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DSAM LIFETIME MEASUREMENTS IN THE ODD-ODD NUCLEUS ^{62}Cu

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Abstract. The lifetimes of 10 low spin excited states in ^{62}Cu, below 2 MeV excitation energy, have been measured using the DSA method. The ^{62}Ni(p,nγ) reaction was used, at an incident beam energy of E_p = 6.7 MeV. The results are discussed theoretically in the frame of the Interacting Boson-Fermion-Fermion Model (IBFFM).

Key words: Doppler Shift Attenuation Method, excited levels lifetime measurement, Interacting Boson-Fermion-Fermion Model.

1. INTRODUCTION

As an odd-odd isotope of the *fp* shell, ^{62}Cu presents a high level density [1, 2]. The theoretical analysis of this level scheme within the framework of the shell model [3] requires a large configuration space and is restricted to low-lying levels.

The success of the Interacting Boson Model (IBM) [4] and of the Interacting Boson-Fermion Model [5] in explaining the low energy structure of medium and heavy nuclei has led to attempts to extend the formalism to odd-odd nuclei. Lopac *et al.* [6] have described the structure of ^{198}Au in the framework of two fermions coupled to a boson core. The same model was employed to describe also some odd-odd Ga and As nuclei [7, 8]. The concept of dynamical symmetry in IBFM has been used to describe Cu nuclei. An analytical calculation has been performed for the ^{62}Cu nucleus by Hübsch and Paar [9].

The present work is based on the ^{62}Ni(p, nγ) reaction studied at E_p = 6.7 MeV at the 8 MV Tandem Van de Graaf accelerator of NIPNE Bucharest. This reaction provides the opportunity to study for the first time the lifetimes of odd-odd ^{62}Cu isotope.

2. EXPERIMENTAL METHOD

The ^{62}Cu levels were populated via the ^{62}Ni(p, nγ) reaction 6.7 MeV incident energy. This reaction provides rather low recoil velocities, but it is not selective and it also has the advantage that it can be performed close to the threshold and populate directly only the levels of interest.

The proton beam, with an intensity kept around 10 nA, was provided by the FN tandem Van de Graaff accelerator in Bucharest. The target was a thick self-suporting foil (~ 125 mg/cm^{-2}), isotopically enriched in ^{62}Ni. γ-rays were detected in two 20% efficiency HPGe detectors with full width at half maximum (FWHM) energy resolutions of 2.2 and 2.3 keV for the 1.112 MeV γ-line of the ^{152}Eu source, respectively, placed at ~ 13 cm from the target. Singles spectra were recorded simultaneously with both detectors at eight different angles from 15° to 143° with respect to the beam axis, choosing for each detector a random order of the angle sequence in order to avoid systematic errors.

A continuous monitoring of the energy calibration was performed by measuring between runs a set of ^{60}Co, ^{137}Cs, and ^{152}Eu sources. The ^{60}Co source was also kept in a convenable position near the reaction chamber during all measurements. Since the (p, n) reaction at our energies provides very low recoil velocities, the DSA method, based in this case on the observation of the peak centroid shift with the angle, requires a very precise energy calibration.

The proton incident energy chosen was a compromise between the requirement of being close to the threshold energies of the levels up to about E_x = 1.6 MeV (so that the recoils have a narrow velocity distribution close to the center of mass velocity), and that of having sufficient cross section for the levels of interest in order to keep the measuring time for each angle reasonably short, up to 3 h, to prevent gain shifts of the electronic chains.

Fig. 1 shows two examples of measured spectra, at forward and backward angles respectively, to illustrate the typical statistics of the measurements as well as how the measured γ-ray transitions of ^{62}Cu were seen.

Fig. 2 gives a detail of the two spectra from Fig. 1, showing the shifts observed for the three γ-ray transitions in ^{62}Cu.

