New Results on Excited States in the one-particle one-hole nucleus ^{56}Co measured with MINIBALL detectors

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Abstract. The non-yrast states of the odd-odd nucleus ^{56}Co have been investigated by studying the γ-rays induced in the predominantly fusion-evaporation reaction ^{56}Fe(p,nγ)^{56}Co at an incident energy of 10 MeV. The γ-rays were measured in-beam with four high-resolution MINIBALL-triple germanium (Ge) detectors. The experiment provided excellent data in γ-γ coincidences. The complex level scheme of ^{56}Co was constructed mainly based on the analysis of these γ-γ coincidences. The angular distributions of the γ-rays were also analysed and allowed us to assign spin-parity values to most of the excited states in this nucleus. Despite the extensive work previously done studying the ^{56}Co nucleus, the analysis presented in this work has resulted in a large improvement in the knowledge of its structure.

1 Introduction

In the present work we have studied the γ-ray de-excitation of the non-yrast states in the odd-odd nucleus ^{56}Co (Z=27, N=29) populated in the mainly fusion-evaporation reaction ^{56}Fe(p,nγ)^{56}Co at an 10-MeV incident proton beam. From the shell-model point of view, in the simplest analysis, ^{56}Co is just one-proton hole and one neutron outside the doubly magic nucleus ^{56}Ni (Z=N=28). Ideally, spectroscopy of the ^{56}Co nucleus ought to yield direct information on the particle-hole residual interaction in the *fp*-shell.

The study of ^{56}Co in this work was initially motivated by the observation of two 0^+ states in its mirror nucleus ^{56}Cu (Z=29, N=27) in a β^+ decay experiment of ^{56}Zn carried out at GANIL (Caen, France) [1]. These two states are populated through Fermi-type decay and correspond to the splitting of the isobaric analogue state (IAS). Two very similar states exist in ^{56}Co and were recently investigated in the ^{56}Fe(^{3}He, t)^{56}Co charge exchange (CE) reaction performed at the Research Centre for Nuclear Physics RCNP in Osaka (Japan) with high resolution [2]. No γ detection was possible in this work.

2 The experiment

The experiment was performed at the Maier-Leibnitz-Laboratory (MLL) of the Technische Universität München (TUM, Germany). The gamma radiation emitted in the de-excitation of the excited states in ^{56}Co was measured in-beam with four high-purity germanium (Ge) MINIBALL-triple detectors. The MINIBALL array [3] is a γ-ray spectrometer optimized to achieve a high photo-peak efficiency in combination with position sensitivity γ-ray detection.

For the present experiment at the TUM, two MINIBALL clusters were located forward and two backward with respect to the beam direction (see Fig. 1). The target chamber was positioned at the centre. We used a ^{56}Fe target with a thickness of 1.1 mg/cm^2, which was mounted in an aluminium frame. The clusters were positioned at slightly different distances from the chamber, in order to maximise the solid-angle coverage.

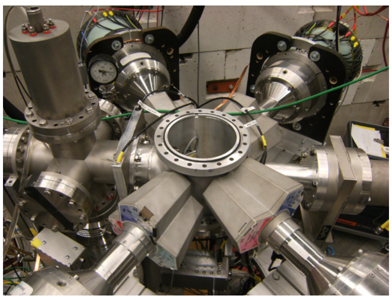

Figure 1. The experimental setup is shown. Two MINIBALL clusters were located forward and two backward with respect to the beam direction. The target chamber was positioned at the centre.

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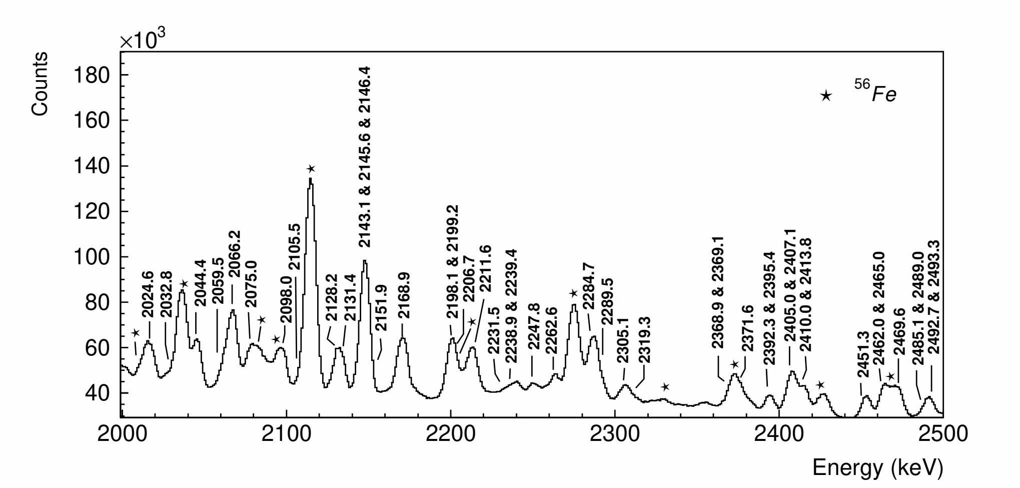

