EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-INTC-2002-027
INTC-P-161
05 August 2002

Proposal to the INTC Committee

New spectroscopy by two-neutron-pickup of neutron-rich nuclei.

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Summary

With a neutron-rich ^{10}Be target ($T_{1/2} = 1.6$ Ma) the two-neutron-pickup can efficiently be detected by the characteristic two-α decay of ^{8}Be ($T_{1/2}$=0.07 fs). Due to Q-value matching and enhanced pair transfer we expect rather large cross sections in the 5 mb range. At the Munich target laboratory ^{10}Be targets with about 100 μg/cm^2 of ^{10}Be (enrichment 61.4%) on a 40 μg/cm^2 carbon backing and a diameter of the ^{10}Be spotsize of 3 mm are produced. ^{10}Be decays via β^--decay with an endpoint energy of 0.56 MeV to the stable ground state of ^{10}B. The total pure β-activity of a target is about $3 \cdot 10^4$ Bq, much below the free handling level of 10^6 Bq [12]. We request **24 shifts of beam time** to study the two-neutron transfer ^{10}Be(^{A}Mg,$^{A+2}$Mg)^{8}Be for A=(24, 26), 29, 30 measuring the preferred transfer between nuclei of similar configurations. Starting from e.g. the spherical ^{30}Mg one will dominantly populate the excited spherical 0^+, 2^+-states in ^{32}Mg and much more weakly the deformed 2p-2h ground state.

1 Introduction and Motivation

The two-neutron-pickup opens up interesting spectroscopic features due to the reaction mechanism [1]. Transfers between states, which are obtained by adding the coupled spin 0^+ two-neutron cluster have a large coefficient of fractional parentage and a correspondingly large spectroscopic factor. The picture, that at the point of the pair transfer the shape of the incoming nucleus is preserved, appears to be a reasonable approximation. Here we want to follow a configuration in an isotopic chain, like that of the spherical 0^+ state in ^{32}Mg, where the ground state becomes a deformed 2p-2h intruder state.

The level scheme of ^{32}Mg is displayed in Fig. 1 together with theoretical predictions. Fig.1 shows the known ground state rotational band and the until now unobserved 0p-0h excited 0^+ state, predicted by theory for this island of inversion. Starting from the spherical ^{30}Mg we expect to populate predominantly the spherical 0^+-state in ^{32}Mg and not the ground state, which is strongly deformed. With selective population we achieve a better understanding of the potential landscape in these nuclei.

We want to discuss the reaction in two simple models: a collective model and a shell model. If one considers in a simple two-level model the two shapes with different quadrupole deformations, then the two eigenstates $|0_1^+>$ and $|0_2^+>$ are given by:

$$|0_1^+>= a|0_{sph}^+> -\sqrt{1-a^2}|0_{def}^+> \quad (1)$$

$$|0_2^+>= +\sqrt{1-a^2}|0_{sph}^+> +a|0_{def}^+> \quad (2)$$

with a mixing amplitude a. In the case of no mixing (a = 0) we will find only a transition to the spherical $|0_2^+>$-state. For weak mixing the population of the $|0_2^+>$ state allows to determine a^2. A similar treatment frequently is used for E0-transitions between $|0^+>$-states with different deformations [18].

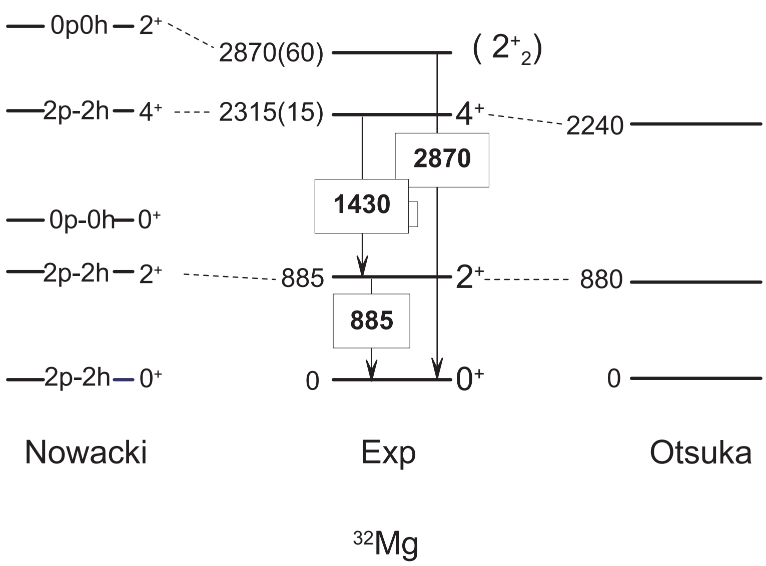

Figure 1: Experimental level scheme of ^{32}Mg together with theoretical predictions by F. Nowacki and T. Otsuka [11].