3. EXPERIMENTAL RESULTS

For the lifetime determination we used the Doppler Shift Attenuation Method (DSAM). For the transitions of interest, the variation of the energy corresponding to the peak centroid (first moment) with the angle of observation has been determined. In the final analysis of the experimental data, the peak position was determined relative to the position of the closest of the unshifted “reference” peaks

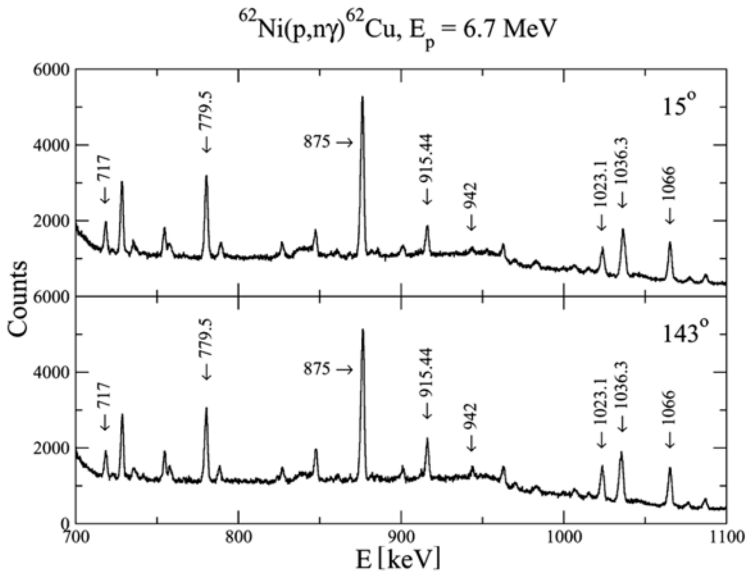

Fig. 1 – Examples of spectra measured at two angles, forward and backward. Only the peaks of interest are marked by their (unshifted) energy, together with one of the reference peaks used in the analysis.

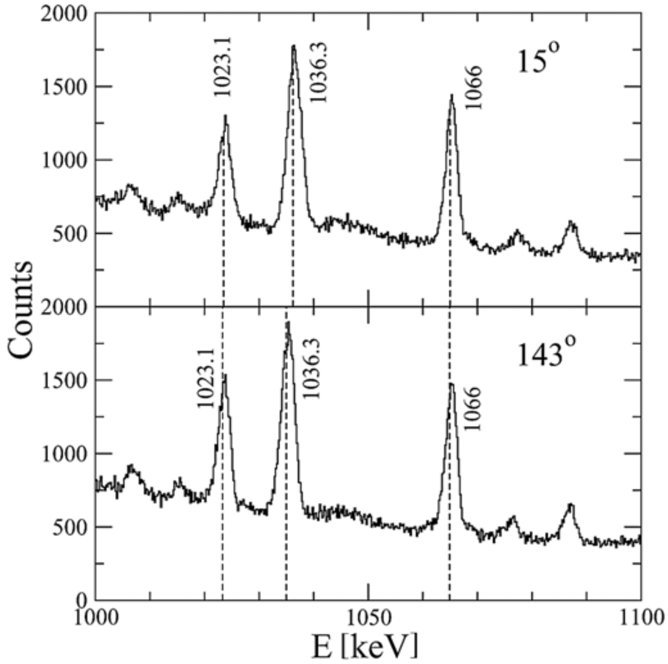

Fig. 2 – Detail of the two spectra from Fig. 1. The dashed lines indicate the centroids of the γ-ray peaks.

(511 and 875 from background, 1173 and 1332 from the ^{60}Co source). By fitting straight lines to the data, the experimental attenuation factors $F_{exp}(\tau)$ were determined for the different γ-rays, according to the usual expression:

$$E_\gamma = E_0\left(1 + F_{exp}\frac{\overline{v}}{c}\cos\theta\right) \tag{1}$$

where E_0 is the unshifted γ-ray energy and $\overline{v}$ is the mean initial velocity of the recoiling nuclei. Very close to the reaction threshold the recoil velocity is practically equal to the center of mass velocity. In practice, however, the measurements have to be performed at some energies above the threshold, where the cross sections for populating the levels of interest are sufficient to allow reasonable measuring times (not longer than a few hours, during which the electronic gain shifts are, hopefully, less than the precision in the determination of the γ-ray centroids). The emission of the neutrons with non-zero energy widens somewhat the distribution of the recoil velocity. Due to the compound nucleus mechanism, we may assume that the center of mass angular distribution of the outgoing neutrons (and, consequently, of the recoils) is isotropic, resulting in recoils that move in the laboratory system within a cone centered on the forward direction. The resulting velocity distribution can be, nevertheless, reasonably well approximated by a unique recoil velocity, equal to that of the center of mass.