Figure 2. The γ-γ coincidence matrix-projection spectrum is shown, in the 2-2.5 MeV range. All the γ-rays observed and placed in the level scheme of ^{56}Co in this work are labelled. Note that the peaks coming from the de-excitation of excited states in ^{56}Fe are indicated with a symbol $\star$.

3 The level scheme of ^{56}Co

The level scheme of the ^{56}Co nucleus was constructed mainly based on the analysis of the γ-γ coincidence matrices. The γ-γ coincidence matrix-projection spectrum is shown in Fig. 2 in the 2-2.5 MeV range, which gives an idea of the complexity of the experiment.

In the present work, a large amount of new information has been obtained. In the following, we summarise the experimental results:

- A total of 223 γ-transitions, of which 169 were previously unobserved, have been observed and placed in the level scheme.
- A much higher sensitivity level for the γ-de-excitation of excited states in ^{56}Co than reported in the literature has been reached for states with spins between 0 and 6. A total of 77 excited states have been observed (up to 4.4-MeV excitation energy), 37 of which were previously known but no gamma de-excitation had been observed. In 42 cases the energy precision of the levels has been improved and 14 excited states have been observed for the first time.

  Due to the complexity of the experiment most of the γ-transition energy and intensity values have been determined in the gated-spectra of the γ-γ coincidence matrices (see [7]). The spin and parity assignments to the excited states have been made based on their γ-decay pattern and the angular distributions of the γ-ray transitions measured.

4 Theoretical interpretation

For the present discussion large-scale shell-model calculations in a truncated *fp*-shell valence space have been carried out using the NuShellX@MSU code [4] and the effective interactions KB3G [5] and GXPF1a [6]. The calculations constrained the full *fp*-shell model space by insisting that at least 2 protons and 2 neutrons are in the $1f_{7/2}$ shell.

Since the magic numbers of Z and N (=28) provide a good core for ^{56}Ni, the majority of low-lying states in ^{56}Co can be described in terms of the one-particle-one-hole (1p-1h) configurations (or multiplets), i.e., $(1f_{7/2})^{-1}_{\pi} \times (2p_{3/2}, 1f_{5/2}, 2p_{1/2})^{1}_{\nu}$. The low-lying experimental states in ^{56}Co have been identified as the main components of the 1p-1h multiplets with the help of the shell-model calculations (see [7]). Tentative identification between the experimental levels and theoretical predictions using the two previously mentioned effective interactions have been also made up to 3 MeV.

On the other hand, the study of the isospin mixing between two 0^+ states in ^{56}Co (the IAS of the ^{56}Fe$_{g.s.}$ and a nearby state) was one of the main motivations of this work. The determination of the M1 transition intensities from both states has offered new and relevant information about the effects associated to the relative phases of the isospin-mixed states and has shown that these two states decay in a different way (see [7]).

References

[1] S.E.A. Orrigo, B. Rubio, Y. Fujita, W. Gelletly *et al.*, Phys. Rev. Lett. **112**, 222501–1 (2014)

[2] H. Fujita, Y. Fujita, T. Adachi, H. Akimune *et al.*, Phys. Rev. C **88**, 054329 (2013)

[3] P. Reiter, J. Eberth, H. Faust *et al.*, Nucl. Phys. A **701**, 209 (2002)

[4] B.A. Brown and W.D.M. Rae, Nuclear Data Sheets **120**, 115 (2014)

[5] A. Poves, J. Sánchez-Solano, E. Caurier and F. Nowacki, Nucl. Phys. A **694**, 157 (2001)

[6] M. Honma, T. Otsuka, B.A. Brown and T. Mizusaki, Phys. Rev. C **69**, 034335 (2004)

[7] A. Montaner-Pizá, Ph.D. Thesis, *Isospin mixing and in-beam study of non-yrast states in* ^{56}*Co* (University of Valencia, 2018)