particle state \( \nu 2d_{3/2} \) \([9]\). Should \( N = 50 \) retain its magic property then such a weak coupling structure should be found in the more exotic \( N = 51 \) odd-isotones towards \(^{78}\)Ni. An hypothetic assignment to the \( 2^+_1 \otimes \nu 2d_{5/2} \) multiplet can be inferred for states observed in \(^{87}\)Kl\(_{51}\) from radioactivity \([10]\), high-spin and (d,p) direct reaction \([11]\) experiments and in \(^{85}\)Se\(_{51}\) from radioactivity \([12]\) and high-spin experiments. These results are summarized in Figure 4 where one sees that the order of the levels is qualitatively good with respect to what is expected.

Figure 4. Evolution of the energy of the proposed members of the \( 2^+_1 \otimes \nu 2d_{5/2} \) multiplet and evolution of the \( \nu 3s_{1/2} \) quasi-particle state (connected with dashed lines) for the \( N = 51 \) isotonic chain. The state marked with a ‘•’-symbol is from \([4]\), those marked with ‘♦’-symbols are from this work.
in the framework of the weak coupling scheme. In particular, the $\frac{3}{2}^+$ member appears to be systematically lower in energy than the other members. The centres of gravity of those multiplets are situated at less than 100 keV from the observed $2^+_1$ energy of their respective semi-magic cores (see Figure 4). Then it is tempting to assign our two observed states of $^{83}$Ge to the $2^+ \otimes \nu 2d_{\frac{5}{2}}$ multiplet. Assuming that the ground state of the mother nucleus $^{83}$Ga has a $\pi 1f_{\frac{5}{2}}$ nature, then the lowest-lying states in $^{83}$Ge which have, for most of them, a positive parity, are fed mainly through first-forbidden non-unique transitions ($\Delta J = 0, 1; \Delta \pi = -$). This leaves the possibility for the states that we observed to be $\frac{3}{2}^+, \frac{5}{2}^+$ or $\frac{7}{2}^+$. Considering the systematics, the state at 867 keV could well be the $\frac{7}{2}^+$ lowest-energy member of this multiplet. We suggest then that the second one at 1238 keV could be the $\frac{3}{2}^+$ or the $\frac{5}{2}^+$ member of the multiplet since its energy is very close to the one of the $2^+_1$ state of $^{82}$Ge (1348 keV).

The main features in the structure of $^{83}$Ge are then (i) a decrease in energy of the members of the multiplet following naturally the decrease of the $2^+_1$ state of the associated even-even core and (ii) a decrease in energy of the first $\frac{1}{2}^+$ state which is not correlated to the previous one and should be understood as the fact that the two neutron orbitals $\nu 2d_{\frac{5}{2}}$ and $\nu 3s_{\frac{1}{2}}$ get closer for the $N = 51$ isotones as protons are removed. That last fact is of high interest and deserves a more detailed investigation in the future. This observation is most likely due to a possible monopole drift: the monopole part of the residual proton-neutron interaction is attractive between the $1f_{\frac{5}{2}}^1$ proton orbital and the $2d_{\frac{5}{2}}^1$ neutron orbital, a decrease of the number of the $1f_{\frac{5}{2}}^1$ protons would result in a release of the $2d_{\frac{5}{2}}^1$ ”upwards” leading to a closing relative to the $3s_{\frac{1}{2}}^1$ which is much less sensitive to such a residual interaction.

2.2. Low energy states of $^{81}_{31}$Ga$_{50}$

In our experiment, $\gamma$-rays de-exciting levels in $^{81}$Ga fed in the $\beta$-decay of $^{81}$Zn were observed. The sources of $^{81}$Zn ($T_{\frac{1}{2}} = 290 \pm 50$ ms) were obtained at the PARRNe mass-separator facility operating on-line with the same experimental set-up as the one previously described. The rate of implanted $^{81}$Zn was estimated to a few tens per second. Enhancement of the activity of interest as respect to the longer lived activities from the other collected isobars and the consequent Compton background was made by moving cyclically (every 2100 ms) the tape after a short build-up (900 ms) and decay time (1200 ms). The $Z$-identification of the $\gamma$-rays was provided by the analysis of the evolution of their activities during the decay part of the cycle. The activity of the line is assumed to be characterized by the same half-life as the mother nucleus. More details on the experimental set-up and procedure can be found in [8] and Refs. therein. Part of the $\gamma$-spectrum recorded at mass 81 is displayed in Fig. 6 along with the identification of the $\gamma$-lines. It is seen that the activity is dominated by that of $^{81}$Ga. In spite of this, a $\gamma$-line at 351.1 keV previously not reported at $A = 81$ is clearly visible. The fit of the decaying part of the associated activity (see the insert in Fig. 6) gives a half-life value of 391(65) ms which is consistent with the known value for $^{81}$Zn $T_{1/2} = 290(50)$ ms : it was then attributed to a transition in $^{81}$Ga. The statistics was sufficient to allow coincidence observation : a 451.7 keV $\gamma$-line was observed in coincidence with the 351.1 keV line which establishes the existence of a 802.8 keV level in the scheme of $^{81}$Zn (see Fig. 5) [13].
Figure 5. Tentative experimental level scheme for $^{81}$Zn decay

Figure 6. Part of the $\beta$-gated $\gamma$-spectrum recorded at mass 81. The observed $\gamma$-lines have been identified as transitions fed in the $\beta$-decays $^{81}$Ga $\bullet$, $^{81}$Ge $\ast$, $^{81}$As and the $\beta$-n decay of $^{81}$Ga ($P_n = 11.9\%$). The new line at $351.1$ keV $\Diamond$ is clearly visible and well isolated. The projection on the time scale of the background substracted events in this peak is shown in the insert.

REFERENCES

13. D. Verney et al., in preparation