STRUCTURE OF $N = Z$ NUCLEI FROM STUDIES WITH GASP AND EUROBALL*

Santo Lunardi

Dipartimento di Fisica dell'Universita' and INFN
Sezione di Padova, Padova, Italy

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Large γ-detector arrays coupled with selective ancillary devices has allowed to progress greatly in the nuclear structure studies of $N = Z$ nuclei up to relatively high spin. At GASP and Euroball a series of experiments have been performed ranging from nuclei close to ^{32}S to the mass $A = 90$ region. The new data provide important information on the role of proton neutron pairing correlation, on isospin symmetry and isospin mixing in nuclear states and, for lighter nuclei, constitute an excellent test of the shell model description of nuclear collective motion. Two examples of the work done at Legnaro in this field are presented.

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1. Introduction

The study of high spin states in nuclei has provided, during the last 30 years, a wealth of information on the nuclear many body system through the discovery of new phenomena whose interpretation has refined our comprehension of nuclear interaction. Only recently, with the advent of large gamma-ray detector arrays, high spin states has become accessible and studied in nuclei with equal number of protons and neutrons ($N = Z$). The meaning of "high spin" is of course different here with respect to nuclei lying in the valley of stability where spins as high as $I = 60$ can be reached. For heavy $N \approx Z$ nuclei, in view also of the experimental difficulties to populate them, states with spin 8–10 are considered of "high spin". The knowledge of such levels can anyway give important information on fundamental properties of nuclei, such as proton–neutron (p–n) pairing interaction and the charge independence of the nuclear force. In the following, two experiments

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will be described which allowed to identify for the first time excited states up to $I^{\pi} = 8^{+}$ and $I^{\pi} = 11^{+}$ in the two nuclei ^{88}Ru and ^{50}Fe, respectively. In the first one (the $N = Z$ ^{88}Ru nucleus) the goal was to search for a delayed alignment in the rotational ground-state sequence, that could be a possible signature of p–n pairing correlations. In the second one (the $N = Z - 2$ ^{50}Fe nucleus) the validity of isospin symmetry in nuclei could be tested in a rotational sequence up to the back-bending region.

2. Delayed alignment in the rotational ground state sequences of $N = Z$ nuclei as a signature of p–n pairing correlations: the nucleus ^{88}Ru.

One of the strongest motivation for studying the $N = Z$ nuclei is given by the possibility of evidencing effects of the p–n pairing interaction. We expect p–n pairing both with isospin $T = 1$ and $T = 0$ to compete with the usual $T = 1$ like nucleon pairing. The pairing between like nucleons is extremely important in nuclei and has been extensively studied. In $N \neq Z$ nuclei it strongly overweight the effects of the p–n pairing, due to the large number of like pairs. In the $N = Z$ nuclei the p–n pairing should be relatively enhanced, and it is likely that only here it will be possible to observe its effects on the nuclear properties.

It is much discussed in the literature how one can recognise the effects of p–n pairing. Since this type of pairing (especially the $T = 0$ one) is more robust against rotation, it has been suggested that one of its possible signature might be a delay in the rotational frequency where the Coriolis force begins to break the nucleon-nucleon correlations (particle alignment). Such effects have been reported so far in ^{72}Kr [1, 2] and ^{76}Sr, ^{80}Zr [2], and therefore, it is important to investigate heavier nuclei in this respect. The question of "delayed alignment" in $N = Z$ nuclei has been discussed theoretically and alternatively explained as due to the $T = 0$ or $T = 1$ part of the p–n pairing [3–7]. One should ephasise, however, that the discussion of the p–n pairing question has to be placed in the more complicated context of the complex interplay of pairing correlations, deformations, and angular momentum.

In order to investigate higher mass $N = Z$ nuclei, increasing experimental difficulties are encountered. With the available (stable) target-projectile combinations they are populated with extremely small cross sections compared with the huge background created by other reaction channels. Due to the low yield, the spectroscopic experimental information that could be obtained for the heaviest $N = Z$ nuclei investigated so far is rather poor and consists mainly of a few yrast levels observed through their γ-decay. At present, the heaviest $N = Z$ even–even nucleus for which some experimental information on the excited states exists is ^{84}Mo [8]. We have, therefore, performed an experiment to investigate the structure of the next unknown $N = Z$ even–even nucleus, ^{88}Ru.

