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NUCLEAR STRUCTURE EXPERIMENTS WITH THE NEW EUROBALL-3 DETECTORS* **

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In a series of Coulomb excitation and transfer reaction experiments the newly developed CLUSTER detectors have been combined with the Darmstadt–Heidelberg Crystal Ball to a very powerful γ-spectrometer. An overview of four experiments performed at the UNILAC will be described. This includes spectroscopic studies of harmonic multi-phonon vibrations and investigations of the nuclear reaction mechanism in very heavy ion systems which are also used for the synthesis of superheavy elements.

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1. Introduction

A variety of fundamental nuclear structure problems could not be solved in the past due to the rather limited sensitivity of the available γ-spectrometers. To overcome this restriction the EUROBALL project has been initiated. In particular the granulated CLOVER detectors presently used in EUROGAM-2 and the newly developed CLUSTER detectors [1] for EUROBALL-3 [2] lead to a high total-absorption efficiency and prevent a deterioration of the good energy resolution by Doppler effects. For the GSI experiments we used a combination of the CLUSTER detectors with the Darmstadt–Heidelberg Crystal Ball [3]. This γ-spectrometer is a very powerful instrument for Coulomb excitation and nuclear reaction studies especially if very heavy ion beams are employed. The set-up and its capability is described in Section 2, while Section 3 and Section 4 are focussing on our experiments to study harmonic multi-phonon vibrations of the nuclear surface by Coulomb excitation. The investigation of the reaction mechanism

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in the system $^{238}U+^{181}Ta$ is discussed in Section 5. Finally an experiment for the synthesis of superheavy elements is included in Section 6. Some concluding remarks can be found in Section 7.

2. The Crystal Ball extended by EUROBALL Ge-detectors

The Crystal Ball — consisting of 162 individual NaI-detectors — can be combined with EUROBALL CLUSTER Ge-detectors by removing the first two rings of the NaI-crystals around the nominal beam entrance and filling the space by a ring of five Cluster detectors. This solution keeps the mechanical stability of the Crystal Ball and allows one to use a standard frame for the CLUSTER detectors. Each CLUSTER detector consists of 7 individual Ge crystals. By moving the CLUSTER ring as close as possible into the Crystal Ball a solid angle of $\Omega_{\rm CLU}$=0.12 was obtained, corresponding to a full energy efficiency of $P_{\rm ph} = 0.022$ at $E_\gamma = 1.33$ MeV (comparable to todays most powerful EUROBALL-1 arrays: GASP and EUROGAM-1). The active solid angle of the Crystal Ball is reduced to $\Omega_{\rm CB} = 0.86$, lowering the full energy efficiency to a still very reasonable value of $P_{\rm ph} = 0.60$. Since the gaps between CLUSTER detectors and NaI crystals are rather small the sum energy and multiplicity resolution is almost completely restored in the combined system.

An important feature of the set-up is that the energy resolution of the CLUSTER detectors is almost unaffected by Doppler broadening effects. Considering a velocity of the γ-ray emitting nuclei of $v/c = 0.1$, typical for Coulomb excitation using very heavy UNILAC beams, the energy resolution still remains $\triangle E/E \sim 2.7\times10^{-3}$. For these scattering experiments an array of position-sensitive parallel-plate avalance gas counters were installed in the Crystal Ball to measure the impact parameter and to correct for the Doppler shift.

3. Study of the 2-phonon octupole vibrational states in ^{208}Pb

For many years the doubly-magic nucleus ^{208}Pb has provided a crucial testing-ground for nuclear theories. In this connection the properties of the 2.615 MeV, $I^\pi = 3^-$ first excited state have played a vital role. This first excited state has been interpreted as the one-phonon vibration of octupole character. The collective nature of the 3^- level is inferred from the observed enhancement of 34 Weisskopf units over the single-particle value of the transition probability to the ground state. As a consequence of the phonon vibration character of the 3^- state, one expects a quadruplet of 2-phonon octupole states with spins and parities 0^+, 2^+, 4^+ and 6^+ at about twice the energy of the 1-phonon state, *i.e.* around 5.2 MeV. In many experiments over the last 40 years one has searched for this fundamental mode of nuclear excitation. A possible way to excite the 2-phonon octupole vibration is to use electromagnetic excitation with very heavy ions. In a recent paper [4] we have published the results of the experiment ^{208}Pb+^{208}Pb at 6.2 MeV/u. A new level at 5.683 MeV was observed which has been interpreted as one member of the 2-phonon octupole multiplet. A partial level scheme of ^{208}Pb showing the γ-transitions observed in that experiment is presented in Fig. 1. This state could only be observed with the best Ge detectors available at that time and at a bombarding energy which was 10% above the Coulomb barrier. Therefore the nuclear states were not only excited by the electromagnetic field but also by the nuclear potential which yields a substantial contribution to the total cross section.

