The dipole response of proton-rich nuclei
Pygmy and Giant Resonances in ^{32}Ar and ^{34}Ar

Spokesperson: K. Boretzky (GSI)

Collaboration:

F. Aksouh[1], Y. Aksyutina[1], T. Aumann[1], K. Boretzky[1], A. Chatillon[1], L. Chulkov[1], H. Emling[1], H.Geissel[1], G. Ickert[1], H. Johansson[1], B. Jonson[5], A. Kelic[1], O. Kiselev[2], A. Klimkiewicz[4,] J.V. Kratz[2], R. Kulessa[4], T. Le Bleis[1], K. Mahata[1], C. Müntz[3], T. Nilsson[5], C. Nociforo[1], G. Nyman[5], D. Rossi[2], H. Simon[1], J. Stroth[3], K. Sümmerer[1], H. Weick[1], W. Walus[4], C. Wimmer[3]

1) GSI Darmstadt
2) Univ. Mainz (Germany)
3) Univ. Frankfurt (Germany)
4) Univ. Krakow (Poland)
5) Univ. Göteborg (Sweden)

Abstract. *We propose to search for proton dipole pygmy resonances in nuclei near the proton drip line. Experimental evidence only exists for neutron pygmy resonances, but calculations infer the occurrence of proton pygmy resonances in proton-rich nuclei in the mass region A = 30 – 50. According to recent RQRPA calculations, low-lying E1 transitions, well below the giant dipole resonance, reveal the dynamics of excess protons oscillating versus the core. The experiment uses Coulomb projectile excitation of secondary* ^{32}*Ar and* ^{34}*Ar beams of 700 MeV/u energy from the FRS in-flight separator and the upgraded LAND reaction setup in Cave C. In total, 10 days of beam time are requested.*

1. Physics background

The occurrence of the pygmy dipole resonances, pictured as the resonant dipole oscillation of a neutron or proton skin against the isospin-symmetric proton-neutron core in exotic nuclei is currently much under debate and subject to theoretical and experimental investigations. In fact, the onset of low-lying E1 strength assigned to a neutron pygmy resonance was already observed in stable nuclei, ^{44,48}Ca, ^{208}Pb [Rye-02][End-03][Har-04], and some N=82 isotones [Zil-01], all of which exhibit an only moderate neutron excess. As far as unstable nuclei of large neutron excess are concerned, the LAND collaboration observed a sizeable fraction of low-lying E1 strength in ^{20,22}O [Lei-01] and, very recently, in ^{130,132}Sn [Adr-05] isotopes. In general, microscopic calculations conclude that in lighter neutron-rich nuclei the low-lying dipole strength is not collective, but arises from single-neutron excitations. In contrast, the low-lying dipole states in (medium-) heavy neutron-rich nuclei such as ^{130,132}Sn display to some extent the features of a neutron pygmy resonance [Par-03][Par-05a].

One of the main questions behind studies of neutron skins and, in turn, of skin vibrations such as the dipole pygmy mode is that of the density dependence of the symmetry energy. The density dependence of the symmetry energy is strongly correlated to the skin thickness in heavy nuclei. The slope of the symmetry energy, for instance, was shown to be directly related with the neutron radius in heavy nuclei [Bro-00]. Measurements of neutron radii and thus of skin thicknesses with sufficient precision, however, are presently not available. But recently, it was shown by Piekarewicz [Pie-06] that data on the strength of the pygmy resonance can constrain the density dependence of the symmetry energy: From the pygmy strength observed in our experiment for ^{130,132}Sn [Adr-05], Piekarewicz concluded that an overly stiff symmetry energy can be discarded.