The plots of the differences between the energies of the peaks of interest and the energies of the closest "reference peak" *versus* cosθ are shown in Fig. 3. The solid line on each graph indicate the linear fit to the experimental data. The different slopes of these lines correspond to different lifetimes of the levels that emit the γ-rays while slowing down in the target material.

The error bars of the data points are determined by the statistical uncertainty of the centroid determination and an error originating from the determination of the position of the (unshifted) reference line which was close to the peak of interest.

From the linear fits one can extract the experimental attenuation factor $F(\tau)$ (see Eq. 1). In extracting lifetimes from such low-energy recoil data, a large uncertainty comes from the poor knowledge of the stopping powers. Actually, since these stopping powers are not known experimentally, one has to rely on calculated ones. In calculating the $F(\tau)$ values we have treated the nuclear stopping power with the Blaugrund formalism [10] and the electronic stopping power was chosen according to two different models: one based on the Lindhard-Scharff-Schiott (LSS) formalism [11], and one based on the formalism of Ziegler *et al.* [12]. The lifetime values (τ) were extracted by comparing the values $F_{exp}(\tau)$ with the calculated $F(\tau)$ curves. In Table 1 we report the lifetimes resulted from the use of the LSS stopping powers. The ZBL stopping powers provide lifetime values systematically larger than the LSS ones by 19–20%. In Table 1, the errors quoted for the lietimes result from the statistical errors in $F(\tau)$ and a 20%

