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HIGH SPIN STATES IN THE f-p SHELL

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The general topic I will talk about is that of high spin states (HSS) in the f-p shell where collective and single-particle aspects are strongly mixed. Although extensive studies in this f-p shell have been made, the nature of these studies selectively picks out states with $J \leqslant 6$.

In (heavy ion, few nucleons, γ) reactions, a compound nucleus is formed with quite a lot of angular momentum ; the light particles emitted cannot carry out much angular momentum, so that HSS in the final nucleus are preferentially populated and one observes a cascade of yrast states [1]. From these investigations, important information was collected, unaccessible by other means. Let me just recall that the physics of HSS is now twelve years old for $A \geqslant 120$, since the pioneer work of Morinaga and Gugelot [2] (1963). A year ago, at the Nashville meeting, Ward [3] gave a broad survey of this domain, with different aspects of collectivity as backbending, downbending, forking, etc.. The highest spin thus produced is J = 22. For $A < 120$, the physics is much newer (1973), due to more experimental complications (the lower coulomb barrier also allows the emission of charged particles). The Firenze-Munich-Padova Universities group have shown [4] that essentially the HSS of the $(f_{7/2})^n$ configuration are observed and study the decrease of collectiveness with increasing spin (one of the best examples is the ^{50}Cr). Since three years ago, a lot of new and interesting information was obtained. I can refer you to the surveys about $f_{7/2}$ shell of Signorini [4] made last year at Varenna and of Kolata [5] from the Brookhaven group given this year in an APS meeting. Undoubtedly, Professor Ricci will discuss in his talk the last news about this very rich $f_{7/2}$ shell. The highest spin observed in this shell is $J \leqslant 12$.

I shall concern myself with the HSS in Fe, Co, Ni (Z = 26,27,28) isotopes. I would like to start by emphasizing that the work I will discuss here is the result of a close collaboration with the authors given in the reference list [6]. When we started this study two years ago, no HSS at all were reported in the literature for these nuclei ; they exhibit features characteristic of soft or transitional nuclei, ^{56}Fe being a well deformed prolate nucleus and the Ni isotopes often thought of as spherical. For these nuclei, in fact, the prolate and oblate solutions are very close, the prolate being lower [7]. We have under study a region which presents some analogies with the Pt-Os one, where there exist prolate-oblate transitions for nuclei around the N = 82 shell closure, the spectra being vibrational in character.

Before I show you some samples of our results, I want to spend just few minutes to recall the methodology used to identify these HSS. All the experiments I shall talk about are based on the detection of γ rays with Ge(Li) detectors. The quality of the results is strongly connected with the qualities of these detectors, resolution, efficiency, etc.

1°) We optimize a reaction for a particular residual nucleus under interest. A very nice feature in this work is the possibility to produce a nucleus in a large number of ways (Fig.1) and this helps to check the consistency of the results.

2°) Having chosen the best reaction (best feeding for HSS, least background, etc.) and the best energy, which corresponds to the maximum of the excitation function for the residual under interest, we observe γ-γ coincidences. These data, plus the yield of the γ rays taken at an appropriate angle (to avoid correlation effects : 55° for example) is enough, in principle, to build the scheme of the nucleus.

3°) To assign the spins, one uses the large γ anisotropies obtained in such reactions and performs γ angular distributions. But, for A < 100 the angular distributions are not only fitted for stretched (i.e. J -> J - L, where L is the multipolarity of the γ ray) quadruple transition cascade, as it is often the case for heavy nuclei but may also be fitted by dipole quadrupole mixture. Therefore, the spin assignment must be supported by other considerations. The general γ-γ angular correlation is time-consuming (∿ 3 days for 1 point). It is possible to restrict the ambiguities by using the excitation functions [2]. At Saclay, we systematically use the so called

DCO (directional correlation of oriented nuclei) or Ratio method as suggested by Krane et al [9] which, by combining the angular distribution data plus one point of a triple γ-γ correlation (beam, γ_1, γ_2) in an asymmetric geometry (practically the γ-γ coincidences made previously), gives result that we found equivalent to a complete angular correlation to assign spin and mixing ratios.

