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FIRST USE OF POST-ACCELERATED ISOMERIC BEAMS FOR COULOMB EXCITATION STUDIES OF ODD-ODD NUCLEI AROUND N=40

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We report on the first use of post-accelerated radioactive isomeric beams. Long-lived isomeric states in ^{68}Cu and ^{70}Cu have been produced and separated at ISOLDE, CERN. Subsequently they were post-accelerated to 2.86 MeV/u and sent to a target in the center of the MINIBALL spectrometer, used for the detection of the γ-rays of interest. The preliminary results from the Coulomb excitation of the $I^{\pi} = 6^{-}$, 1^{+} states in ^{68}Cu and the $I^{\pi} = 6^{-}$ one in ^{70}Cu, compared to a large-scale shell model calculations, hint the importance of the excitations across the $Z = 28$ gap for the understanding of the nuclear structure in the neutron-rich $N = 40$ region.

1. Introduction

The fast developments of the radioactive nuclear beam techniques in the last years contribute to the great enlargement of the variety of the species accessible for the nuclear structure studies. As an example one can mention the odd-odd nuclei. In the Nature there are only five of them, heavier than Oxygen, namely ^{40}K, ^{50}V, ^{138}La, ^{176}Lu and ^{180}Ta. They are practically all radioactive and have survived up to nowadays due to their very long half-lives of the order of 10^9 years or longer. The coupling of an odd-proton to an odd-neutron in the odd-odd nuclei usually causes very high level densities at low excitation energy and makes them quite complex for investigation. Therefore the application of a variety of techniques is indispensable for their understanding. With the possibility to use post-accelerated ISOL beams, which one obtained after the construction of REX-ISOLDE, the low-energy Coulomb excitation becomes a very powerful method for the study of the radioactive nuclei. This is of special importance for the odd-mass and the odd-odd nuclei for which, due to the high-level density at low energy, the intermediate energy Coulomb excitation technique is not applicable.

A unique characteristic of the beams available at ISOLDE is the possibility of isomeric selection[1] using the Resonant Ionization Laser Ion Source (RILIS).[2] Studies on specific isomeric states in the Copper isotopes have already been performed at ISOLDE via β-decay,[3] magnetic moments-[4] and mass-measurements[5] using low-energy (60 keV) ISOL beams. Here we report an experiment in which isotopes in a specific isomeric state have been post-accelerated for the first time up to ~ 3 MeV/u and have been Coulomb excited.

The interest towards the neutron-rich region of the nuclear chart around $N = 40$ has been triggered long ago with the discovery that the first excited state in ^{68}Ni has spin/parity of 0^+[6] and that the energy of the first 2^+ state is quite high compared to the neighboring Nickel nuclei.[7] Both these observations were interpreted as a signature of an appearance of a new magic (sub-) shell closure at $N = 40$ and many experimental and theoretical works have been performed aiming at the understanding of the nuclear structure in the region (see e.g. Ref. 8 and the references there in).

The general question concerning the modification of the nuclear shell structure away of the valley of β-stability is widely discussed and one of the mechanism proposed for its explanation is related to the isospin dependence of the nuclear force and more precisely to its tensor component.[9] It is expected that these variation are to be observed at N/Z ratios different from those close to the stability line. However, the changes in the shell structure far from stability are expected to be rather rapid and strongly localized.[10] Therefore, in order to put stronger constrains to the nuclear theories it is essential to pin down how far from ^{68}Ni is propagating the influence of $N = 40$ on the structure of the nuclei in the region. This was our main motivation in order to perform a Coulomb-excitation study on a chain of Copper nuclei, just one proton above the $Z = 28$ Nickel isotopes, from ^{67}Cu ($N = 38$) up to ^{71}Cu ($N = 42$). This should allow us to determine the proton- and neutron effective charges, and eventually their modification, right bellow and above $N = 40$.

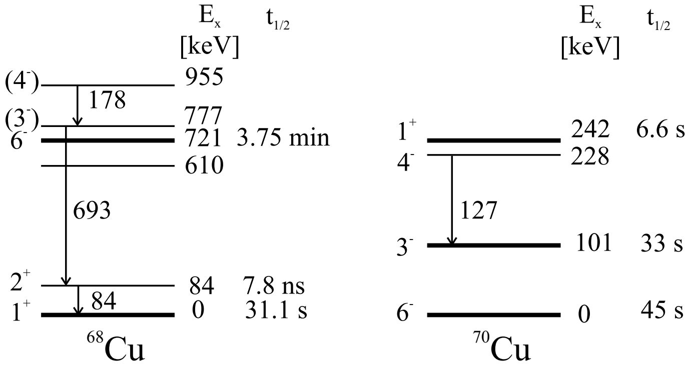

Fig. 1. Low-energy level schemes of ^{68}Cu and ^{70}Cu relevant to the present measurement. Transitions observed in the Coulomb excitation of ^{68m,g}Cu and ^{70g}Cu are also shown.