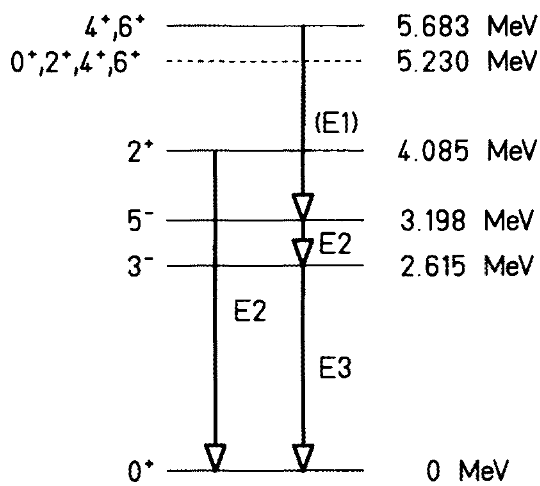

Fig. 1. Partial level scheme of ^{208}Pb. The dashed line corresponds to the harmonic vibrator limit of the 2-phonon octupole states.

The present experiment was performed at a bombarding energy of 5 MeV/u which is a safe energy for pure Coulomb excitation. The excitation probability of the 2-phonon states is one order of magnitude lower than in the previous experiment but this reduction was compensated by the higher photopeak efficiency of the CLUSTER detectors. For a target thickness of 1 mg/cm^2 and a beam current of about 1 pnA we expect a particle-γ coincidence rate of 54 counts/h for the observation of the 6^+ state.

4. Multi-phonon states in ^{232}Th

In deformed nuclei one usually observes a ground state rotational band and higher lying bands interpreted as being built on collective surface vibrations. These low-lying excited bands in even deformed nuclei are often referred to as β-vibrational and γ-vibrational states according to whether the K quantum numbers are 0 or 2. In addition to these quadrupole vibrations, octupole vibrations are observed. Although rotational bands built on 1-phonon surface vibrations were found in many deformed nuclei, there are only two nuclei — ^{168}Er [5] and ^{232}Th [6] - known, which can be unambiguously ascribed to a harmonic 2-phonon vibration.

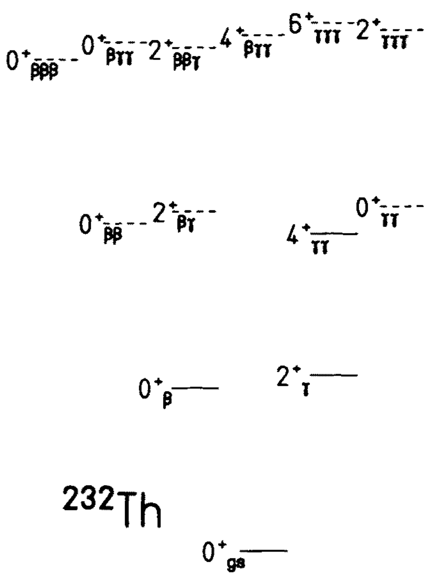

Fig. 2. Partial level scheme of ^{232}Th (solid lines). The dashed lines correspond to predicted surface vibrations with up to three quadrupole phonons.

In two experiments [6, 7] at the Crystal Ball it was possible to identify one member of the 2-phonon quadrupole γ-vibration in ^{232}Th shown in Fig. 2, namely the $K^{\pi}=4^+$, $\gamma\gamma$-vibrational band. The decay of this state could also be observed in a Coulomb excitation experiment with a ^{58}Ni beam which was performed with the GaSp spectrometer [8]. In contrast to the previous measurements the gated angular distributions are well described by E1 transitions. Therefore, the band head at 1.4 MeV is interpreted as the missing $K = 3$ octupole band, which can only decay into the $K = 2$ γ-vibrational band while the decay into the ground state band is forbidden. In order to clarify this discrepancy and to search for the multi-phonon quadrupole vibrational states in ^{232}Th a Coulomb excitation experiment was performed with a ^{208}Pb beam at an incident energy of 5.3 MeV/u.