4°) We begin a systematic study of the lifetimes of these HSS because the observation of enhanced E2 matrix elements is the cleanest and most definitive evidence for the existence of deformed states. These measures are made by the Doppler shift attenuation method during the angular distribution measurement ; or, for longer lifetimes, by the plunger method where the large velocity (≳ 1 % of c) and the narrow cone at forward angle for the recoil nuclei are very suitable characteristics.

With this methodology, we are collecting, at present, information on $^{54-58}Fe$, $^{56-58}Co$, $^{58-61}Ni$. I shall show you now a sample of our results.

<u>^{56}Co (Fig.2)</u> ref. 6-a

As you can see, by this method, there is a tremendous selectivity. Often, these HSS are more pure (fewer configurations) than the low spin states because only a few configurations can contribute to build such a high spin in any shell model calculation. In this particular example, the shell model calculations [6-a], using different spaces show that the J = 7^+ is not fragmented. It is clear that the one-to-one correspondence of theoretical levels and experimental ones is much easier if you have only one level of a certain spin instead than 10 or more. So in such a case, the location of states with a given spin is fruitful and can help to fix the parameters of the model.

In our domain (Fe, Co, Ni) the calculations are much more complicated than in the f 7/2 shell : we have to use at least the f 7/2, p 3/2, f 5/2, p 1/2 shells. We have not at our disposal a tool such as the (MBZ) [4] model (or its revised version : KBO model) to correlate our results. The space that must be used is too large to be handled (∿ 10^6 configurations !) [10] and, moreover, such calculations are not very useful since they are only a limited number of eigenvectors with any interest. These huge calculations are the starting point to try to isolate essential features of the model. All the problem is the "art of truncating large space"[10].

We will see different methods with other results.

^{57}Co (Fig.3) ref. 6-e

Again we see how fruitful this method is : all the levels above 1.7 MeV are new. This is a general feature ; when you begin the study of HSS in an even-even nucleus you always have a good starting point : the transition $2^+_1 \rightarrow$ gs. But for odd nuclei, especially if the ground state has a large spin, we just jump above the numerous low spin states to reach the next yrast state. In these studies the Nuclear data table [11] is not of great help. It is evident that in the near future we will have a new version of this book including hundreds of new states just discovered.

To come back to the physics of ^{57}Co, in the shell model calculation using a ^{40}Ca core plus the valence nucleons in the $f_{7/2}$, $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ shells it is not possible to predict existence of levels with $J \geq 15/2$ [6-e]. But it seems now possible to calculate the level scheme due to the aligned coupled scheme which has been successfully applied to the quasiband structure of fp shell nuclei with 3 or 4 valence nucleons outside the core. The important point in such calculations is that this treatment introduces the concept of the intrinsic deformation into the shell model [12,13].

^{58}Ni (Fig.4) ref. 6-d

For this nucleus, close to the doubly core N = Z = 28, the low lying HSS are expected to be rather pure in the shell model sense. In a classical shell model calculation [14] including a ^{56}Ni core plus the two valence neutrons in $p_{3/2}$, $f_{5/2}$, $p_{1/2}$ orbits, you can only reach $J \leq 6$. A few calculations have appeared recently to predict the HSS : one from Parikh [7] mixing various bands and one from Shimizu and Arima [15] in a pseudo SU(3) coupling scheme. Since the SU(3) coupling scheme was used with a large success in the s-d shell as a basis for truncating the space and due to the similarity of the ^{56}Ni core with ^{16}O core, it is tempting to treat ^{56}Ni $\pm$ x nucleons as ^{16}O $\pm$ x nucleons. In this calculation the $0^+_1, 2^+_1, 4^+_1$ states are understood, as usual, as two particle states and the 4^+_2, 6^+_1, 8^+_1, etc. as 3p-1h states. The $2^+_1, 4^+_1, 4^+_2, 6^+_1$ are well-reproduced in this calculation. Odd spin states are not predicted in any calculation up to now. So, obviously these calculations have to be completed.