Turning to proton-rich nuclei, at a first glance, the circumstances for the evolution of low-lying dipole strength and proton pygmy resonance appear less favorable. The proton drip line is much closer to the line of β stability than the neutron drip line, and bound nuclei with an excess of protons over neutrons are found only for nuclei with $Z < 50$. In addition, because of the presence of the Coulomb barrier, nuclei close to the proton drip line generally do not exhibit a pronounced proton skin, except for very light elements. Since in light nuclei, the multipole response is less collective, all these effects seem to preclude the formation of proton pygmy states. Nevertheless, in a recent publication [Par-05b], Paar, Vretenar and Ring showed that according to their calculations, a proton pygmy resonance should clearly evolve in nuclei of mass numbers A = 30 – 50 if located close to the proton drip line. For example, a pronounced proton pygmy resonance is observed in their calculation for the two even isotopes ^{44}Cr and ^{46}Fe right at the proton drip line, both, however, out of experimental reach. They performed also calculations for the chain of even-even proton-rich Ar isotopes, see Figs. 1 and 2. Starting from the lightest isotopes, a proton pygmy resonance is revealed in the calculation up to the ^{32}Ar isotope, for ^{34}Ar the pygmy strength drops sharply and vanishes for the N=Z nucleus ^{36}Ar and the heavier isotopes. For the case of ^{32}Ar, Fig. 2 illustrates that the low-lying states at excitation energies between 8 to 10 MeV indeed exhibit the expected characteristics of a vibrating proton skin. As seen from the transition densities, protons and neutrons in the nuclear interior vibrate in phase while only protons contribute to the transition density at the nuclear surface. The corresponding distributions in the contributing unperturbed2qp

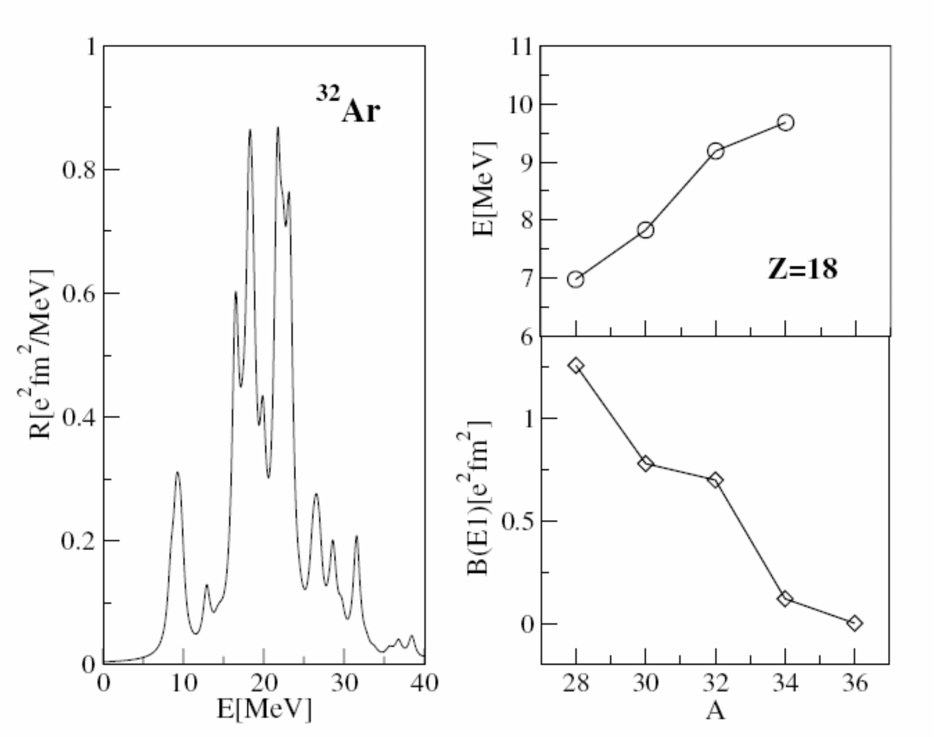

Fig.1: *The isovector dipole strength distribution in ^{32}Ar, calculated in the framework of RHB and RQRPA (left panel). In the right panel the mass dependence of the pygmy peak and the corresponding integrated dipole strength below 10 MeV are shown. From [Paa-05b].*