In a shell model picture we could transfer the neutron pair into the sd-shell: ^{30}Mg$\otimes$(sd)^2, which corresponds to a spherical 0p-0h configuration of ^{32}Mg. We could also transfer the neutron pair into the fp-shell:^{30}Mg$\otimes$(fp)^2, which corresponds to a spherical 2p-2h configuration of ^{32}Mg. If the pair transfer occurs into the (fp)-shell the system afterwards can develop into the superdeformed shape with an energy gain of about 3 MeV. Therefore we expect the population of highly excited 2p-2h configurations and only a weak population of the low-lying 2p-2h configurations. Probably there are higher order processes, where the excitation energy is dissipated in the transfer process and a weak population of these low-lying strongly deformed states occurs.

Certainly one also has to consider consecutive single-neutron transfer reactions interfering with the one-step process of two-neutron transfer, but this does not change the selectivity to transfer between similar nuclear shapes. In the one-neutron tranfer reactions also ^{30}Mg$\otimes$(sd)(fp) could be reached.

The same situation prevails for the two neutron transfer in neighbouring odd nuclei. Spherical single particle levels are populated and decay to the lower-lying deformed Nilsson orbitals. The odd ^{29}Mg is regarded as a spherical nucleus with a 1$d_{3/2}$ ground state and a close-lying 2$s_{1/2}$ first excited state. ^{31}Mg for its low-lying states has strong (fp)^2 intruder admixtures. For the $3/2^+$ ground state more than 50% of the deformed intruder (fp)^2 configuration are deduced [22]. This should be visible in the spectroscopic factors, where only the spherical components are projected out.

Experimentally the one neutron pickup of neutron-rich radioactive beams was investigated at REX-ISOLDE in a very sensitive way by using a ^{9}Be-target [2], where the two rather prompt α-particles of the ^{8}Be breakup give a very characteristic signature in the Si-strip detectors. Typical cross sections were 150 mb. We now extend this method to the two-neutron pickup by using ^{10}Be targets. For a correlated 2n-pair transfer we expect about a factor of ten smaller cross sections than for a one-neutron transfer for optimum Q-values [10]. Excited states, observed after the one-neutron pickup, show a yield which is about one order of magnitude larger when compared to Coulomb excitation of a primary beam with one neutron more, because the production of the primary, more neutron-rich beam drops by one order of magnitude. Correspondingly, with the two-neutron-pickup for neutron-rich nuclei we gain a factor of about ten. The study of the 2n-pickup for neutron-rich nuclei with a ^{10}Be-target not only is favourable due to the easy detection of the two α-particles but also due to the rather large cross sections for optimum Q-values and the enhanced pair-transfer. Due to the small two-neutron separation energy of ^{10}Be with 8.477 MeV many interesting 2n-transfer reactions can be studied far outside the valley of stability with good Q-value matching. The steepness of the valley of stability for light nuclei compared to the much more shallow valley of stability for heavy nuclei results in the fact that ^{10}Be, being only about two neutrons away from from the valley of stability, has a two neutron separation energy which is similar to that of ^{30}Mg.

