EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Single-proton-hole orbitals in the N=126 nucleus ^{205}Au

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Abstract: Single-proton states in the N=126 closed neutron shell nucleus ^{205}Au will be identified via the (t,^{4}He) reaction in inverse kinematics at the ISOLDE Solenoid Spectrometer. Excited states dominated by a proton-hole in the $s_{1/2}$, $d_{5/2}$ and $g_{7/2}$ orbitals and their spectroscopic factors will be established. The understanding of the evolution of proton states in neutron-rich N=126 nuclei is key for the prediction of the properties of the r-process path nuclei.

Summary of requested shifts: 16 shifts (15 shifts measurement + 1 shift tuning and debugging)

Physics case

Information gained on neutron-rich N~126 nuclei is essential for the understanding of nuclear structure in heavy nuclei. Studies around doubly magic systems allow direct tests of the purity of shell model wave functions. From a longer-term perspective, experiments in this region pave the way toward the understanding of the nuclear-astrophysical *r*-process waiting point nuclei along the N = 126 shell closure.

The most neutron rich N=126 nuclei for which basic observables such as the ground-state lifetime and mass were determined are ^{204}Pt (Z=78) [Morales2014] and ^{206}Hg (Z=80) [Chen2009], respectively (the mass of ^{205}Au, for its ground-state and long lived isomer was also measured by the SuperFRS collaboration, presented at conferences, but not published yet). Therefore information on features which determine these values, single-particle energies and nucleon-nucleon interactions are crucial in order to increase the predictive power of nuclear theories. Nuclear structure information, like excited state energies, gamma-ray transition energies and transition strength are known “down” to ^{203}Ir (Z=77) [Steer2011]. Single proton-hole energies, which are basic inputs into the shell model calculations, were identified in Z=81 ^{207}Tl. In the next odd-mass N=126 nucleus, ^{205}Au, only the $d_{3/2}$ dominated $3/2^-$ ground-state and the $h_{11/2}$ dominated $11/2^-$ long-lived isomeric states are known [Podolyak2009], and also several three-proton states [Podolyak2009a].

The recent pioneering experiment with the Isolde Solenoidal Spectrometer (ISS) used a radioactive ^{206}Hg beam impinging on a deuterium target. Excited states in ^{207}Hg were populated via the (d,p) reaction and the properties (energies and spectroscopic factors) of the single-neutron states $g_{9/2}$, $d_{5/2}$, $s_{1/2}$, $d_{3/2}$ and $g_{7/2}$ have been determined [Tang2020]. We suggest a continuation of the study of the heavy neutron-rich region using heavy ^{206}Hg mercury beam, this time to identify proton-hole states.

Single-proton states will be studied in the semi-magic ^{205}Au nucleus populated in (t,^{4}He) reaction. At ISS we aim to identify the $s_{1/2}$, $d_{5/2}$ and $g_{7/2}$ proton-hole dominated states. We note that already in ^{206}Hg there is already a discrepancy between shell-model calculations and experiment. Both the extracted $B(E2;2^+\text{->}0^+)$ value from Coulomb excitation at ISOLDE [Morrison2023] and the B(E3;5- ->2+) [Steer2008] from isomer spectroscopy at GSI suggest that the wave function of the 2^+ state in this two-proton hole nucleus is not well understood.

The shell model was employed to predict the states dominated by single-particle proton-hole configurations. The hole-hole TBMEs are extracted with the Kuo-Herling interaction [Herling1972], adjusted as in Ref. [Warburton1991]. The single-hole energies are from the experimental level schemes of ^{207}Tl (for protons) and ^{207}Pb (for neutrons), as shown in Fig. 1 of [Warburton1991]. The presented parametrization describes very well the known excited level schemes in N=126 nuclei: ^{206}Hg, ^{205}Au, ^{204}Pt and ^{203}Ir [Steer2008,Steer2011,Podolyak2009,Podolyak2009a], and reasonably well the N<126 nuclei [Steer2011]. The level scheme of ^{205}Au as predicted by the shell model is shown on figure 1.