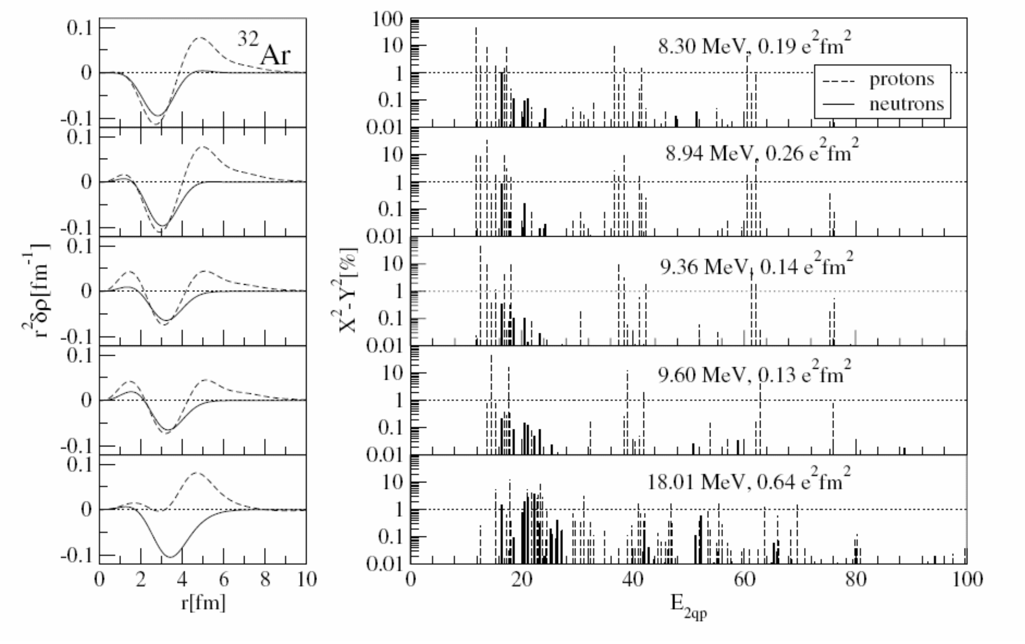

Fig. 2: *Proton and neutron transition densities (left panel) and RQRPA amplitudes as a function of the unperturbed energies of 2qp configurations (right panel) for selected 1^- states [Paa-05b]. The lowest panel is for that a state in the giant dipole regime at 18.01 MeV, the upper panels for states in the energy regime of the pygmy resonance (8.3 – 9.6 MeV).*

states reflects the fact that the low-lying states in the pygmy domain gain strength, i.e., are of collective nature, and are down shifted. For comparison, Fig. 2 shows also one of the prominent states in the giant dipole resonance energy domain.

^{32}Ar is the lightest known even Ar isotope, discovered in 1977 [Hag-77]. Its half life of $\tau_{1/2}$=98 ±2 ms and its Gamow-Teller beta decay properties were investigated with high resolution [Bjö-85]. ^{32}Ar plays an important role in the search for scalar weak interactions in $0^+ \rightarrow 0^+$ decays [Ade-99][Bor-89]. A Coulomb excitation experiment at intermediate energies on ^{32}Ar determined the strength for the transition to the first excited 2^+ state [Cot-02] and a precise mass measurement was carried out using ISOLTRAP [Bla-03], serving as a test of the isobaric-multiplet mass equation. From a measurement of the interaction cross section together with results on the optical isotope shifts, a proton-skin thickness of ΔR=0.362±0.221 fm was deduced for ^{32}Ar (see [Oza-02] and ref. therein). For ^{34}Ar ($\tau_{1/2}$=845 ms) a value of ΔR=0.132±0.086 fm was derived. Recently further studies of the ground state properties, the occupancy of the $0d_{5/2}$ neutron state in ^{32}Ar have been performed [Gad-04]. In this paper we propose to study the dipole response of ^{32}Ar over a wide range of excitation energies, covering the region of the predicted pygmy resonance and the giant dipole resonance.

2. The Experiment

A. Proposal

We propose a measurement of the E1 strength distribution in the most neutron-deficient even Argon isotope ^{32}Ar and the neighboring ^{34}Ar isotope. According to the calculation discussed above, ^{32}Ar should show a developed proton pygmy resonance, while for ^{34}Ar, the resonance strength drops drastically. The E1 distribution is obtained from Coulomb projectile excitation at relativistic energies, a method well established both in applications with stable [Bor-03] and unstable secondary [Lei-01][Adr-05] beams. The excitation energy distribution is obtained from the invariant mass including all decay products of the excited projectile.

In order to scan the E1 distribution up to the domain of the giant resonance, beam energies of more than 500 MeV per nucleon are required because of the adiabatic cut-off in Coulomb excitation. GSI is the only laboratory that provides secondary beams of unstable nuclei at such high energy.

The ^{32,34}Ar beams can be produced with sufficient intensity from a primary ^{40}Ca beam at the GSI in-flight separator FRS, the experiment will be performed at the LAND setup in Cave C.