Here we present the first preliminary results from the study of the odd-odd ^{68m,g}Cu and ^{70g}Cu nuclei of the chain. The odd-mass nuclei from the above mentioned sequence are subject of a different study. Two β-decaying isomeric states are know in ^{68}Cu (see Fig. 1). The lower-lying one, $I^\pi = 1^+$, $T_{1/2} = 31.1$ s, can be considered as the coupling of a $2p_{3/2}$ proton to a $2p_{1/2}$ neutron, giving rise to a multiplet of states $(1^+, 2^+)$. The second isomeric state in ^{68}Cu, $I^\pi = 6^-$, $T_{1/2} = 3.75$ min, is the highest-spin member of the $(6^-, 5^-, 4^-, 3^-)$ multiplet, constructed by a proton on the $2p_{3/2}$ orbital coupled to a neutron on the $1g_{9/2}$ one. The levels from the $(\pi p_{3/2} \otimes \nu g_{9/2})$ multiplets in ^{68}Cu and ^{70}Cu have been previously investigated in transfer reactions.[11] There are also some recent results on life-time measurements of shorter-living (nanoseconds) isomeric state in ^{68}Cu.[12] A Coulomb excitation study starting from any of the different isomeric state should probe a completely different structure of the nucleus and in this way allow us to gain a particular insight to the importance of the neutron $g_{9/2}$ orbital in it.

Three β-decaying states have been observed in ^{70}Cu.[3,5] Two of them (6^-, $T_{1/2} =$ 44.5 s; 3^-, $T_{1/2} = 33$ s) are members of the above mentioned multiplet involving the neutron $g_{9/2}$ orbital, while the third one (1^+, $T_{1/2} = 6.6$ s) is the homologue of the 1^+ state in ^{68}Cu. During the present study we have performed a Coulomb excitation only on the lowest lying 6^- state. As the analysis is still going on the final results will be published latter on.[13]

2. Experimental Details

The nuclei of interest, ^{68}Cu and ^{70}Cu, were produced using a 1.4 GeV proton beam impinging on an UC$_2$ target at ISOLDE and mass separated using the High Resolution Separator (HRS). The chemically selective laser ion source RILIS[2] was utilized in order to suppress any isobaric contamination. Additionally, the use of a narrow-bandwidth lasers allowed for the separation of the different isomeric states in the same nucleus.[1] In the present experiment we have selected three different beams, namely the 6^- and the 1^+ isomers of ^{68}Cu and the 6^- (ground) state of ^{70}Cu. The optimum frequencies of the resonant laser ionization, that maximize the production rates of each specific isomeric state, were known from previous experiments.[3−5]

After the mass-separation, the nuclei of interest were post-accelerated up to 2.86 MeV/u using the REX-ISOLDE[14] and sent to a 2.3 mg/cm^3 ^{120}Sn target, position in the center of the Miniball array.[15] A CD-shaped double-sided Silicon strip detector (CD-detector),[16] covering the range between 16.4° and 53.3° in the laboratory frame, was used to obtain the energy- and direction information for the scattered beam- and recoiling target particles.

The Miniball array consists of eight clusters, each of which is composed of three six-fold segmented HPGe detectors hosted in a common cryostat. The energy information from the Ge detectors and the position information from their segments, combined with the energy and the directional information from the CD detector, was used in order to perform a Doppler correction for the detected γ-rays.

An important point for the success of a radioactive beam experiment is the knowledge of the exact composition of the beam. The isobaric contamination is the usual source of contamination in an ISOL type of beams. In the here-presented experiment we had an additional source of uncertainty of the composition of the beam, namely the ratio between the desired and unwanted isomeric state of the selected nucleus (isomeric contamination). In order to monitor the isobaric contamination of the beam we have used two methods. The first one consisted of a $\Delta E - E$ telescope (ionization chamber followed by a Si detector), positioned on a neighboring beam line. The post-accelerated beam was periodically switched to this line for monitoring. The second method consisted of a regular alternation between measurements with the lasers of RILIS switched ON and OFF. This gives the percentage of the laser ionized ions versus the ions produced by any other (non-laser) ionization. Both methods have shown that the only isobaric contamination in our beams were due to surface ionized Ga atoms. The values we obtained were 74(2)% and 70(5)% respectively for the isobaric purity of the ^{68}Cu and ^{70}Cu beams.