^{56}Fe ref 6-i

For this nucleus we observe a strong E2 stretched cascade $6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow$ gs with very weak transitions reaching the 6^+ at 3.388 MeV level. We have performed very recently the lifetime measurements of these levels. A preliminary value for this 6^+ determined for the first time is

$$\tau = 0.70 \text{ ps} \mp 0.15 \text{ ps}.$$

^{56}Fe is one of the most-studied nucleus in the f-p shell, both experimentally and theoretically. I think in this symposium, perhaps half a dozen theorists have made calculations for this nucleus. All calculations tend to produce a rotational energy spectrum up to J = 10. Jaffrin [13] used the aligned scheme to pay special attention to the rotational nature of the collective states. He interprets the experimental result as a shape transition : the prolate shape change at J = 6 into an oblate shape, producing a cut-off in the ground state rotational band. Jaffrin will explain his calculation in his talk.

CONCLUSION :

The domain of HSS for Fe, Co, Ni is just opening. The (heavy ion, few nucleous γ) reactions are a very expedient method to reach such HSS which are unaccessible for the moment by other methods. However, we must remember that by this method we reach only the yrast, or close to yrast, states and we are quite blind to other states. So it is clear that lot of complementary data must be obtained to have a better understanding of the nucleus. Regarding the theory, the calculations have also just begun ; they must describe simultaneously the collective and non-collective levels. So far, the SU(3), the symmetry conserving generator method [16], and the aligned coupling scheme have been applied. The theorists have not only to produce a correct level scheme but many other observables such as the transition probabilities, mixing ratios, etc.

It seems that the physics of HSS which is such an active area of research throughout the table will keep nuclear spectroscopy alive for long time.

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d) ^{58}Ni : R. Ballini, N. Bendjaballah, J. Delaunay, J. P. Fouan, W. Tokarevsky to be published

e) ^{57}-Co, ^{57}Fe : M. Bendjaballah, J. Delaunay, T. Nomura to be published and contribution to this symposium

f) ^{58}Co-^{58}Fe : idem e)

g) ^{54}Fe-^{55}Fe : N. Bendjaballah to be published

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FIGURE CAPTIONS

Fig. 1 Different reactions to reach ^{56}Fe.

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Fig. 2 Proposed decay scheme deduced for ^{56}Co,
the reaction used $^{50}Cr(^{12}C,\alpha\ pn)^{56}Co$ - (ref. 6a).

Fig. 3 Proposed decay scheme for ^{56}Co,
the reaction used are $^{48}Ti(^{12}C,\ p\ 2n)^{57}Co$ and $^{54}Fe(\alpha,p)^{57}Co$ - contribution of this symposium.

Fig. 4 Proposed decay scheme for ^{58}Ni,
the reaction used is $^{48}Ti(^{12}C,\ 2n)^{58}Ni$ - (ref. 6d).

Fig. 5 Proposed decay scheme for ^{56}Fe,
the reactions mainly used are $^{50}Cr(^{12}C,\ \alpha\ 2p)^{56}Fe$ and $^{54}Fe(\alpha,2p)^{56}Fe$ - (ref. 6i).