Since the proton separation thresholds (S_p) are much lower than the neutron separation thresholds (S_n), for example S_p = 2.4 MeV and S_n = 21.5 MeV in case of ^{32}Ar, the pygmy resonance decays by proton emission; this is also true for the most part of the Giant dipole resonance centered at an excitation energy of 20 MeV.

The LAND apparatus thus needs to be equipped with a detector system for the proton ejectiles. Two large drift chambers are presently constructed by a laboratory in St. Petersburg and will be delivered during May of this year. The chambers will be tested and be used in first experiments in 2006 and should thus be available early in 2007 for the experiment proposed here.

The primary ^{40}Ca beam will be used as a pilot beam through the FRS to Cave C and serves for a number of detector calibrations. We intend, moreover, to measure the Coulomb excitation of ^{40}Ca from which the photo-absorption cross sections (γ,p) and (γ,2p) can be deduced, which by comparison to cross sections known from absorption of real photons [Bra-74] facilitates an independent and very direct proof of the experimental method.

B. Secondary Beam Production

The secondary beam is produced by fragmentation of a ^{40}Ca primary beam in a Be target. A primary-beam intensity of 1×10^{10} ions per spill is required (800 MeV/u, slow-extraction mode) and should be achieved at the SIS18 by means of multi-multi-turn injection. The production cross section of 0.8 μb for ^{32}Ar was estimated using the EPAXII formula [Sue-00] and the yield on the secondary target was estimated by the Monte-Carlo code MOCADI [Sch-94][Sch-96][Iwa-97], including the beam transport through the FRS and the beam-line to Cave C. The expected average ^{32}Ar beam intensity on the secondary target amounts to about 40 ions/sec. A production cross section for ^{34}Ar of 0.4 mb is predicted from EPAXII, a rate of 2×10^4 ions/sec on the secondary target is expected.

C. Experimental Method

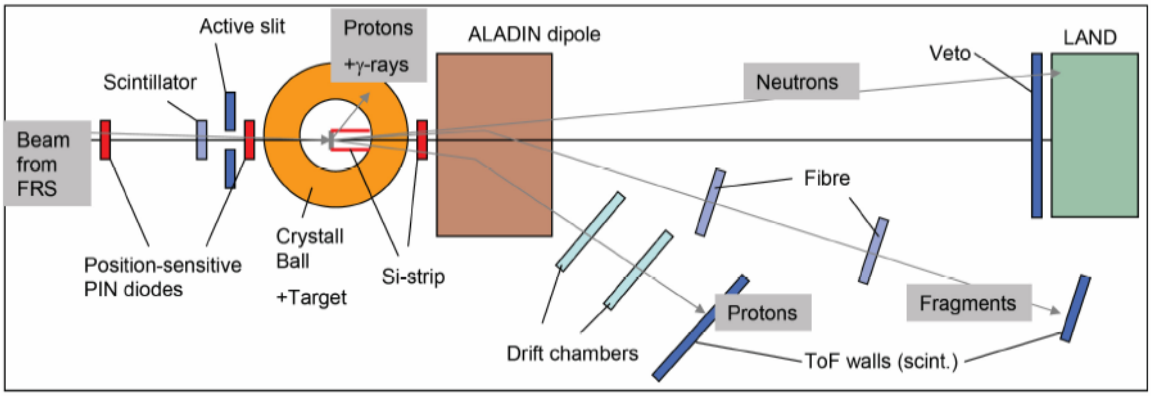

Fig.3: Schematic view of the experimental setup. For details see the text below.