We have used the reaction ^{58}Ni+^{32}S with a ^{32}S beam of 105 MeV delivered by the Legnaro XTU Tandem. The target consisted of a 1.1 mg/cm^2 ^{58}Ni layer evaporated on a 10 mg/cm^2 Au foil. The γ-rays were detected with the GASP array in its standard configuration, *i.e.* with the inner BGO ball. Given the expected low cross section of the evaporation channel ($2n$) leading to ^{88}Ru, six elements, out of the 80 of the inner ball, placed in the most forward ring were replaced by six neutron detectors. Also the ISIS silicon ball was used with the aim of suppressing the strong charged particle channels through anti-coincidence setup. The data were sorted into different γ–γ matrices in coincidence with charged particle and neutrons. Gamma-ray transitions from the $2n$ channel ^{88}Ru are expected to be best observed in a γ–γ matrix sorted in coincidence with the neutrons and in anti-coincidence with the ISIS silicon ball. After a careful analysis of the data four transitions have been assigned to ^{88}Ru, thus establishing its excited states up to spin 8^+ [9]. The relevant spectra which resulted in the assignment of the four transitions to ^{88}Ru are shown in Fig. 1.

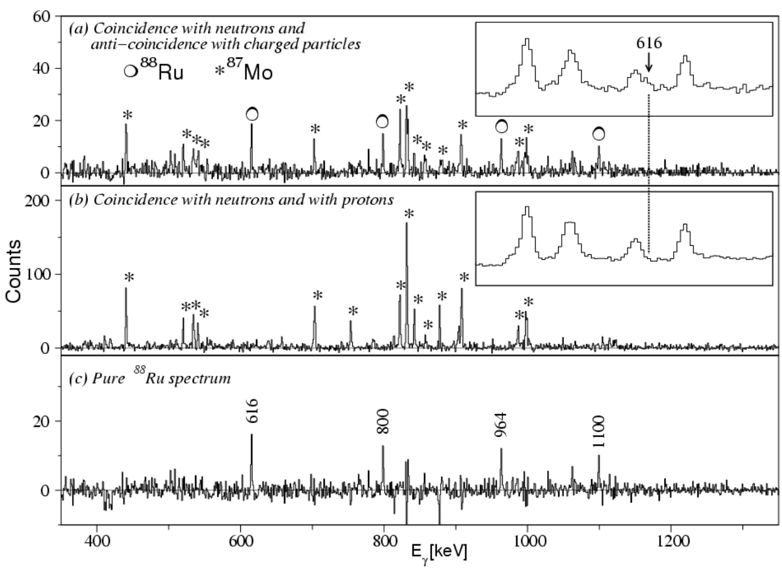

Fig. 1. Sum of gates on the 616,800, and 964 keV transitions assigned to ^{88}Ru in γ–γ matrices with different coincidence conditions on neutrons and charged particles and the "pure" ^{88}Ru spectrum (below) obtained as a difference of the two upper spectra.

The estimated cross section for the $2n$ channel is in the range 5–10 μb. The level scheme of ^{88}Ru is presented in Fig. 2 in the context of the systematics of the ground-state bands in the 80 to 90 mass region.