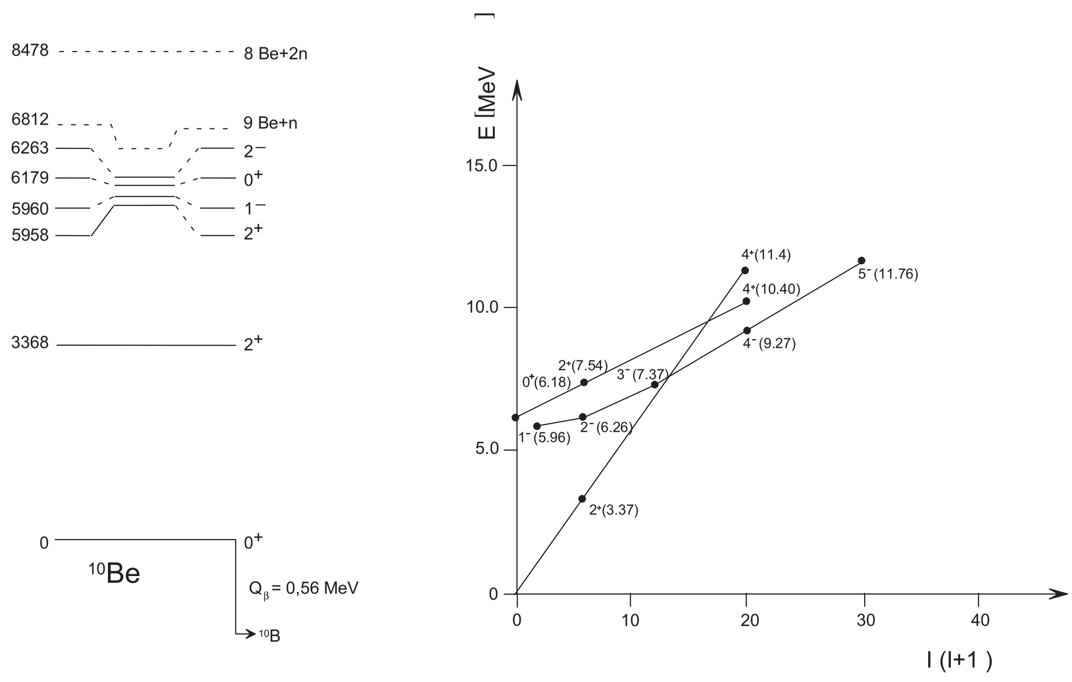

Figure 2: Level scheme of ^{10}Be und graph of rotational band energies as a function of I(I+1) with the spin I [10].

2 Two-neutron-transfer reactions with ^{10}Be

For the understanding of the spectroscopic factors of the two-neutron transfer it is useful to review the structure of ^{10}Be, ^{9}Be, and ^{8}Be.

Fig.2. shows the level scheme of ^{10}Be and the arrangement of the levels into bands. The 0^+ ground state of ^{10}Be and the first excited 2^+ state form a rotational band with a rather small moment of inertia and a rather compact configuration. The ^{9}Be $K^\pi=3/2^-$ ground state band and the ^{10}Be ground state band have very similar moments of inertia. The pick-up reaction ^{10}Be(d,t)^{9}Be shows a dominant excitation of the $3/2^-$ ground state of ^{9}Be [19]. In the **molecular orbit (MO) model** [21] the ^{9}Be ground state consists of an α-α core and one valence neutron in the $3/2^-_\pi$ orbit, while the ^{10}Be ground state has an additional valence neutron in the same $3/2^-_\pi$ orbit. ^{8}Be fits into this sequence of nuclear shapes because its ground state in the MO-model corresponds just to the chain of two α-particles. Therefore, the one and two neutron transfer reactions between the ground states of these nuclei have large spectroscopic factors.

The excited states of ^{10}Be at about 4 MeV can be grouped into rotational bands as shown in Fig.2. These states correspond to elongated shapes with a chain of two α-particles with the two neutrons forming the inbetween bond with a $(1/2^+_\sigma)^2$ configuration [21, 20]. These states are of no relevance for the 2n-transfer.

Next we consider the Q-values of the 2n-transfer reactions, which are well matched for Q-values close to zero MeV. Table 1 shows the Q-values for different reactions. The small S_{2n}-value of ^{10}Be with 8.477 MeV is well suited for matched transfer-reactions which occur for rather neutron-rich reaction partners. For the Mg-isotopes the S_{2n}-values drop down steeply with mass number A to 8 MeV and then level off. For the neutron-rich ^{32}Mg we have S_{2n}=8.06 MeV.

	projectile of reaction in inverse kinematics				
Reaction	^{24}Mg	^{26}Mg	^{28}Mg	^{30}Mg	^{32}Mg
^{9}Be-n	5665.	4778.	2049.	735.	41.
^{10}Be-2n	9946.	6469.	1532.	-418.	-1578.

Table 1: Ground state reaction Q-values in keV. An optimum matching of the transfer reaction occurs for Q_{opt} ~0 MeV with a Q-window of a few MeV.

A rough estimate of the 2n-transfer transfer cross sections can be obtained from the 1n-transfer cross sections and the transfer probabilities. The ^{10}Be $\rightarrow$ ^{9}Be and the ^{9}Be$\rightarrow$ ^{8}Be reactions have approximately the same spectroscopic factors [19] and integral transfer cross sections of about 150 mb. The total reaction cross section of ^{10}Be is about 1 b and the maximum 1n-transfer probability about 10%. We can estimate the integrated cross section of the two step process from two individual neutron transfers to be about (1-10) mb [1]. Since the single step 2n transfer should have a somewhat larger contribution 5 mb is a good estimate for the 2n transfer cross section. We will perform detailed calculations on the 2n-transfer with the coupled channel code FRESCO [23] describing the Be and Mg nuclei in a deformed shell model. We furthermore, will measure the 2n-transfer for stable ^{24,26}Mg-beams in Munich with the Q3D spectrograph and our ^{10}Be targets during a one week beamtime scheduled for October 2002. In this way we will get better estimates for the cross sections and for the selectivity of the reaction dynamics.