The experiment will be carried out in Cave C, using the improved LAND reaction setup, shown schematically in fig 3. Since, in contrast to our earlier measurements of the dipole-strength evolution in neutron-rich nuclei, the deexcitation is dominated by proton emission, the setup will be completed by two types of detectors serving to measure projectile-like protons. These are two large drift chambers placed behind the ALADIN magnet, and Si-strip detectors in front of the magnet. The tracking of the protons through the dipole field allows the determination of their momenta. The reconstruction of the excitation energy using the invariant mass technique on an event-by-event basis relies on the identification and measurement of the momenta of all decay products after the reaction in the target. Moreover, since the experiment will be carried out using a mixed secondary beam delivered from the FRS, the incoming beam particles have to be identified and their momenta need to be determined. The latter is accomplished by means of energy-loss and position measurements with position-sensitive pin diodes, a time-of-flight (ToF) measurement over the large distance between the FRS and Cave C, and from the magnetic rigidity determined at the FRS. The heavy fragments emerging after dissociation in the target are identified and momentum analyzed using Si-strip detectors placed between the target and the ALADIN magnet, and using scintillating fibre arrays (0.5×0.5 m^2, 1mm resolution in the dispersive plane) and a two-layer ToF wall of the same size consisting of 16 position sensitive organic scintillator paddles. Based on the experience from previous experiments at LAND, we expect resolutions of $\sigma_Z = 0.2$ and $\sigma_A = 0.3$ for the charge and mass number of the projectile fragment, and the reaction channel is thus uniquely determined. Protons from the decay of ^{40}Ca and Ar isotopes will be detected with large solid-angle coverage in the forward direction. The gap size of the dipole allows coverage of about ±70 mrad for protons and neutrons in one dimension, and more than ±100 mrad in the second dimension.

Two position measurements in front (target position, Si-strip approx. 0.1 m behind the target) and two position measurements behind the magnetic field (two drift chambers, 0.8×1 m^2) allow the determination of the magnetic rigidity and the momenta of protons stemming from the decay of the ^{40}Ca and Ar projectiles. Finally, time-of-flight and energy-loss information is obtained from a plastic-scintillator wall (1.8×1.4 m^2) consisting of 32 position-sensitive organic scintillator paddles which also serves for identification. The transverse momenta are obtained from the position in the Si-strip detectors, the longitudinal component from the ToF measurement. In addition, the total momentum is measured by the tracking through the dipole field. A momentum resolution of $\Delta p/p \approx 2\times10^{-3}$ is expected.

The Crystal Ball detector, surrounding the target, will serve to detect the γ-rays emitted from the projectile. Although neutrons are not very important for the present experiment, they are detected in LAND. In summary, a kinematically complete measurement of the relevant reaction channels is foreseen, with resolutions for the excitation energy of about 500 keV in the region of the PDR and 2 MeV in the GDR region.

The measurement on the stable ^{40}Ca serves to prove the validity of the experimental method, since for this nucleus, proton decay data from real photoabsorption measurements are available [Bra-74].

D. Beam Time Request

The proposed experiment requires three different beams with energies of 700 AMeV: ^{40}Ca primary beam, ^{34}Ar and ^{32}Ar delivered from FRS as secondary beams, using the fragmentation of ^{40}Ca in a Be production target. In order to determine the dipole response for ^{32,34}Ar, measurements with Pb (500 mg/cm$^{2)}$ and C (250 mg/cm^2) targets and a measurement without an inserted target (background contributions) are needed. The electromagnetic cross section measurement is performed using the Pb target, while the C target serves to investigate the contributions due to nuclear interaction (for details see [Bor-03]). In total, we ask for 10 days of beamtime, which subdivides as follows: 2 days with primary ^{40}Ca beam for the setting of detectors, electronics, and the necessary calibration measurements at the FRS and Cave C, and for the control experiment of ^{40}Ca Coulomb excitation. 1 day is needed for the measurement of the dipole strength distributions in the secondary beam ^{34}Ar. 7 days are devoted to the measurement of the proton-rich isotope ^{32}Ar. In a 3,5 days measurement on Pb target with 40 ions per second, we expect to detect about 500 events in the energy region of the predicted pygmy resonance, assuming a cross section of 100 mb at 9 MeV excitation energy. For the GDR region at 20 MeV, we expect about 1500 events. For the measurement with the C target and without inserted target another 3,5 days are foreseen in total.

Beam	Purpose	Time [shifts]
^{40}Ca	settings, calibrations	3
^{40}Ca	dipole response (Pb and C target, background determination)	3
^{34}Ar	dipole response (Pb and C target, background determination)	3
^{32}Ar	dipole response (Pb target)	11
^{32}Ar	dipole response (C target, background determination)	10
	total	**30**

We would like to perform the experiment in the beginning of 2007 in a series of experiments using exactly the same setup, namely S233 (Coulomb Dissociation of ^{23}Al), S296 (Quasifree Hadronic Scattering Studies of Exotic Nuclei) and S318 (Study of the Borromean Dripline Nucleus ^{17}Ne).

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