5. Spectroscopy and reaction mechanism of the system $^{238}U+^{181}Ta$ in the vicinity of the Coulomb barrier

As an extension of our systematic spectroscopic studies in ^{238}U [9, 10] performed at GSI an investigation of the reaction mechanism of the system $^{238}U+^{181}Ta$ was performed. During the last years, several groups have investigated one and two-neutron transfer by bombarding different lanthanide and actinide targets with projectiles ranging from ^{58}Ni to ^{208}Pb. Employing sophisticated particle-γ coincidence techniques the reaction products and the population of the final states could be identified by characteristic γ-rays.

The most important parameter in these heavy ion reactions is the distance of closest approach. This quantity governs the elastic and inelastic scattering as well as the transfer reactions. In order to summarize our previous results: $> 50\%$ of the total reaction cross section appears in transfer channels. These transfer products are formed with very low excitation energies which result in a high survival probability against fission. Especially in the actinide region transfer may be used as a tool to study high spin states in unstable nuclei.

The aim of the present experiment was the investigation of the inelastic scattering, the identification of the transfer products and the measurement of the excitation energy of the reaction products. The scattering system $^{238}U+^{181}Ta$ was chosen because the decay properties of the expected transfer products may be important for the e^+e^- experiment performed for the same system and beam energy. It is the first experiment between two deformed nuclei for which the inelastic scattering are measured. Fig. 3 shows two representative γ-spectra Doppler-shift corrected for the U-projectile (top) and for the Ta-target nucleus (bottom). From these data the nuclear potential will be determined which also governs the correlated transfer reactions.

6. Synthesis of superheavy nuclei

Elements up to $Z = 112$ were synthesized and identified in experiments at SHIP using ^{208}Pb or ^{209}Bi targets [11–13]. In all investigated reactions the largest cross sections were measured "below the barrier" which has been calculated according to Bass [14]. The energy relations determining the barrier are drawn in Fig. 4 in case of the reaction $^{64}Ni + ^{208}Pb$. All three measured cross sections were observed at energies well below the Bass barrier. A tunneling process through this barrier cannot explain the measured cross sections.

The conclusion is that additional effects — like the transfer of a few nucleons — must allow for fusion. Already after the transfer of 2 protons

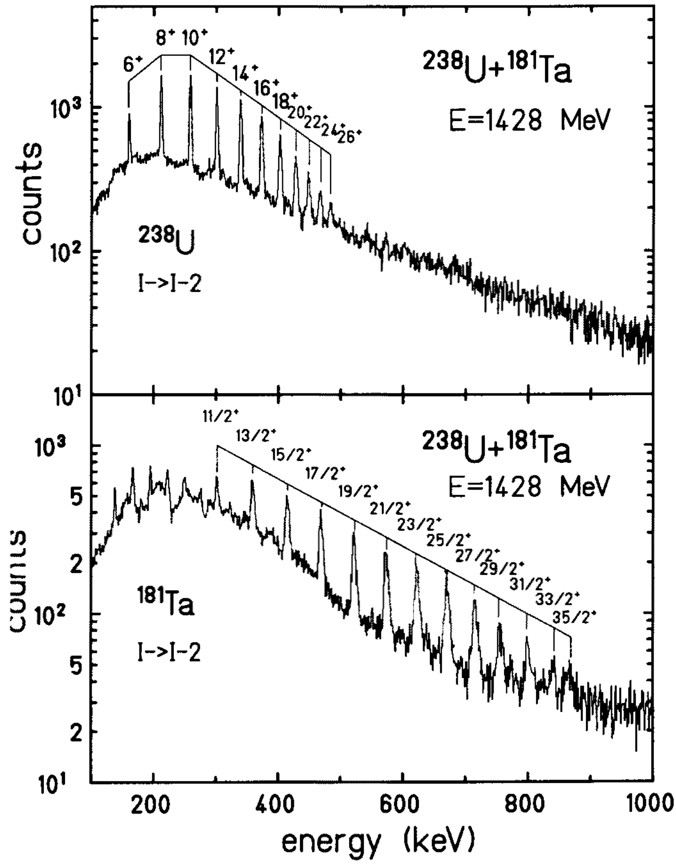

Fig. 3. γ-ray spectra obtained from the measurement of the system ^{238}U+^{181}Ta at a bombarding energy of 1428 MeV. The same raw data have been Doppler-corrected for the excitation of the U-projectile (top) and for the excitation of the Ta-target nucleus (bottom).