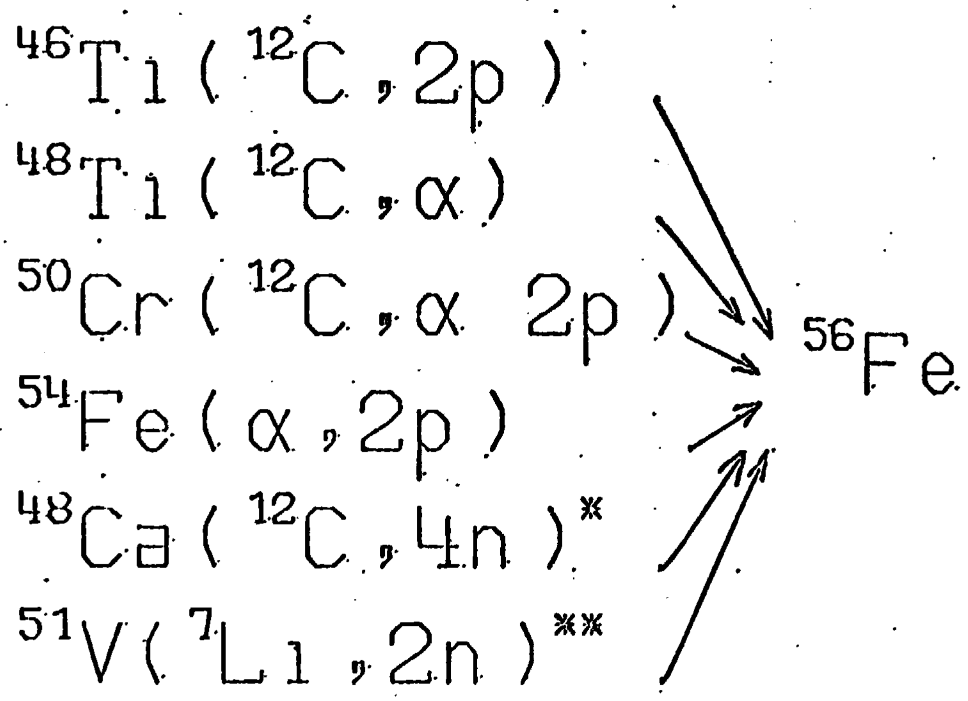
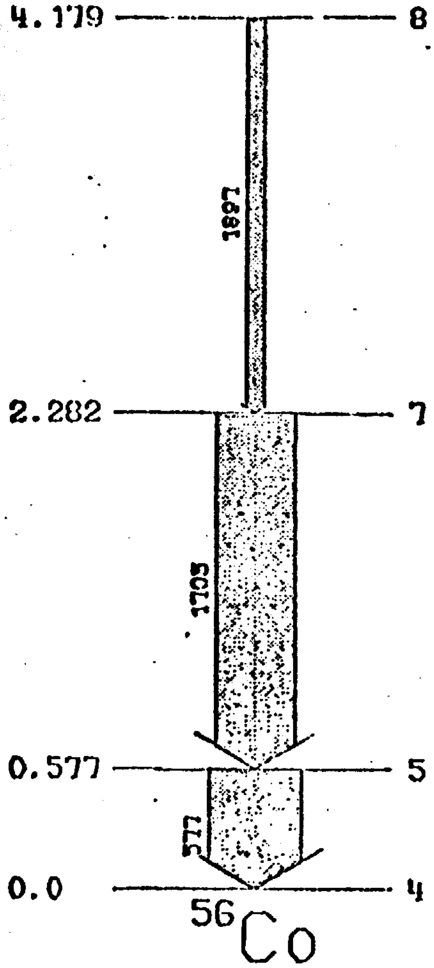

46Ti(12C,2p)
48Ti(12C,α)
50Cr(12C,α 2p)
54Fe(α,2p)
48Ca(12C,4n)*
51V(7Li,2n)**
56Fe

Fig.1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5
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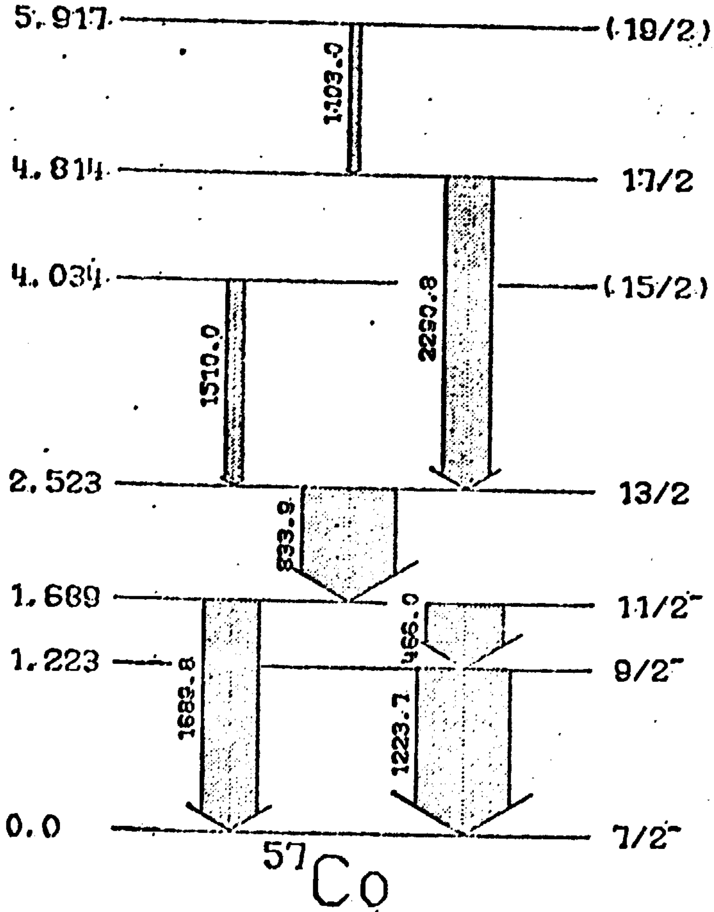
4
56Co