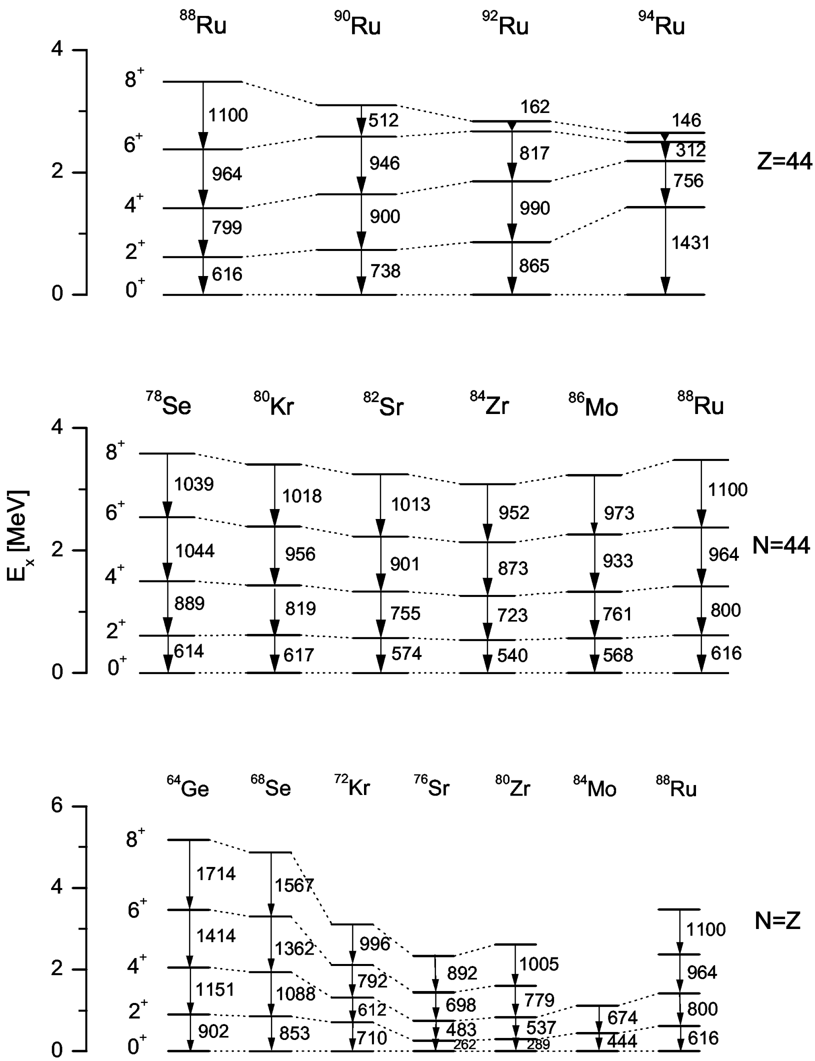

Fig. 2. The ^{88}Ru level scheme compared with the yrast bands of neighbouring even–even nuclei.

Going back to the question of the "delayed alignment" as a signature of the p–n pairing, we have to consider the behaviour of the yrast sequence at spin $I \approx 8$ where the nuclei of this mass region are known to present a back-bending which takes place generally at the 8^+ state (see Fig. 2), due to the alignment of a pair of $g_{9/2}$ nucleons. The plot of the kinematic moment of inertia *versus* the rotational frequency is shown in Fig. 3 for ^{88}Ru and its closest neighbours along the $N = 44$ and $Z = 44$ lines. It is striking in this figure that only in ^{88}Ru there is no sign of irregularity around $\hbar\omega \approx 0.5$ MeV. The nucleus ^{88}Ru seems, therefore, to continue a trend already observed in other lighter $N = Z$ nuclei, since in ^{72}Kr, ^{76}Sr and ^{80}Zr no sign of sudden alignment has been observed up to even higher frequencies. Such a delay in the crossing frequency seems a common feature of heavy $N = Z$ nuclei and, although other interpretation may be possible, it constitutes a strong confirmation of recent theoretical works where, in particular, the "delay" is explained in terms of the isoscalar $T = 0$ pair field [6, 7].