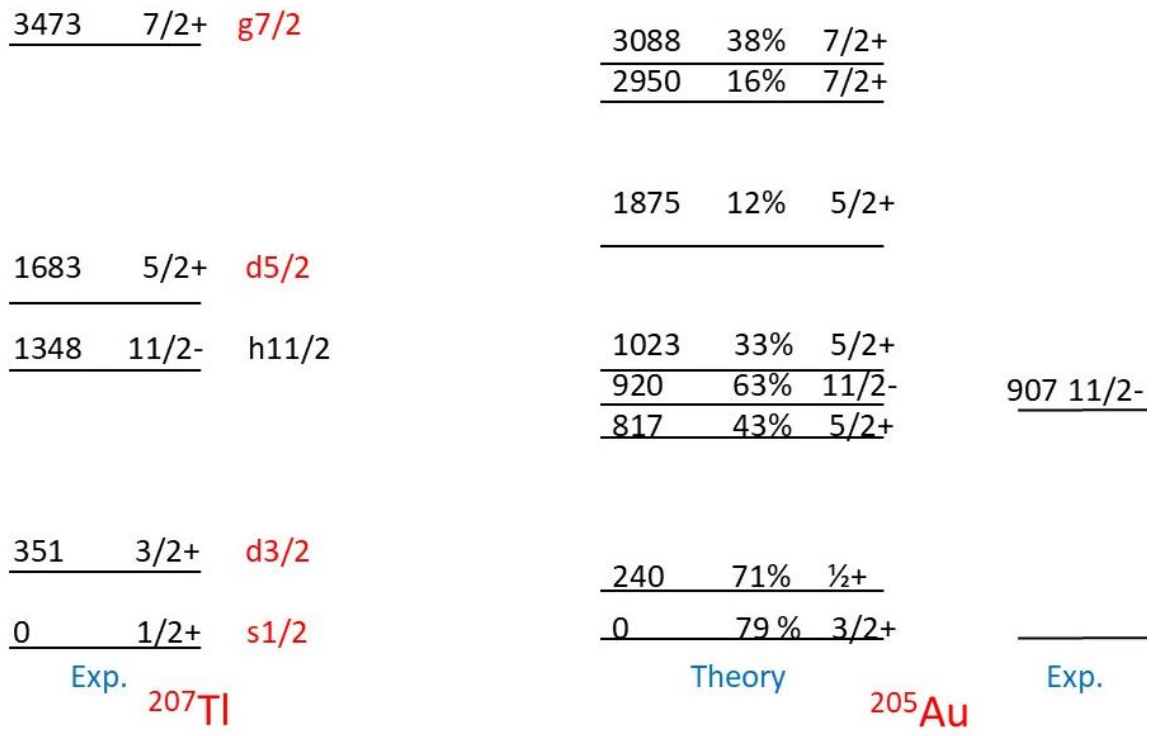

Fig.1. *(left)* The hole-proton states in the Z=81 ^{207}Tl nucleus. *(middle)* Predicted level scheme of ^{205}Au showing the states dominated by single-proton configurations. The contribution of the single-proton orbitals to the wave functions are indicated. *(right)* The corresponding experimental scheme of ^{205}Au [Podolyak2009].

Experimental details

The ^{206}Hg radioactive beam will be produced by protons impinging on a molten lead target. The produced cocktail of isotopes will be laser ionised (VADLIS mode), mass separated, then charge bred in an electron-beam ion source (REX-EBIS). ^{206}Hg nuclei with a charge state of 46^+ will post-accelerated using the HIE-ISOLDE linear accelerator to an energy of 7.5 MeV/u, with the expected repetition rate of ~2-3 Hz. The expected ^{206}Hg beam intensity is 5x10^5 pps. This ^{206}Hg intensity was already achieved in two previous experiments at HIE-ISOLDE [Tang2020, Morrison2023].

The ^{206}Hg beam will impinge on a triton loaded titanium target. The atomic ratio of 1:1 of tritium to titanium ions corresponds to an effective target thickness of 0.03 mg/cm^2 of tritium. We note that a similar tritium target (40 μg/cm^2 ^{3}H on a ^{3}H/Ti target) was used at ISOLDE before [Wimmer2010] and there is an approved tritium target experiment at ISS using Xe beams [Wimmer2021].