Fig.2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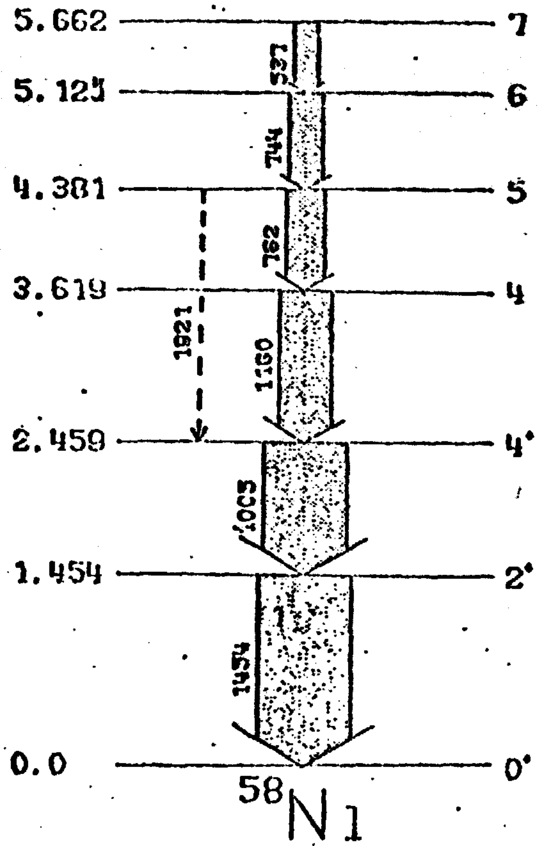
1103.0
4.814
17/2
4.034
(15/2)
1510.0
2290.8
2.523
13/2
833.9
1.689
11/2⁻
466.0
1.223
9/2⁻
1689.8
1223.7
0.0
7/2⁻
57Co

Fig.3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1.454
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7
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4⁺
2⁺
0⁺
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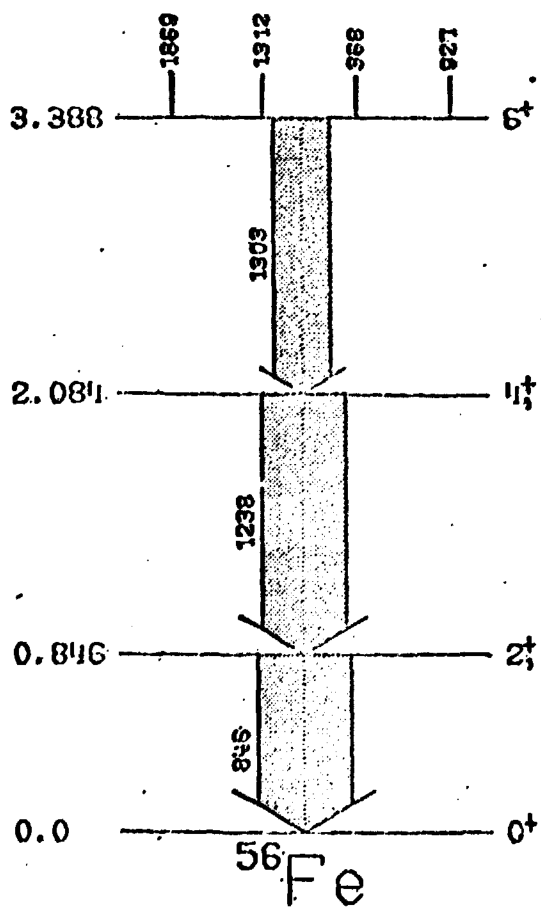
1005
1454
58Ni

Fig.4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6⁺
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0⁺
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1238
846
56Fe

Fig.5