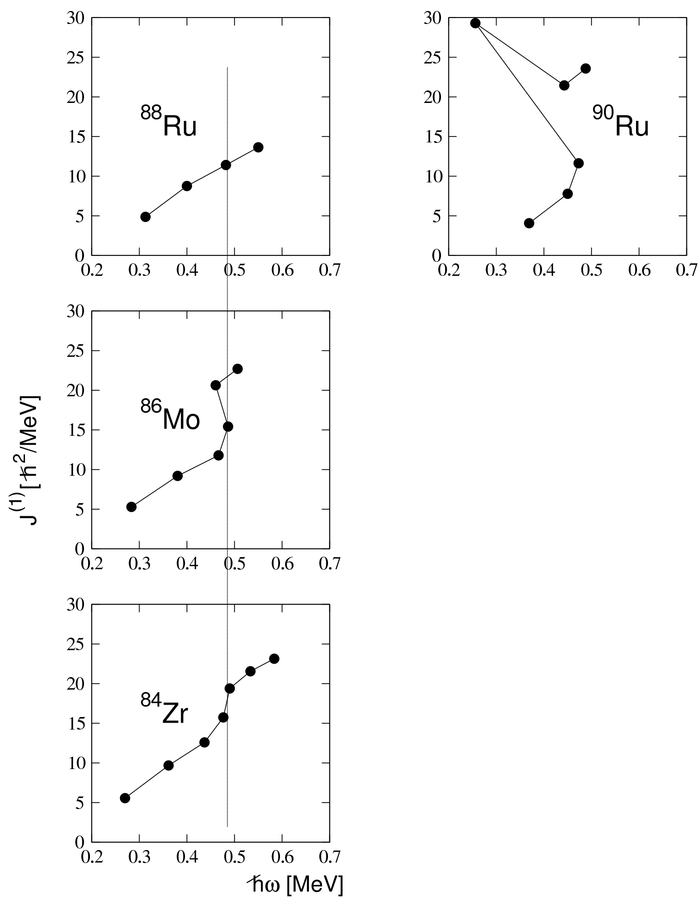

Fig. 3. Kinematic moment of inertia as a function of rotational frequency for the $N = Z$ nucleus ^{88}Ru and its neighbours. Only in ^{88}Ru there is no sign of up-bending or back-bending, due to the alignment of $g_{9/2}$ nucleons.

3. Coulomb energy difference in $T = 1$ mirror rotational bands in ^{50}Fe and ^{50}Cr

The charge independence of the strong interaction is a fundamental assumption in nuclear physics. This introduces an "isospin symmetry" which experimentally has been observed in the nearly identical spectra of levels in pairs of mirror nuclei, *i.e.* nuclei with interchanged number of neutrons and protons. Thanks to the improvements in detection sensitivity, is has become now possible to explore the isospin symmetry of the mirror nuclei in the $1f_{7/2}$ shell to very high angular momenta, allowing to test for the first time this symmetry under rotational stress. With increasing Z, already for mass $A \approx 50$, one of the mirror partners lies very far from stability which makes very difficult its experimental study. With Euroball coupled to the n-wall we can do spectroscopy down to cross sections of $\approx 10\mu b$. This allows to study excited states in nuclei lying even on the left of the $N = Z$ line which is the case of the $N = Z - 2$ ^{50}Fe nucleus (see Fig. 4). This nucleus is the mirror partner of ^{50}Cr whose structure is known since more than 20 years [10].

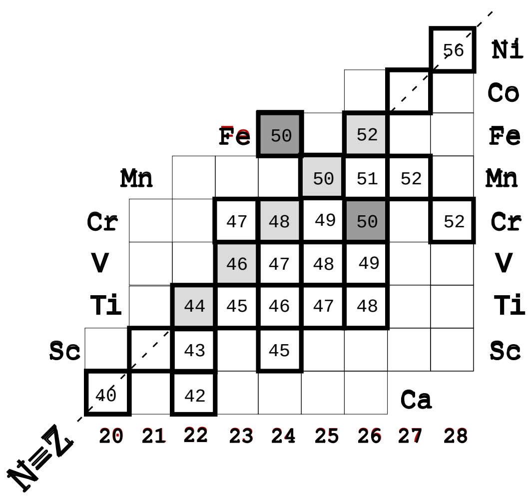

Fig. 4. Part of the nuclide chart along the $N = Z$ line for mass A≈50. The ^{50}Fe nucleus with 26 protons and 24 neutrons is the mirror partner of ^{50}Cr with 24 protons and 26 neutrons.

The energy spectra of mirror nuclei, if the charge independence of nuclear interactions holds, are expected to be equal; when small differences between energy levels arise, these can be interpreted entirely in terms of Coulomb effects. With the term Coulomb Energy Difference (CED) one indicates the energy difference between levels in mirror nuclei [11]. The angular momentum dependence of CED has been investigated recently in series of nuclei of the $1f_{7/2}$ shell allowing to study the spatial behaviour of the active valence nucleons [11–14]. As a consequence, the smooth variation in the CED reflects in detail the change as a function of spin of the nucleus: from a deformed rotor (which is typical of $1f_{7/2}$ nuclei in the middle of the shell), through one or two particle alignment in the backbending region, to an almost spherical non-collective band termination state. Since the Coulomb energy is due only to protons, it has been pointed out that when a $J = 0$ proton pair recouples to another J configuration, the Coulomb energy would decrease [15]. In fact, in the $J = 0$ coupling the overlap of the wave functions (and, therefore, the Coulomb repulsion) is maximum. In an odd mass nucleus, the blocking effect due to the unpaired nucleon, favours the alignment of the other type of nucleon pairs. When a proton pair in the $f_{7/2}$ shell changes from a coupled $J = 0$ state to an aligned $J = 6$ state, the repulsive Coulomb interaction decreases in the odd-neutron nucleus while in its odd-proton mirror no Coulomb effect is expected when a pair of neutrons align. Thus, at the backbending the corresponding transition energy in the odd-neutron partner will be smaller than that in its odd-proton mirror.