Alpha particles form the (t,^{4}He) reaction will be detected by the Isolde Solenoid Spectrometer (ISS), with the Si detectors placed at forward angles.

The cross sections of the ^{206}Hg(t,^{4}He) reaction were calculated, considering the level scheme of figure 1. The predictions are shown in figure 2. The ^{206}Hg(t,d)^{207}Hg contaminant reaction is expected to have similar cross section. This, based on the experimental excited-state energies and their spectroscopic factors [Tang2020] is shown in the lower part of figure 2. Both deuterons and alpha particles are emitted in forward angle in the laboratory, with overlapping energies, therefore one cannot distinguish between them (not even time-of-flight measurement would help).

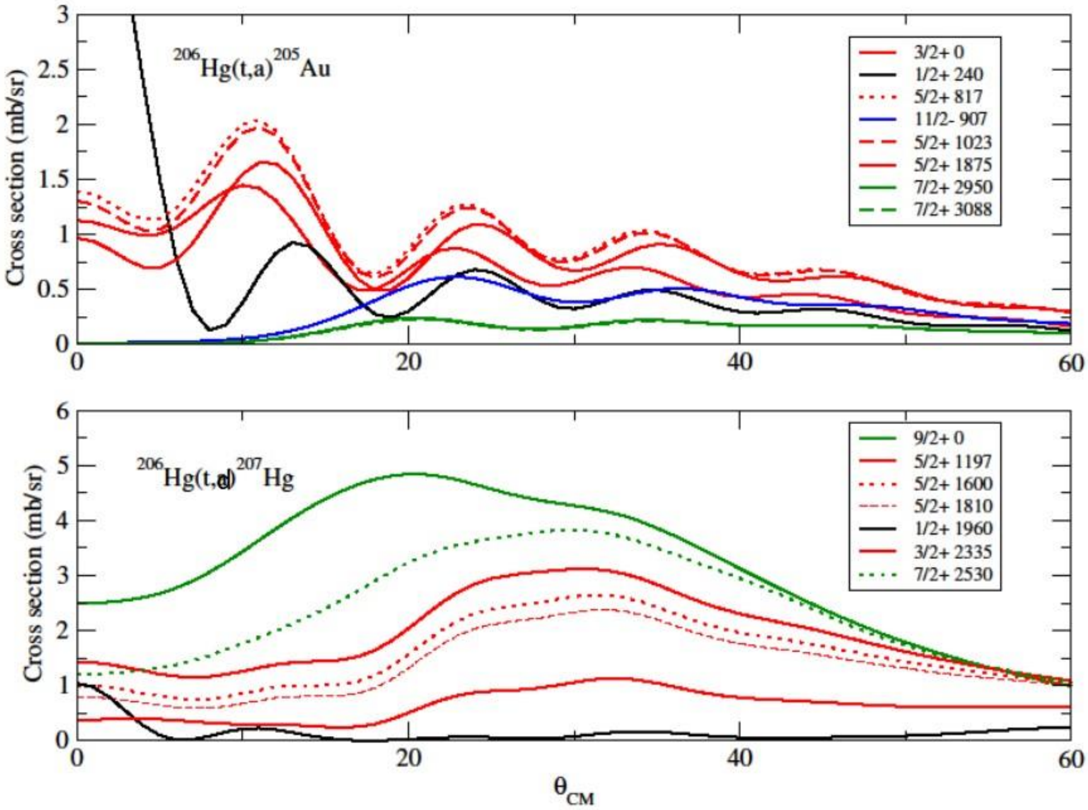

Fig.2. Predicted cross sections for the (t,^{4}He)^{205}Au reaction of interest, together with the competing (t,d)^{207}Hg reaction.

A full simulation was run to access the yields, and the effect of the contaminant reaction. The integrated cross-sections of figure 2 were used, taking in to account the angular coverage and efficiency of the silicon array (510 mm long active area with a 66.7% coverage in (θ,φ)).

The charged particle energy E_{lab} vs position on the Z axis was simulated using the ISS Simulation package in NPTool. This accounts for the angular distributions and energy losses of the reaction products and gives realistic expectations of the obtained spectra. This is shown in figure 3.