The isomeric contamination in the beam was monitored via the characteristic γ-rays from the β-decays of these states. The results of the analysis have shown that during the selection of the 6^- states 86(3)% and 85(5)% of the total ^{68}Cu and respectively ^{70}Cu ions were arriving at the detection point in that particular state.

The first isomeric beam we have selected during the experiment was of the 6^- state of ^{68}Cu. The results of this measurement are presented in Fig. 2. In the upper part of the figure is presented the raw (non-Doppler corrected) spectrum of the energies of the γ-rays detected in the Miniball array in coincidence with a particle, detected in the CD detector. Three γ-lines are clearly observed. Two of them (84 keV and 693 keV) show no Doppler broadening, from which one can conclude that these γ-rays are emitted from nuclei stopped in the CD detector and the nuclear levels that they de-excite have lifetimes of-the-order-of or longer than the time-of-flight of the ions between the excitation target and the CD detector ($\sim$ 1 ns). The 84 keV transition has been reported before.[17] Its half-life has been

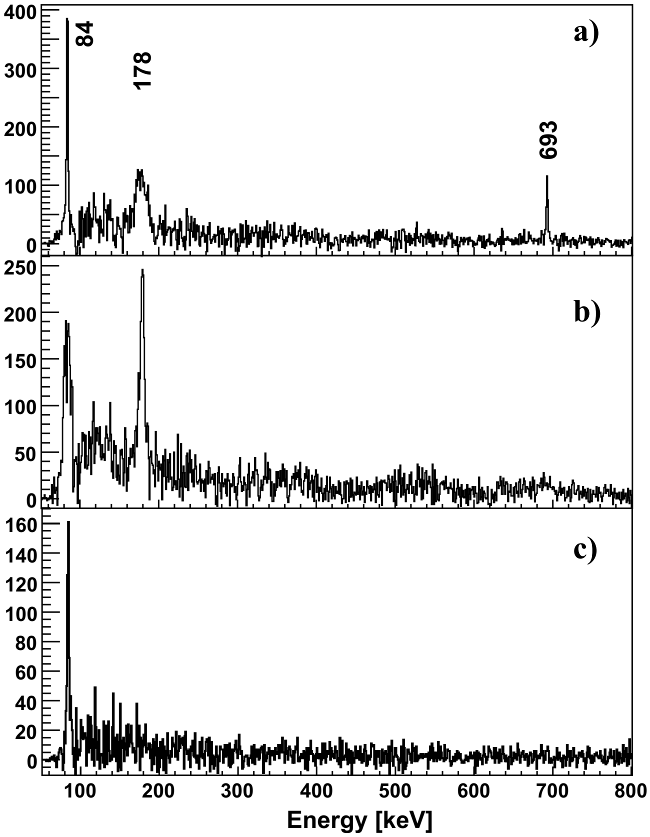

Fig. 2. Energy spectra from the Coulomb excitation of ^{68}Cu. (a) 6^- beam, no Doppler corrections; (b) 6^- beam, Doppler corrections for mass 68; (c) 1^+ beam, no Doppler corrections.

measured as $T_{1/2} = 7.84$ ns, in agreement with our observations, and spin/parity of $I^\pi = 2^+$ has been attributed to it (see Fig. 1).

The 693 keV transition has also been previously reported[12] as connecting the (3^-) and the 2^+ states in ^{68}Cu and limits of its half-life have been suggested (0.7 ns $< T_{1/2} <$ 4 ns). This transition is practically not observed in the γ-ray energy spectrum after a Doppler correction has been applied to it (Fig. 2(b)) which hints that its half-life is closer to the upper side of the above suggested limits.

The 178 keV transition observed in the Coulomb excitation of ^{68}Cu(6^-) is Doppler broadened and the width of its γ-line is reduced after the Doppler corrections for the mass 68 are applied (see Fig. 2(a) and (b)). This suggests its prompt character.

In the Coulomb excitation of the 1^+ isomeric state of ^{68}Cu a single γ-transition of 84 keV was observed (Fig. 2(c)). This is clearly showing a distinctively different pattern of the Coulomb excitation of the 6^- and 1^+ states and subsequently their different structure.

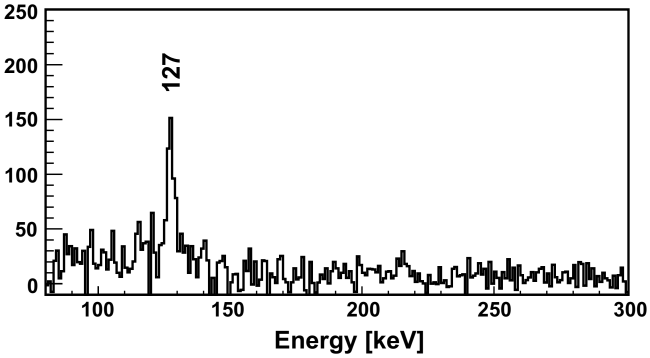

Fig. 3. Energy spectrum from the Coulomb excitation of the 6^- state in ^{70}Cu, Doppler corrected for mass 70.