For the case of even–even mirror nuclei the experimental information is very scarce. Recently, some theoretical predictions have been reported for odd-even and even–even mirror nuclei in the $f_{7/2}$ shell in the framework of the cranked shell model [16].

One of the better rotors in the $f_{7/2}$ shell is the nucleus ^{50}Cr which presents a first backbending around spin $I = 10$ [17]. Different explanations have been given to this behaviour such as a change of shape or a crossing with a band based on an oblate deformation [18]. Another description in terms of a bandcrossing with a high-K band has been also suggested. From the previous lifetimes measurements [19] performed at GASP, the ground state deformed band seems to continue above the $I = 8^+$ yrast state up to the yrare $I = 12^+$ state.

To have the strongest test of the mirror symmetry in nuclei and to look for an experimental fingerprint of the nucleon alignment at the backbending, high spin states in the $N = Z - 2$ nucleus ^{50}Fe, in which no gamma transitions were known previously, have been investigated. The ^{50}Fe nucleus was produced in the reaction ^{28}Si+^{28}Si at 110 MeV bombarding energy, after the evaporation of one α-particle and two neutrons. The beam was delivered by the XTU Tandem accelerator of the Legnaro National Laboratory. The target consisted of 0.8 mg/cm^2 of ^{28}Si (enriched to 99.9%) with a Au backing of 15 mg/cm^2. Gamma rays were detected with the EUROBALL array (Clovers and Clusters only), charged particles were detected with the ISIS silicon ball (40 $E - \Delta E$ telescopes) and the neutrons with the Neutron Wall.

Events were collected when at least: (a) three Ge detectors plus one neutron detector fired in coincidence or (b) two Ge detectors fired and one neutron was identified in coincidence in the Neutron Wall. Data were sorted in γ–γ matrices in coincidence with charged particles and neutrons. For the identification of γ-lines candidates to belong to ^{50}Fe, we have looked at spectra taken in coincidence with neutrons, with only one α-particle and in anti-coincidence with protons. Six transitions have been found, in mutual coincidence with each other, which satisfy all conditions to be in ^{50}Fe. The coincidence spectrum shown in Fig. 5 corresponds to a sum of gates on these transitions.

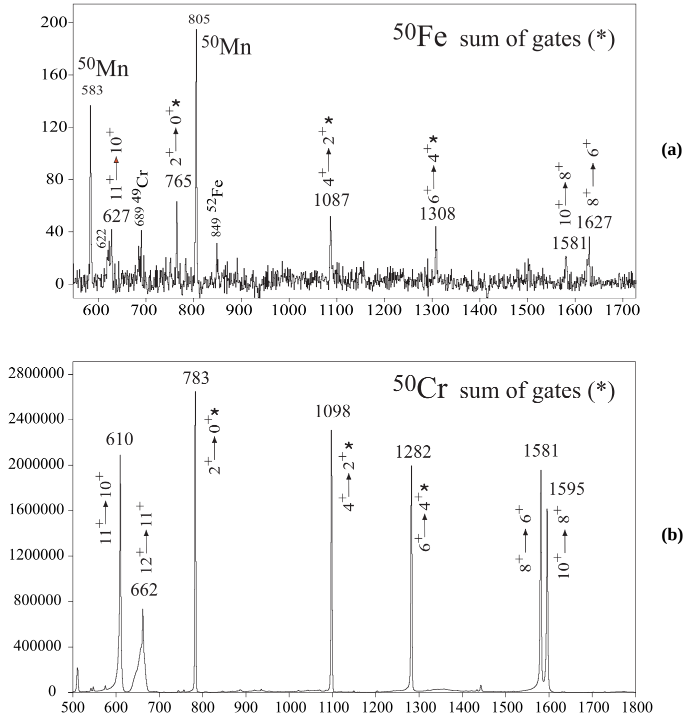

Fig. 5. Summed coincidence spectra with gates on the transitions of the ground state bands of the two mirror nuclei ^{50}Fe and ^{50}Cr. Gates are set on transitions labelled by *.

