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# Spectroscopy of neutron-rich Co nuclei populated in the $^{70}\text{Zn}+^{238}\text{U}$ reaction

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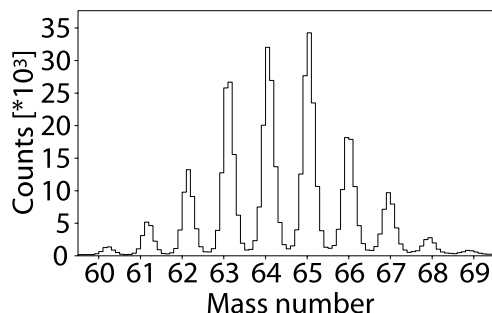
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**Abstract.** Neutron-rich Co isotopes from  $N = 34$  to 40 were studied through multinucleon transfer by bombarding a  $^{238}\text{U}$  target with a 460 MeV  $^{70}\text{Zn}$  beam at LNL. Gamma-recoil coincidences were recorded identifying the ions by a high-acceptance magnetic spectrometer (PRISMA) and detecting the gamma radiation by an array of HPGe clover detectors (CLARA). The results are discussed in comparison with the predictions of large-scale shell-model calculations.

## 1. Introduction

The investigation of neutron-rich nuclei has proved its effectiveness in highlighting the role of terms of the nuclear interaction that are buried in the Hamiltonian when the study is limited to the stable or near-stable isotopes. Such terms, previously only theoretically predicted [1, 2] for long time, have not been explicitly included in most of the calculations. In particular their role as a function of the isospin degree of freedom has been much discussed in view of an evolution of the shell structure [3] or of the emergence of a variety of exotic nuclear phenomena [4].



**Figure 1.** Mass distribution of the Co isotopes produced in the  $^{70}\text{Zn}+^{238}\text{U}$  reaction as identified by the PRISMA magnetic spectrometer

With 40 neutrons and 28 protons,  $^{68}\text{Ni}$  presents characteristics of a doubly magic nucleus [5, 6]. This can be deduced from the measured excitation energy of the  $2^+$  state and its transition probability to the ground state. However, the robustness of the  $Z=28$  and  $N=40$  shell closure when increasing the  $N/Z$  ratio is questionable and the rapid appearance of intruder states have attracted many experimental and theoretical investigations. It has been shown that adding pairs of neutrons in the  $g_{9/2}$  orbital beyond  $N=40$  polarizes the nucleus due to the tensor part of the residual interaction [7, 8]. The effect is the following: The interaction between  $f_{7/2}$  protons with neutrons in both  $f_{5/2}$  (attractive) and  $g_{9/2}$  (repulsive), weakens when the proton  $f_{7/2}$  orbital is not completely full, and therefore the gap between the neutron orbitals  $f_{5/2}$  and  $g_{9/2}$  decreases. The same interaction makes the neutron occupying the  $g_{9/2}$  orbital to induce the lowering of the shell gap between the  $f_{7/2}$  and  $f_{5/2}$  proton orbitals favoring particle-hole excitations across  $Z=28$  [9, 10].

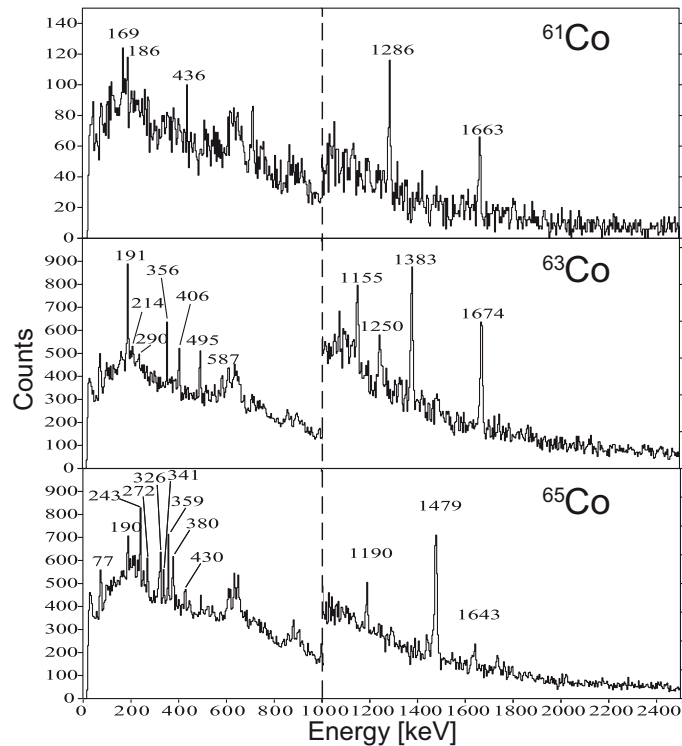
In this work we present recent data on neutron-rich odd-mass Co isotopes, obtained in the Legnaro National Laboratories using the CLARA-PRISMA detector complex. Data are compared to recent shell model calculations obtained by diagonalizing the new effective interaction LNPS [11]. The adopted shell model space is the  $pf$  shell for protons and the  $f_{5/2}$   $p_{3/2}$   $p_{1/2}$   $g_{9/2}$   $d_{5/2}$  for neutrons. This interaction is able to describe both collective and single-particle behavior near  $N=40$  and to follow the rapid evolution of the nuclear structure along isotopic and isotonic chains.