3 The radioactive neutron-rich ^{10}Be targets

The unique situation of these experiments is that a neutron-rich radioactive ^{10}Be target is used in combination with neutron-rich radioactive beams.

3.1 ^{10}Be-target production

Several groups [19, 7, 8] before have used ^{10}Be targets. E.g. Goosman from Ohio University produced such targets [6] where the ^{10}Be was obtained by the ^{13}C(n,α)^{10}Be reaction in a reactor subsequently removing the carbon by burning. The 200-600 μg cm^{-2} BeO targets were deposited onto a 1.2 mg cm^{-2} thick Pt backing foil. Targets with 5% enrichment of ^{10}Be [7] but also with 94% [8] were available.

The Munich ^{10}Be-targets, however, are produced on thin carbon backings. The target frames are produced in such a way that several targets can be stacked. At ORNL enriched ^{10}Be was produced by feeding a calutron-separator with Be containing 700 ppm of ^{10}Be, which was obtained by long-term neutron irradiation of the Be-moderator in the Materials Testing Reactor at ARCO, Idaho. We purchased 2 mg of this material in 1986 in the form of ^{10}Be(NO$_3$)$_2$ for approximately 14000.- \$. Because of its high thermal and chemical stability BeO is the most suitable compound for a ^{10}Be-target. In contrast to actinide nitrades Be(NO$_3$)$_2$ cannot be converted in situ into BeO during evaporation, because it is very volatile and partly sublimes in vacuum. Therefore the conversion was performed in air, heating $Be(NO_3)_2 \cdot$ x H_2O in a platinum crucible to 500^0C, until the conversion to BeO was completed. The targets [4] were produced with the standard micro-evaporation module [5], condensing a BeO-film of 3 mm diameter and $\sim$ 100 μg cm^{-2} thickness of Be onto a carbon backing of $\sim$ 40 μg cm^{-2} thickness. The ^{10}Be isotope enrichment was 61.4 %.

3.2 ^{10}Be-target safety concerns

Beryllium as a chemical element is known as a hazardous element. However, in the experiments with ^{10}Be targets much smaller amounts of Beryllium compared to former ^{9}Be-targets are used. Even when the material of a target would be totally evaporated within a volume of 1 liter of air it would not cause a health problem. When a target would get destroyed by the large air flow during a failue of the pumping system, the evaporated BeO film would still stay on fragments of the carbon backing and no dust of Be, which is the poisoneous form, would be produced.

The total radioactivity of a target of $3 \cdot 10^4$ Bq is below the allowed free level of 10^6 Bq for ^{10}Be as given in the guide lines of EURATOM [12].

4 Experimental setup, count rates and requested beam time

The most interesting case to be studied with the radioactive Mg-beams are those, where the ground state of the nucleus after the 2n-transfer has a different deformation than the target nucleus. This is the case for ^{32}Mg, but also for the neighbouring odd ^{31}Mg isotope. Here we want to study the decay of the spherical states by γ-rays to the lower lying deformed states with the MINIBALL, consisting of 24 six-fold segmented Ge-detectors. The 2n-transfer is detected with Si-strip detectors looking for the breakup α's of ^{8}Be. Since the target also contains a smaller fraction of ^{9}Be our former measurements on the 1n-transfer [2] can be used to correct for these contributions.

beam	ISOLDE (atoms/s)	REX-ISOLDE (ions/s)	photopeak counts/h	shifts
^{26}Mg	(stable)			
^{27}Mg	$4 \cdot 10^7$	$3 \cdot 10^6$	100	1
^{28}Mg				
^{29}Mg	$1.6 \cdot 10^6$	$1 \cdot 10^5$	4	9
^{30}Mg	$7 \cdot 10^5$	$5 \cdot 10^4$	2	14
total				**24**

Table 2: Counting rates and required shifts for runs with Mg beams

Typical cross sections of 5 mb and typical target thicknesses of 100-200 μg cm^{-2} result in reaction probabilities of about 10^{-7}. Assuming for the MINIBALL a γ-efficiency of 10% at 1 MeV, we require 10^{10} particles to collect 100 events in the full energy peak. Assuming a REX-ISOLDE efficiency of 7% for producing high energy beams from ISOLDE we require the following number of 8-hour-shifts for the Mg-experiment:

We request **a total of 24 shifts of radioactive Mg beam time using a UC_2 target and a laser ion or plasma ion source.**

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