Sub-shell closures in neutron-rich Vanadium isotopes

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Abstract. Excited states in the neutron-rich $^{55,57}$V nuclei have been populated in multi nucleon transfer reactions and observed by using the large acceptance magnetic spectrometer PRISMA and the highly efficient $\gamma$-detector array CLARA. These results confirm the sub-shell closure for $N=32$ but there is not clear evidence of the existence of the $N=34$ sub-shell closure.

1. Introduction
Continuous developments in nuclear spectroscopy instrumentation are followed by improvements of nuclear structure models, severely tested with new experimental data.

Neutron-rich nuclei are now subject of substantial interest because of clear experimental indications that the extrapolation of the traditional shell model to this region of the isotope table is not straightforward. Unexpected modifications to the shell structure have been already encountered and there is evidence that the usual magic numbers change when increasing the neutron number. Responsible for these changes could be both the developments of a diffuse neutron surface that could fade the spin-orbit interaction and the proton-neutron monopole interaction that could reorder the single-particle orbits. This last effect has already been observed close to stability, in the $N=50-82$ shell but there are evidences of this effect for lighter nuclei, especially in the $sd$ and $pf$ shells. This changes of the nuclear magic numbers when going far from stability is one of the points of current interest in nuclear structure with important consequences in both nuclear dynamics and astrophysics. A recent example could be the experimental studies in the Ti isotopes [1] that would indicate an $N=32$ shell closure that have been theoretically predicted by the shell-model GXPF1 interaction [2].

There is not combination of stable beams and targets to produce neutron-rich nuclei in fusion reactions and a new generation of radioactive beam accelerators is necessary to go up in spin. Most of the available information on the nuclear structure of neutron-rich nuclei has been obtained in $\beta$-decay studies or in multi-nucleon transfer and deep-inelastic reactions with thick targets and the cross coincidence method, but gamma identification is possible only when some previous information in the nuclear structure of the nucleus under study or its binary reaction partner is known.

2. The experiment
To identify online the gamma-ray emitter, produced through direct or deep-inelastic reactions, it is necessary to use sophisticated instruments specially if dealing with reaction channels that have relatively low cross section and a broad velocity distribution. In the last years different high efficiency gamma-ray detector systems have been used in combination with ancillary detectors of increasing complexity.
A research program on nuclear structure of slightly neutron-rich nuclei is being carried out at LNL with the gamma-ray array CLARA [3], coupled to the high efficiency magnetic spectrometer PRISMA [4], to study the gamma decay of excited nuclei populated by multi-nucleon transfer and deep-inelastic collisions.

The V isotopes were produced in the reaction $^{64}$Ni + $^{238}$U with a 400 MeV Ni beam delivered on a 400 $\mu$g/cm$^2$ thick self supporting uranium target by the Tandem-ALPI accelerator complex at the Legnaro National Laboratory. The projectile-like nuclei were detected with the PRISMA spectrometer placed at 64° in the laboratory frame. For each ion detected in PRISMA, we obtain the atomic number $Z$, the mass number $A$, the initial direction of the ion flying away from the target and the absolute value of its velocity. The $\gamma$-rays following the de-excitation of the reaction products were detected with the CLARA array, a high-granularity, Ge array, consisting of 25 EUROBALL Clover detectors, placed in the hemisphere opposite to the PRISMA spectrometer, 29.5 cm from the target, uniformly covering the azimuthally angles from 98° to 180°. The Doppler correction for the photons in coincidence with the ions detected in PRISMA was performed on an event-by-event basis, using the recoil velocity vector obtained after trajectory reconstruction in the spectrometer. The $\gamma$-ray energy resolution obtained was 0.8% FWHM over the whole broad velocity distribution of the projectile-like products, ranging from 4.5% to 10% of the speed of light. From the $\gamma$-ray spectra obtained in coincidence with the detection of different V isotopes we build up the level schemes taking into account the relative yields and the region systematics. For all these nuclei we observed a very intense population of the yrast levels compared with a weak population of non-yrast states.

In Figure 1 we report the first identification of yrast states in heavy odd-A Vanadium isotopes $^{55}$V and $^{57}$V, compared with recent shell model calculations performed with the code ANTOINE [5] and the KB3G [6], FPD6 [7] and GXPF1 [2] interactions. By comparing these results with the even Ti isotones (see for example references [1] and [8]), it is possible to see that the $N$=32 sub-shell closure is confirmed in the odd-Z $^{55}$V nucleus, but there is no evidence of a $N$=34 sub-shell closure in $^{57}$V. In these Proceedings Liddick et al. present other arguments to sustain the $N$=34 closure. However, a definitive answer could come from the measurement of $N$=34 Ca or Sc isotopes, together with the measurement of transition probabilities.

3. References
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Figure 1. Comparison of experimental results for $^{55,57}$V with recent shell model calculations (see text).