## 2. Experiment and discussion

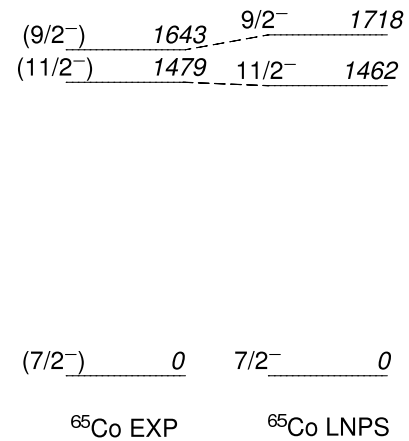
The possibility to populate new nuclei in the  $N=40$  neutron-rich region is offered by the use of a  $^{70}\text{Zn} + ^{238}\text{U}$  reaction in a multi-nucleon transfer regime. Several neutron-rich isotopes were populated and identified using the PRISMA magnetic spectrometer. The mass spectra obtained for Co isotopes is shown in Fig. 1. Among the nuclei that can be studied with such a reaction  $^{67}\text{Co}$  is of special interest since it is expected that at least its low lying excited levels could be interpreted as proton hole states in the doubly closed shell nucleus  $^{68}\text{Ni}$ .

The  $\gamma$ -ray spectra obtained in coincidence with the detection of the odd-even Co isotopes from  $A = 61$  to  $A = 65$  are shown in Fig. 2. Similar spectra have been obtained also for the Cr, Mn and Fe isotope chains [12, 13, 14]. In almost all cases new  $\gamma$ -rays have been assigned for the first time to these nuclei.

The variety of the structure and its rapid evolution along the isotopic and isotonic chains when approaching  $N=40$  is a challenge for any nuclear model, and in particular for the shell model. In fact, such a description implies to consider a wide shell model space and the development of an effective interaction that involves more than one main shell. While Cr isotopes up to  $N=34$  can be very well described within the  $fp$  shell, neutron-rich Fe isotopes up to  $N=36$  need



**Figure 2.** Doppler corrected  $\gamma$ -ray spectra in coincidence with an odd Co recoil detected by the PRISMA magnetic spectrometer.



**Figure 3.** Level scheme of  $^{65}\text{Co}$  from the data of the present experiment compared with preliminary results of shell-model calculations using the LNPS interaction.

the inclusion of the  $g_{9/2}$  neutron orbital in the model space ( $^{48}\text{Ca}$  core) [13]. However, when approaching  $N=40$  these  $fp$  calculations fail to describe the structure of neutron-rich nuclei, in particular,  $^{60-64}\text{Cr}$  [12, 15] and  $^{66-68}\text{Fe}$  [14, 16]. It has been pointed out that to reproduce the quadrupole collectivity in this mass region, the inclusion of the neutron  $d_{5/2}$  orbital is needed [10]. Recently, a new interaction for this model space (LNPS) has been developed that can reproduce the different phenomena suggested by the available data in this mass region [11].

In Fig. 3 we show the deduced level scheme of  $^{65}\text{Co}$  in comparison with preliminary shell model calculations performed with the LNPS interaction. It is important to note that in the new level scheme of  $^{65}\text{Co}$  the spin assignment of the low lying yrast states at 1479 and 1643 keV have been changed with respect to a previous work [17] on the basis of the measured angular distributions. The data on  $^{67}\text{Co}$  are extremely promising and will be the subject of a future publication.

### 3. Conclusions

The development of deformation in the neutron-rich nuclei around  $N=40$  for  $Z<28$ , is a subject of current interest from both the experimental and the theoretical points of view. Data are being obtained by means of different experimental techniques. In particular, data on neutron-rich Co isotopes recently obtained with the CLARA-PRISMA setup at LNL have been presented and discussed here. A new spin assignment is proposed for low lying yrast states in  $^{65}\text{Co}$  which compares well with shell model calculations in a large model space.

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