from ^{64}Ni to ^{208}Pb the Coulomb barrier is decreased by 14 MeV allowing to keep the reaction partners in close contact and to continue fusion initiated by transfer. Important factors, which determine the cross section at the very beginning of the fusion process, are: the probability for a head-on collision and the probability to transfer a first pair of protons in competition to reseparation.

These first steps of the fusion process at low bombarding energies can be investigated experimentally by observation of transfer products. Therefore, the results of our performed ^{208}Pb + ^{64}Ni experiment should yield infor-

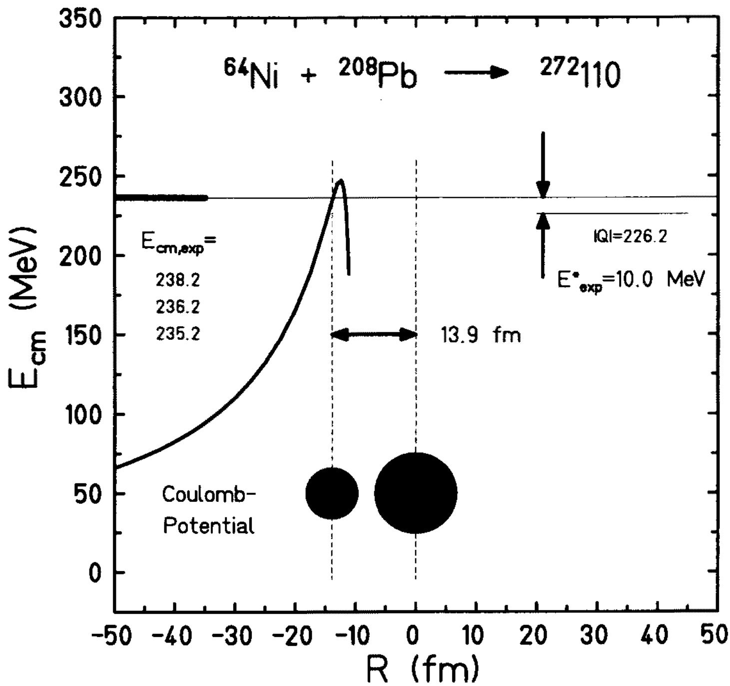

Fig. 4. Energy relations determining the barrier for the reaction $^{64}Ni+^{208}Pb \rightarrow$ $^{272}110^*$ [15].

mation, if "fusion initiated by transfer" is an essential part of the process. The transfer products will be identified with the Ge detectors while the excitation energy will be measured with the Crystal Ball.

A completely different situation shows the bombardment of ^{40}Ca by ^{238}U which has also been studied. The ^{238}U projectile is deformed and, at barrier energies, only a fraction at certain orientation will lead to fusion. The Q-value allows for minimum excitation energies of $\sim$ 35 MeV only. A number of 3 or 4 neutrons needs to be evaporated, a process that is accompanied with high probability by fission. Nevertheless, recent results in Dubna have shown that element 110 could be produced with a ^{244}Pu target and after the evaporation of 5 neutrons [16]. It seems that the production of heavy and superheavy elements covers a broad range of phenomena from well-ordered microscopically-determined systems to processes governed by statistical disorder.

7. Concluding remarks

The unique properties of the new γ-ray spectrometer — a combination of the Crystal Ball with five Cluster Ge-detectors — were successfully used to perform various nuclear spectroscopy and reaction studies. Using Pb- and U-ions uniquely provided by the UNILAC accelerator the evidence for a two-phonon octupole state in ^{208}Pb may be consolidated by a determination of its spin and its B(E3)-value as well as by the possible observation of other members of the two-phonon octupole quadruplet. Two and three phonon vibrational states in deformed nuclei are also likely to be detected via Coulomb excitation. The same set-up was used for investigations of nucleon-nucleon correlations at high angular momentum in transfer reactions.

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