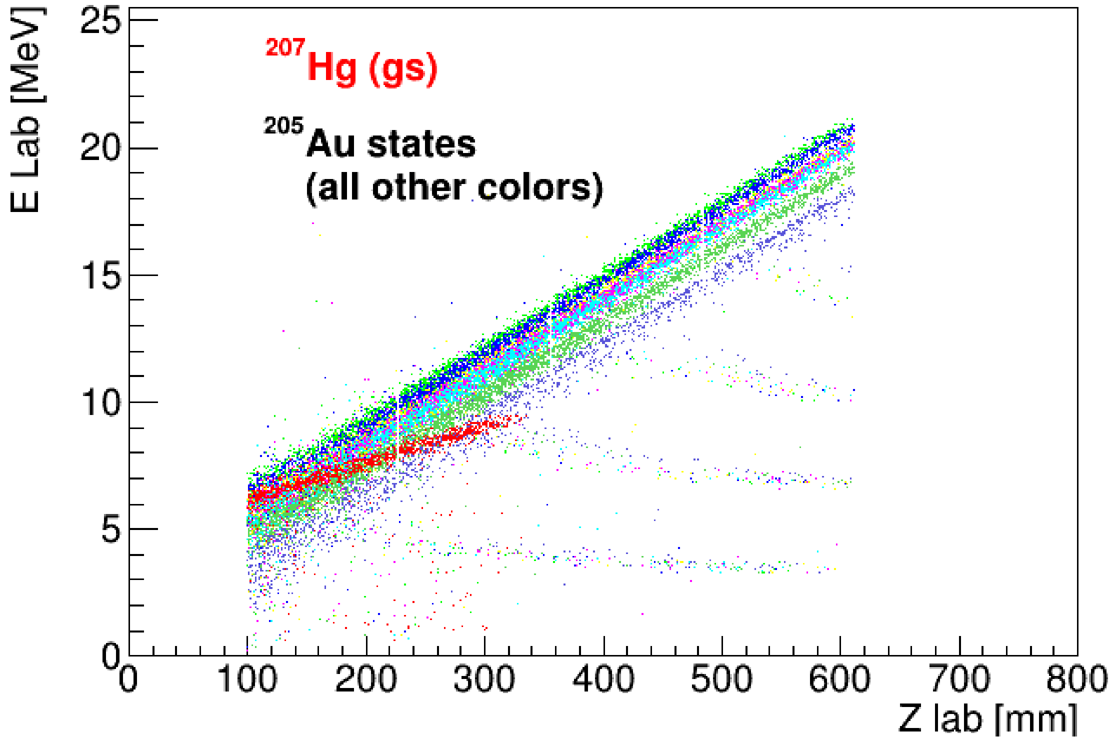

Fig. 3: Energy of the light charge particles in the laboratory reference frame as function of the position along the beam axis obtained for all ^{205}Au states (shown on figure 1) and the ^{207}Hg ground-state (in red). The excited states of ^{207}Hg would appear below the ground-state region in red, and they are not shown.

The simulated excitation spectrum of ^{205}Au is shown in figure 4. This was obtained by applying a Z>350 mm (Z is the position along the beam line), thus removing the ^{207}Hg contaminant. For ^{205}Au he energy resolution (sigma) is 290 keV, and with a cut in Z >350mm, one gets a value of 180 keV. This large difference indicates that the target is the main contributor.

The peak at ~2 MeV excitation energy is separated from all others. This can be used to determine the experimental resolution. This will aid the fitting of structures containing more excitations. To note is that the states with different *l* values are very far apart from each other, therefore no ambiguity on the *l* values for any observed state (and no need to get the measure the angular dependence of the cross section). But angular distribution can be used to enhance different excited states within the same structure (e.g. $d_{3/2}$ ground-state and $s_{1/2}$ excited state).

The other reactions of interest for the kinematics are elastically scattered titanium and triton ions from the target; these do not overlap with the reactions of interest. Fusion-evaporation reactions on triton and ^{46}Ti nuclei were also considered. No alpha emission is expected (the compound nuclei ^{209}Tl and ^{250}No will decay by neutron emission and fission, respectively).