In the same Fig. 5 (a) coincidence spectrum (with gates on all the relevant transitions) is shown also for the mirror nucleus (^{50}Cr) produced in the same reaction after $\alpha 2p$ evaporation. The comparison of the two spectra illustrates clearly the rapid decrease of population for nuclei lying far from stability. From the present data a cross section of around 15 μb is estimated for the ^{50}Fe nucleus.

From the coincidence data and the transitions intensity a level scheme has been built for ^{50}Fe which is shown in Fig. 6 together with the one of the mirror nucleus ^{50}Cr. Spin and parity assignment for levels in ^{50}Fe are based on the great similarity of the two level schemes of Fig. 6. The energy difference among levels is ranging from few keV to a maximum value of ≈40 keV, to be compared with absolute values of energy up to 7 MeV. This confirms, in a first approximation, the validity of the mirror symmetry which is connected to the charge independence of the nuclear force. Such small energy differences which, as stated above, can be understood as Coulomb effects are plotted in the right part of Fig. 6 as a function of spin as $\mathrm{CED}(I) = E^*_{\mathrm{Fe}}(I) - E^*_{\mathrm{Cr}}(I)$.

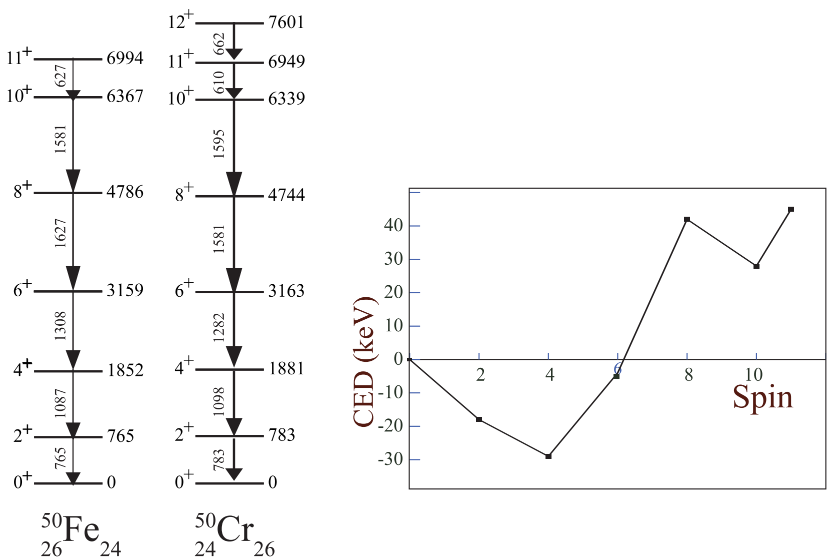

Fig. 6. Ground state bands in the two $T = 1$ mirror nuclei ^{50}Fe and ^{50}Cr (left) and the Coulomb energy difference (CED) calculated as the difference in relative excitation energy at each spin (right).

The behaviour of the CED can be explained in the following way: a neutron pair is aligning at $I = 8^+$ in ^{50}Fe while a proton pair aligns in ^{50}Cr; at spin $I = 10^+$ a second alignment of the other type of nucleon pairs occurs, a proton pair in ^{50}Fe and a neutron pair in ^{50}Cr. The data is only qualitatively described by cranked shell model calculations of Ref. [16]. Recent full pf shell model calculations, on the other side, reproduce with great precision [20] the shape and the absolute value of the CED curve depicted in the right part of Fig. 6. The fact that such small energy differences are understood and reproduced with high accuracy in calculations is significant of the importance of mirror symmetry in nuclei.

The experimental data presented in this talk are the result of the work, from the data taking to the data analysis, of many colleagues who are members of the GASP and Euroball collaboration. I would like to thank in particular N. Marginean, D. Bucurescu and S. Lenzi for providing me with the material and helping in the preparation of the talk.

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