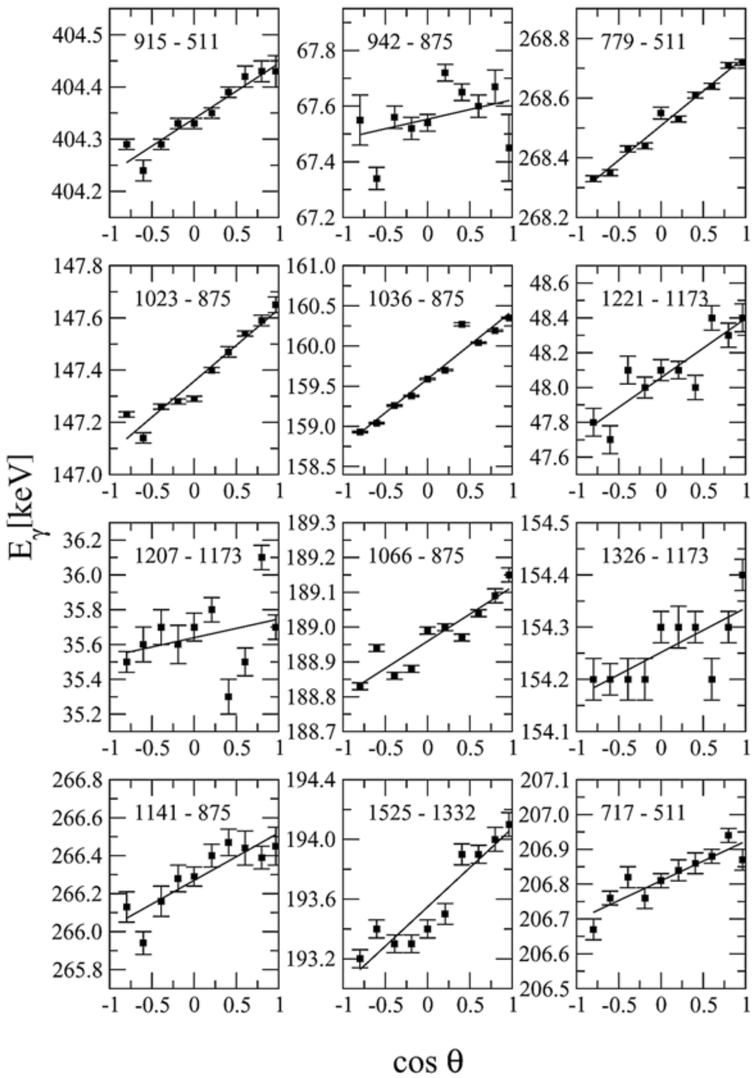

Fig. 3 – Variation with the angle of the energies of ^{62}Cu transitions, relative to the closest "reference" peaks.

systematic error, which is introduced to take into account the typical uncertainties in the calculated stopping powers. The measured $F_{exp}(\tau)$ in Table 1 constitute absolute data which can be used to re-evaluate the lifetimes if more reliable stopping powers will become available.

Concerning the peak at an energy of about 717 keV (see the lower-right corner of Fig. 3), it can originate from two very close γ-rays: 717 keV from a level at 1141.8 keV and 717.9 keV from a level at 1416.1 keV, both seen in the ^{62}Ni(p, nγ) reaction (Ref. [13]). Their relative intensities were not measured, so the Doppler shift which is clearly visible could not result in any determination of a lifetime.

Table 1

Lifetimes of the excited states in ^{62}Cu measured in the present work. The excitation energies (first column) and the γ-ray energies (second column) are from Ref. [13]

E_{level}	E_γ [keV]	tg(α)	$F_{exp}(\tau)$	τ [fs]
915.33	915.44	0.077 ± 0.014	4.48 ± 0.81	$1239.7^{+500.0}_{-279.6}$
982.71	942	0.170 ± 0.067	9.60 ± 3.71	$424.9^{+392.4}_{-143.8}$
1023.02	779.5	0.217 ± 0.011	14.85 ± 0.75	$245.4^{+16.5}_{-14.7}$
	1023.1	0.255 ± 0.031	13.29 ± 1.61	$282.1^{+49.8}_{-37.8}$
1077.2	1036.3	0.821 ± 0.048	42.25 ± 2.47	$58.9^{+5.9}_{-5.3}$
1221.51	1221.5	0.345 ± 0.074	15.11 ± 3.23	$240.1^{+84.8}_{-52.1}$
1248.67	1207.9	0.160 ± 0.103	7.07 ± 4.55	> 333.9
1354.3	1066	0.142 ± 0.029	7.12 ± 1.45	$631.1^{+236.2}_{-137.7}$
1367	1326	0.096 ± 0.024	3.86 ± 0.97	$1590.2^{+1231.8}_{-488.6}$
1429.58	1141.91	0.274 ± 0.056	12.80 ± 2.62	$295.8^{+99.4}_{-61.8}$
1525.91	1525.9	0.519 ± 0.073	18.15 ± 2.55	$190.5^{+40.1}_{-29.5}$

4. THEORETICAL INTERPRETATION

The first calculations for describing the low-energy states of ^{62}Cu were those of A. K. Singh *et al.* [14]. In Fig. 4 the experimental energy level scheme is compared with the results of the calculations. It has been shown that the positive parity states below 1 MeV excitation energy are described fairly well in this framework. We see also that the energy and the spin of the lowest negative parity states are correctly reproduced.

In general the agreement between the IBFFM model predictions and experimental measurement is found to be fairly satisfactory up to about 5 MeV excitation energy. However, that involves detailed knowledge of the different configurations of the core.

In spite of its relative success, the IBFFM calculations cannot reproduce the lifetimes and the magnetic moment of the ground state of ^{62}Cu. The contribution of the states lying outside the IBFFM space may be important in explaining this situation.

REFERENCES

1. G. Chouraqui, Th. Muller, M. Port, J. M. Thirion, Nucl. Phys **A277**, 221 (1977).
2. M. L. Halbert, Nucl. Data Sheets **26**, 5 (1979).