The comparison of the γ-rays observed in the Coulomb excitation of ^{68}Cu to its level scheme (Fig. 1) shows that the 6^- isomeric state ($T_{1/2} = 3.75$ min) has been excited to the 4^- level which afterwards is de-excited via a sequence of a prompt and two short-living (nanoseconds) transitions to the 1^+ ($T_{1/2} = 31.1$ s) ground state of ^{68}Cu. This represents a clear observation of a de-excitation of a β-decaying isomeric state, following its Coulomb excitation, which is possible due to its specific nuclear structure.

The results of the Coulomb excitation of the 6^- isomeric state in ^{70}Cu are presented in Fig. 3. A single γ-ray transition at 127 keV, with a prompt character, is observed. The comparison to the level scheme of ^{70}Cu shows that the E2 excitation between the 6^- and 4^- states is observed, followed by the 4^- to 3^- de-excitation. Since the 3^- state is an isomeric one ($T_{1/2} = 33$ s) no further decay, within a time window of few-hundred nanoseconds, was observed.

3. Results and Discussion

In order to obtain the transition probabilities, B(E2), for the $6^- \rightarrow 4^-$ excitations within the ($\pi p_{3/2} \otimes \nu g_{9/2}$) multiplet in ^{68}Cu and ^{70}Cu it is necessary to compare the observed γ-rays to the amount of the nuclei impinging on the target. A direct (absolute) measurement of the total amount of the nuclei of interest arriving at the target position is very difficult to be performed with a sufficiently high precision, especially for a radioactive beam. Another (relative) method, which we have applied, uses a normalization of the beam- to the target excitation. The probability for the $0_1^+ \rightarrow 2_1^+$ excitation for ^{120}Sn, the target we used in this experiment, is known to a very high precision. Therefore, the main sources of uncertainties left are:

- the relative efficiency between γ-rays with different energy — a value that can be measured experimentally to a high precision;
- the efficiency of the particle detector — can be determined experimentally for known cases as well as simulated to a high precision;

- the precise composition of the beam (isobaric and isomeric contaminants) impinging on the target;
- the effect of the M1/E2 ration in a number of γ-rays on the deduced B(E2) and the effect of a possible M1 component in the Coulomb excitation.

From the preliminary analysis it is already clear that the B(E2) values of the 6^- to 4^- transition are in both cases of the same order of magnitude ($\sim$ 70 e^2fm^4). The uncertainties on the final values, including the above mentioned points together with the statistical error-bars, is expected to be in the 10% range.

In order to gain more insight into the structure of ^{68}Cu and ^{70}Cu large-basis shell model calculations, using the ANTOINE code,[18] are performed. The realistic interaction used[19,20] is the same that has been previously utilized for the interpretation of the structure of $^{70,74-78}$Cu.[3,21] An inert core of ^{56}Ni is considered and the model space spans over the *fpg* orbitals both for protons and neutrons, without any restrictions. The calculations reproduce the correct ordering of the members of the $\pi p_{3/2} \otimes \nu g_{9/2}$ multiplet and the energy spacing between them is in a good agreement with the experiment. Using the canonical values for the effective proton- and neutron effective charges ($e_p = 1.5$, $e_n = 0.5$) we obtain for B(E2)($6^- \rightarrow 4^-$) values $\sim$ 40 e^2fm^4 for both cases. These values are about 40% too low compared to the experimental results. This hints that it might be necessary to allow particle-hole excitations from the ^{56}Ni core, reducing it down to ^{48}Ca, in order to better reproduce the properties of the nuclei in the region.

4. Conclusions

We have performed the first experiment using post-accelerated isomeric beams in which transition probabilities within the $\pi p_{3/2} \otimes \nu g_{9/2}$ multiplet of ^{68,70}Cu have been determined. We have clearly demonstrated that it is possible to post-accelerate radioactive beam of nuclei in a particular isomeric state and that it is possible, through Coulomb excitation, to de-excite this state in a time scale which is many orders of magnitude (from minutes to nanoseconds) shorter. All this shows the big potential of the use of radioactive ion beams, in combination with isomer-selective methods, for the nuclear structure study of the of odd-odd nuclei. More experimental and theoretical efforts are necessary for the disentangling of the peculiar nuclear structure features around ^{68}Ni.

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