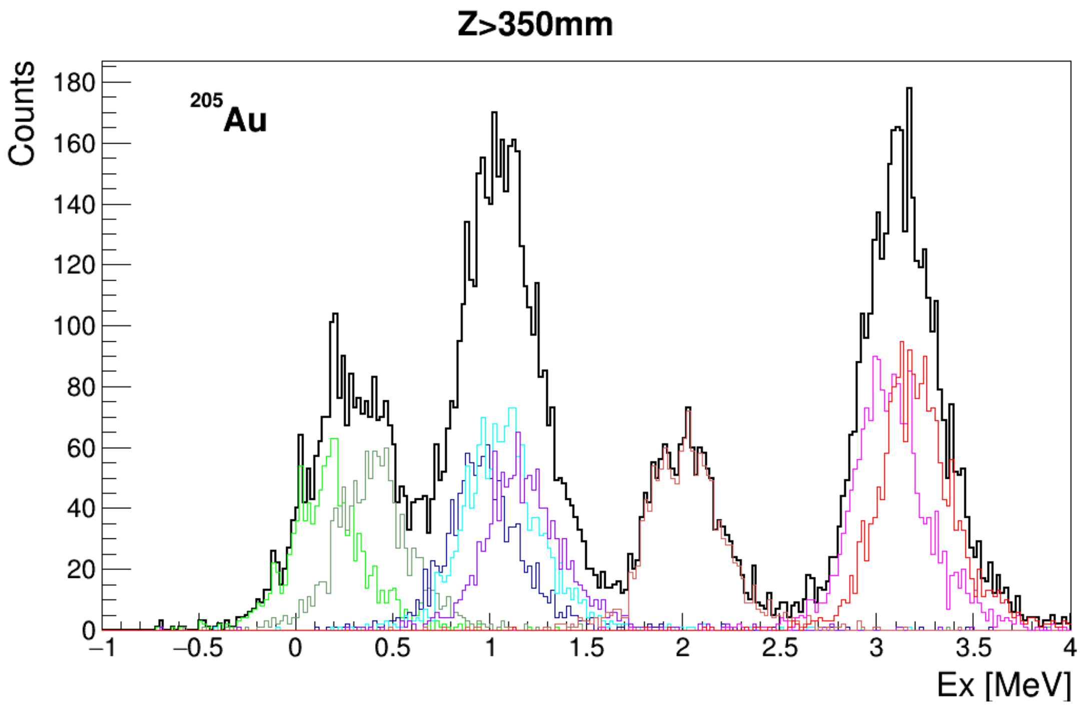

Fig. 4: Simulated spectrum for ^{205}Au (black line). The contributions of different states are also shown. Here it was required that the charged particle was detected at Z>350 mm, which removes the contaminant (t,d) reaction.

Summary of requested shifts: 15 shifts of protons on a molten lead target are requested for this measurement.

References

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[Podolyak2009] Zs. Podolyák et al., Phys. Lett. B 672, 116 (2009).

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[Steer2008] S.J. Steer et al., Phys.Rev. C 78, 061302(R) (2008).

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[Tang2020] T.L. Tang et al., Phys. Rev. Lett. 124, 062502 (2020).

[Warburton1991] E. K. Warburton and B. A. Brown, Phys. Rev. C 43, 602(1991).

[Wimmer2010] K. Wimmer et al, Phys. Rev. Lett. 105, 252501 (2010)

[Wimmer2021] K. Wimmer et al., IS696 accepted ISS proposal (Pairing vibrations beyond N=82)

1 Details for the Technical Advisory Committee

3.1 General information

Describe the setup which will be used for the measurement. If necessary, copy the list for each setup used.

☒ Permanent ISOLDE setup: *ISS*

☒ To be used without any modification

☐ To be modified: *Short description of required modifications.*

☐ Travelling setup (*Contact the ISOLDE physics coordinator with details.*)

☐ Existing setup, used previously at ISOLDE: *Specify name and IS-number(s)*

☐ Existing setup, not yet used at ISOLDE: *Short description*

☐ New setup: *Short description*

3.2 Beam production

For any inquiries related to this matter, reach out to the target team and/or RILIS (please do not wait until the last minute!). For Letters of Intent focusing on element (or isotope) specific beam development, this section can be filled in more loosely.