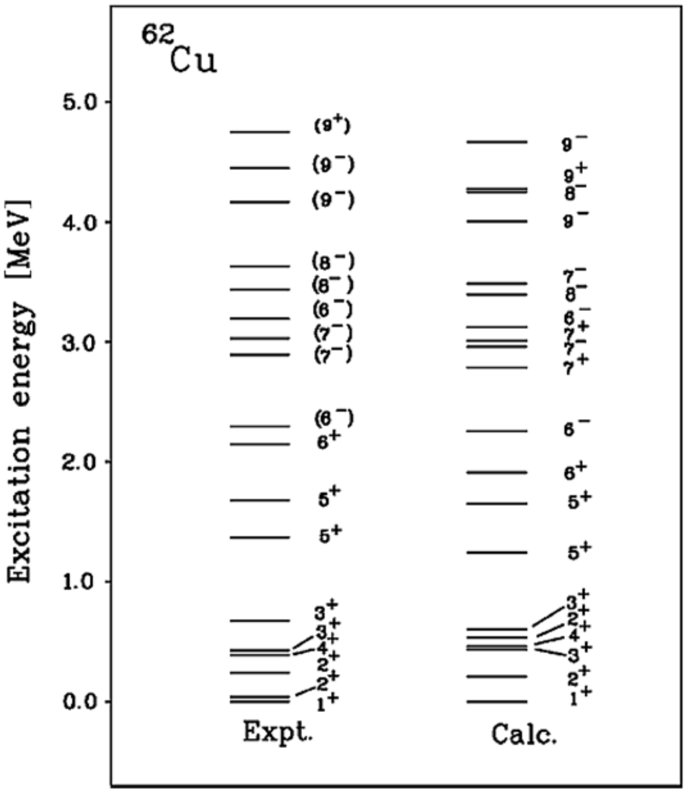

Fig. 4 – A comparison of the experimental and the theoretical (obtained on the basis of IBFFM) level spectra in ^{62}Cu.

3. J. E. Koops, P. W. M. Glaudemans, Z. Phys. **A280**, 181 (1977);
   J. E. Koops, *Shell-model calculations on Ni and Cu isotopes* – Thesis, Utrecht (1978).
4. A. Arima, F. Iachello, Ann. Phys. (N.Y.) **99**, 253 (1976); **111**, 201 (1978); **123**, 468 (1979);
   F. Iachello, A. Arima, *Interacting Bosons in Nuclear Physics*, Cambridge University Press, Cambridge (1987).
5. F. Iachello, O. Scholten, Phys. Rev. Lett. **43**, 679 (1979).
6. V. Lopac, S. Brant, V. Paar, O. W. B. Schult, H. Seyfarth, A. B. Balantekin, Z. Phys. **A323**, 491 (1986).
7. J. Timár, T. X. Quang, T. Fényes, Zs. Dombrádi, A. Krasznahorkay, J. Kumpulainen, R. Julin, S. Brant, V. Paar, Lj. Šimičič, Nucl. Phys. **A573**, 61 (1994).
8. A. Algora, D. Sohler, T. Fényes, Z. Gácsi, S. Brant, V. Paar, Nucl. Phys. **A588**, 399 (1995).
9. T. Hübsch, V. Paar, Z. Phys. **A327**, 287 (1987).
10. A. Blaugrund, Nucl. Phys. **88**, 501 (1966).
11. J. Lindhard, M. Scharff, H. E. Schiott, Matt. Fys. Medd. Dan. Vid. Selsk. **33**(*14*), (1963).
12. J. F. Ziegler, Computer code TRIM, 1992, presented in J. F. Ziegler, J. P. Biersack, U. Littmark, *The Stopping and Range of Ions in Solids* (Pergamon Press, New York, 1985).
13. Evaluated Nuclear Structure Data File database, available at http://www.nndc.bnl.gov/ensdf/
14. A. K. Singh, G. Gangopadhyay, *Phys. Rev.* **C55**, 726 (1997).