- Requested beams:

Isotope	Production yield in focal point of the separator (/μC)	Minimum required rate at experiment (pps)	$t_{1/2}$
Isotope 1 Isotope 2 Isotope 3	206Hg (1.5x10^8/μC)	10^7 pps	8.3 min.

- Full reference of yield information: *IS547 and IS631 experiments*, Pb target
- Target - ion source combination: VADLIS
- RILIS? *Yes*

  ☐ Special requirements: (*isomer selectivity, LIST, PI-LIST, laser scanning, laser shutter access, etc.*)

- Additional features?

  ☒ Neutron converter: No

☐ Other: (*quartz transfer line, gas leak for molecular beams, prototype target, etc.*)

- Expected contaminants: *possibly Xe*
- Acceptable level of contaminants: 10% (5x10^4 pps)
- Can the experiment accept molecular beams? No
- Are there any potential synergies (same element/isotope) with other proposals and LOIs that you are aware of? No

3.3 HIE-ISOLDE

For any inquiries related to this matter, reach out to the ISOLDE machine supervisors (please do not wait until the last minute!).

- HIE ISOLDE Energy: *7.5 MeV/u; 7-7.5 MeV/u acceptable*

  ☒ Precise energy determination required

  ☐ Requires stable beam from REX-EBIS for calibration/setup? *No*

- REX-EBIS timing

  ☒ Slow extraction

  ☐ Other timing requests

- Which beam diagnostics are available in the setup? ISS
- What is the vacuum level achievable in your setup? ISS

3.4 Shift breakdown

The beam request only includes the shifts requiring radioactive beam, but, for practical purposes, an overview of all the shifts is requested here. Don't forget to include:

- Isotopes/isomers for which the yield need to be determined
- Shifts requiring stable beam (indicate which isotopes, if important) for setup, calibration, etc. Also include if stable beam from the REX-EBIS is required.

An example can be found below, please adapt to your needs. Copy the table if the beam time request is split over several runs.

Summary of requested shifts:

With protons	Requested shifts
Yield measurement of isotope 1 Optimization of experimental setup using isotope 2 Data taking, isotope 1 Data taking, isotope 2 Data taking, isotope 3 Calibration using isotope 4	1 tuning +debugging 15
Without protons	Requested shifts
Stable beam from REX-EBIS (after run) Background measurement	0

3.5 Health, Safety and Environmental aspects

3.5.1 Radiation Protection

- If radioactive sources are required: No
  - Purpose?
  - Isotopic composition?
  - Activity?
  - Sealed/unsealed?
- For collections:
  - Number of samples?
  - Activity/atoms implanted per sample?
  - Post-collection activities? (*handling, measurements, shipping, etc.*)

3.5.2 Only for traveling setups

- Design and manufacturing

  ☒ Consists of standard equipment supplied by a manufacturer

  ☐ CERN/collaboration responsible for the design and/or manufacturing

- Describe the hazards generated by the experiment:

Domain	Hazards/Hazardous Activities	Description

Mechanical Safety	Pressure	☐	[pressure] [bar], [volume][l]
	Vacuum	☐	
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	[fluid] [m3]

Electrical Safety	Electrical equipment and installations	☐	[voltage] [V], [current] [A]
	High Voltage equipment	☐	[voltage] [V]
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	[fluid], [quantity]
	Toxic/Irritant	☐	[fluid], [quantity]
	Corrosive	☐	[fluid], [quantity]
	Oxidizing	☐	[fluid], [quantity]
	Flammable/Potentially explosive atmospheres	☐	[fluid], [quantity]
	Dangerous for the environment	☐	[fluid], [quantity]
Non-ionizing radiation Safety	Laser	☐	[laser], [class]
	UV light	☐	
	Magnetic field	☐	[magnetic field] [T]
Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height (climbing platforms, etc.)	☐	
	Outdoor activities	☐	
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards			