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NEW DIPOLE RESONANCES EXCITED BY RADIATIVE CAPTURE REACTIONS: A PROPOSAL FOR NAC

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1.- INTRODUCTION

Radiative capture reactions have played an outstanding role in the study of the detailed structure of the Giant Dipole Resonance, taking advantage of the very good energy resolution inherent in these studies.

Since the capture reactions measure the decay of the GDR through only one channel, extensive investigation has been performed on light nuclei where often one channel carries a significant fraction of the dipole sum rule and where the large spacing between states in the residual nuclei represents a valuable experimental advantage.

A complete review of the capture reactions performed with protons, neutrons and alphas can be found in the article of Weller and Robinson$^{(1)}$ and details can be found in the references therein quoted.

Starting from 1979 the efforts of a few groups have been concentrated in the energy region above the GDR, and the improvements now obtained with high energy gamma ray detectors, in both efficiency and resolution, have allowed high quality spectroscopy and have led to rather unexpected results both in proton(2) and heavy ion(3) radiative capture, opening up two completely new fields of interest in an energy range and with beams characteristic of NAC cyclotron which, as we show in this proposal, can be well exploited from the initiation of its activity.

While not ignoring the opportunities offered by the NAC heavy ion beams, most of our attention is focused on proton radiative capture (PRC) performed in an energy range from $E_p = 25$ MeV to $E_p = 100$ MeV, since there are a few points which clearly indicate that priority given to PRC will allow the performance of a competitive set of experiments at NAC, viz:

a) There is a very clear picture provided by recent experiments on new dipole resonances built on excited states, with consequently a clear definition of the physical problem that we are facing.

b) There is a strong and immediate demand for data in the regions of the second and third harmonics of the GDR as well as for systematics on more nuclei in the region of the first harmonic; all these regions being well within the NAC energy range.

c) The excitation mechanism has yet to be properly described by a detailed and general theory.

d) There will be immediate availability of "65 MeV" protons at NAC and the high quality of the beam parameters places us in a strong competitive position.

e) The experimental set-up is relatively simple and well established by other groups in this field. Results of physical relevance should thus come shortly after the installation of the experimental facilities.

On the other hand heavy ion radiative capture reactions (HIRC) have quite recently opened an equally new and exciting problematic which is actually studied using low energy machines (Tandems), hence there is a need for urgency, and perhaps collaborative complementary Tandem work.

The fact of relevant importance shown recently by HIRC are:

1) There is high selectivity on nuclear shape configurations.
2) There is need for investigations on the complex nature of the states populated by such reactions.
3) There is great interest on the study of different entrance channels leading to the same final nucleus.

We see HIRC as an appropriate second generation experiment at NAC. Unlike the proton capture reaction study, we will need an experimental set up with at least a coincidence technique, but we will get good experience and results with the simple proton case. Also we expect full availability of heavy ion beams at NAC only at a later date and in an energy range somewhat limited towards lower values. These facts suggest that detailed plans for a series of HIRC experiments at NAC should be considered after obtaining a clear physical picture from experiments at the lower energy Tandem accelerators.

2.- PRC ABOVE THE GDR

Let us examine what has been observed in PRC above the GDR. A high quality photon spectrum (Fig. 1) collected (for example) on a ^{11}B target

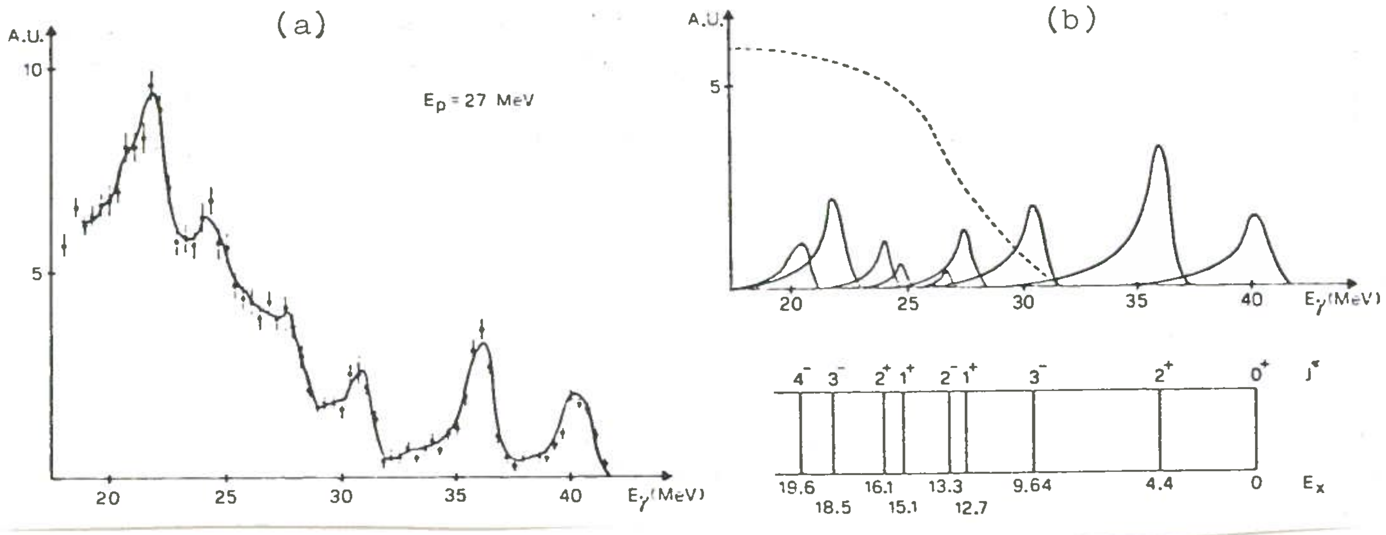

FIG. 1 - High energy photon spectrum from the reaction $^{11}B(p,\gamma)^{12}C$ at $E_p = 27$ MeV. The spectrum deconvolution and the states identified are given.

bombarded with a 27 MeV proton beam$^{(4)}$, by a high resolution, high efficiency gamma spectrometer$^{(5)}$, can be resolved into a series of discrete peaks plus a continuous background. The prominent physical evidence is that we have not only a (p, γ_o) transition to the g.s. of ^{12}C, but that a considerable part of the transition strength is distributed to a particular set of excited states.

In fact all of these are essentially 1p-1h states with a strong correspondence to the entrance channel configuration.

In this ^{12}C example all the states listed in Fig. 1 are basically 1p-1h states with a strong $1P3/2^{(-1)}$ component, thus supporting the idea of a somewhat direct capture mechanism in which the final state can be seen as the target core plus a proton in a single particle orbit.

Further support for the single particle character of the PRC to the excited states comes from the analysis of data belonging to neighbouring nuclei and to states which can be described as the target core plus a proton in the same single particle orbit$^{(6)}$.

For example the ^{13}N g.s. and the ^{12}C 4.43 MeV states both have a proton in the 1p1/2 shell and the ^{12}C 19.2 MeV and the ^{13}N 3.55 MeV states both have a proton in the 1d5/2 shell. The differential cross section and the analyzing power measured at E_p = 28.7 MeV (Fig. 2) for these pairs of states are, within the experimental errors, significantly similar.

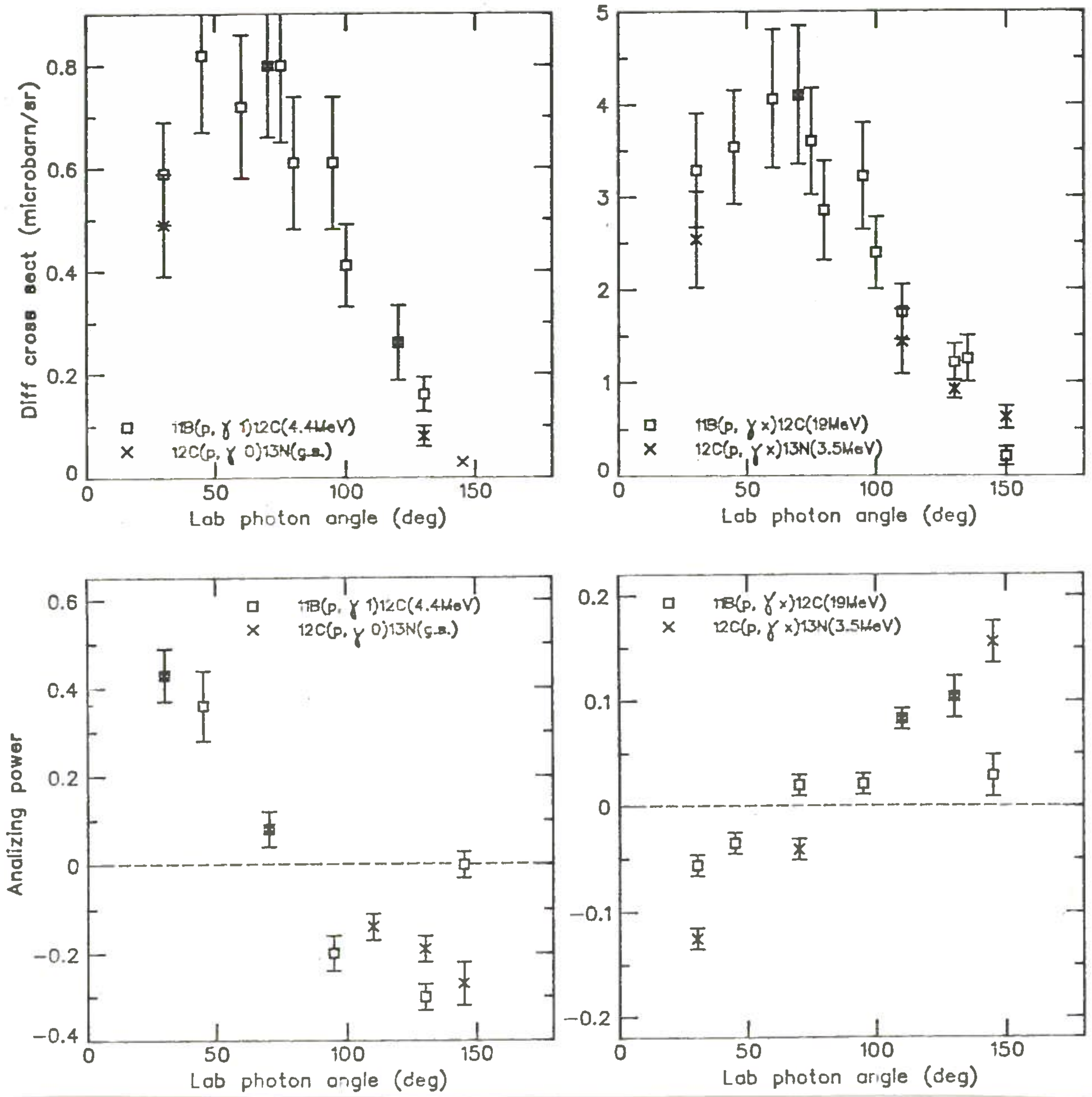

FIG. 2 - Angular distributions and analyzing power for couples of similar single particle states in ^{12}C and ^{13}N as measured at E_p = = 28.7 MeV in the reactions $^{11}B(p,\gamma)^{12}C$ and $^{12}C(p,\gamma)^{13}N$.

Bearing in mind these strong indications of a single particle mechanism, we can analyse the angular distributions and the cross sections for each transition.

Few nuclei have so far been investigated for PCR above the GDR but all the experiments give systematically similar indications on the nature of the transitions to the excited states(7,8).

As we see for the three nuclei ^{12}C, ^{15}N and ^{16}O in Fig. 3, the total cross sections(8) show a resonant behaviour in each exit channel with a significant transition strength concentrated even on states as high as 20 MeV (in ^{12}C). The angular distributions relative to the central energy of each resonance, give, when expanded in a series of Legendre polynomials, coefficients a_1 and a_2 different from zero with small contributions coming from a_3 and a_4 thus supporting a dominant E1 character for these resonances with a not negligible E1 M1 interference specially at low energies.

A further step towards the understanding of the reaction mechanism can be achieved by computing for each resonance the centroid energy given by

$$\langle E \rangle = \int_{th}^{\varepsilon_0} \omega\, \sigma(\omega) d\omega \Big/ \int_{th}^{\varepsilon_0} \sigma(\omega) d\omega$$

as well as the difference ΔE_γ between $\langle E \rangle$ and the residual state energy. It is obviously difficult to compute the centroid energy because of the lack of data, especially at the low energy side of the higher resonances, but the energy shifts are practically constant (Fig. 4a) at a value corresponding to the centroid energy of the well-known GDR built on the g.s.

This fact together with the dominant E_1 behaviour assigned by the angular distributions, supports the very simple and attractive model shown in Fig. 4b, where we have the new evidence that one can build a collective excitation not only the g.s. of a nucleus but in practice also on a large set of excited states having a dominant single particle nature.

The transition to a group of unresolved states around 19.5-20.5 MeV in ^{12}C, having a resonant cross section at about 43 MeV is interpreted as(9) the second harmonic ($2\hbar\omega$) GDR built on the g.s. GDR (1st harmonic at $1\hbar\omega$) and the existence of a second harmonic resonance has been found in confirmation in ^{13}N(10). The Indiana group has also found an increase in photon yield at an excitation energy of 75 MeV which they regards as a candidate for the third harmonic of the giant dipole resonance(6,11).

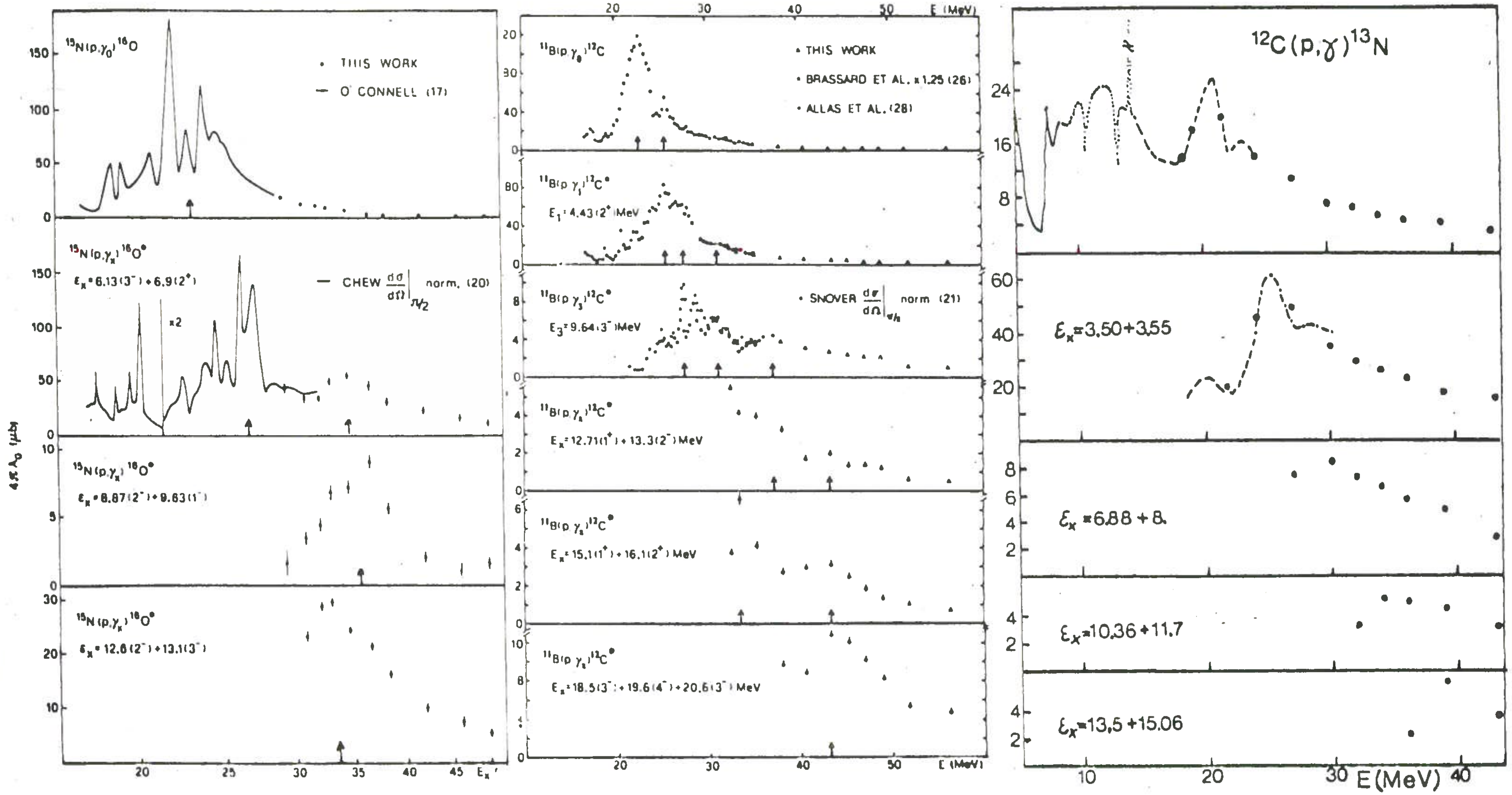

FIG. 3 - Total cross sections of 1p-1h states excited in PRC in ^{12}C, ^{13}N and ^{16}O.

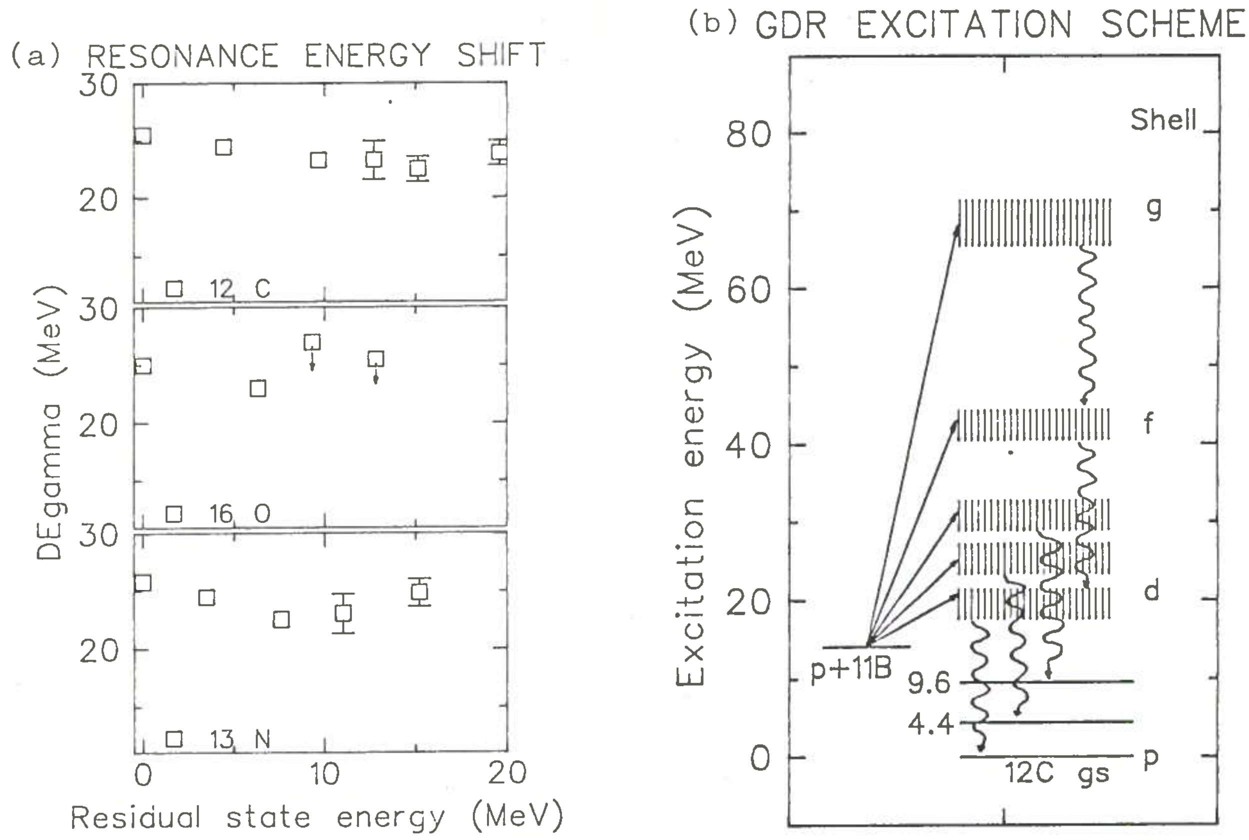

FIG. 4 - (a) The resonance energy shift as a function of the residual state energy; (b) The GDR excitation mechanism as suggested by the energy shift constancy and by the angular distributions results.

The process has been treated theoretically by a few authors, it is considered(12,13) as consisting of a direct reaction mechanism in which the proton radiates a photon undergoing a transition from continuum state to a single particle state relative to the target nucleus, plus a semidirect mechanism in which the proton undergoes the transition exciting a coherent set of p-h states which in turn deexcite emitting a photon, and giving rise to the resonance. The treatment is similar to the one used to explain the basic features of the g.s. GDR and is able to account for the resonance shape and the angular distribution in some instances such as the 19.2 MeV ^{12}C state and the g.s. It fails(13) however in other cases (e.g. the 9.64 MeV 3- in ^{12}C) indicating that more detailed and generalized treatment must be provided as for example within the framework of the RPA and the microscopic models.

If this is a realistic description of the PRC to bound and unbound states in light nuclei, one can sketch the contribution that could be made by NAC in this field.

First of all the existence of the third harmonic of the GDR in ^{12}C has to be confirmed and then identified in other nuclei. The second harmonic region is only superficially explored by experiments that generally show a lack of data on the high energy side of this particular resonance. The GDR built on low lying excited states requires systematics on more and different nuclei, having been limited so far to light nuclei in which the single states spacing is certainly a great advantage in the interpretation of the data, but heavier closed shell or double closed shell nuclei are worth studying and an effort should be dedicated to possible structures of those GDR. The 25-200 MeV range expected for the NAC cyclotron and the availability of a high energy gamma spectrometer of the most recent generation should ensure successful exploration of an entire set of competitive PRC experiments at NAC, covering all the aspects of the new spectroscopy for the excited states that has been exposed by recent experiments.

3.- HEAVY ION RADIATIVE CAPTURE REACTIONS

We should like also to give an example of new evidence shown by recent heavy ion capture experiments, a field in which further developments could hopefully open important perspectives for the NAC cyclotron and for related but complementary Tandem measurements. In HIRC using only a coincidence technique between the emitted high energy photon and the recoiling fused nucleus, a clear separation of transitions to a set of excited states(3) has been exposed. As we see in the example of Fig. 5 concerning the reaction $^{12}C(^{16}O,\gamma)^{28}Si$ with a 20 MeV ^{16}O beam, the states that we quote all have a prolate shape and evidently the inherent prolate configuration of the entrance channel is able to selectively enhance transitions to these states strongly inhibited for other kinds or radiative captures.

The 6.69 MeV state is the lowest in the prolate band of ^{28}Si (Fig. 6) and the analysis of this particular exit channel(3) has shown that a GDR, completely similar in shape and energy to the g.s. one, is built on it, hence resonances can be expected for other excited states in the prolate band of ^{28}Si. This also opens possibility for a new kind of selective spectroscopy.

The role that NAC can play in this field is clearly related to what will come out from lower energy (Tandem) experiments but the field is a rich one, and; taken with the proposed proton capture experiments exploits

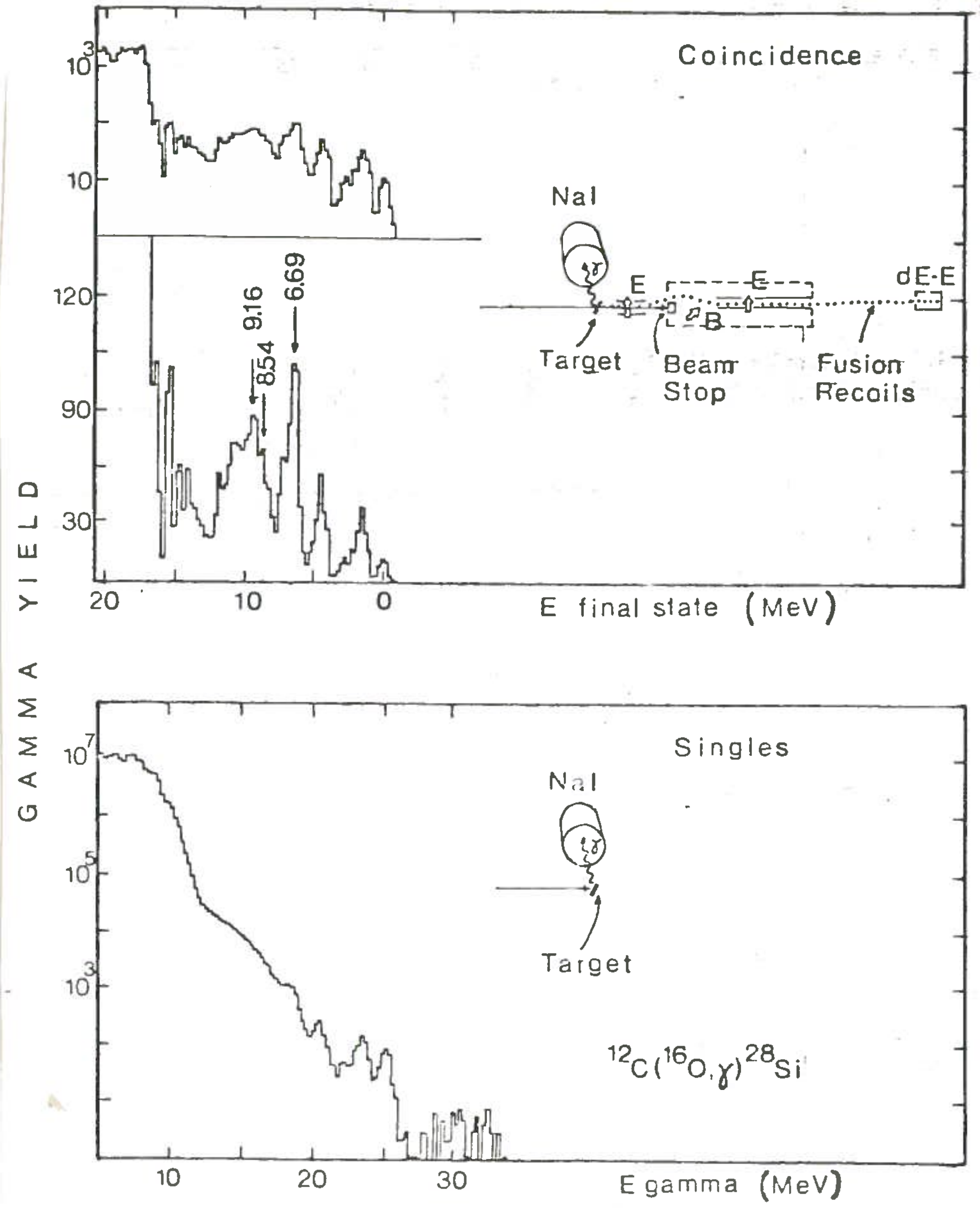

FIG. 5 - The photon spectrum from the reaction $^{12}C(^{16}O,\gamma)^{28}Si$ at beam energy of 20 MeV. The coincidence technique allows clear separation of states in the prolate band of ^{28}Si.

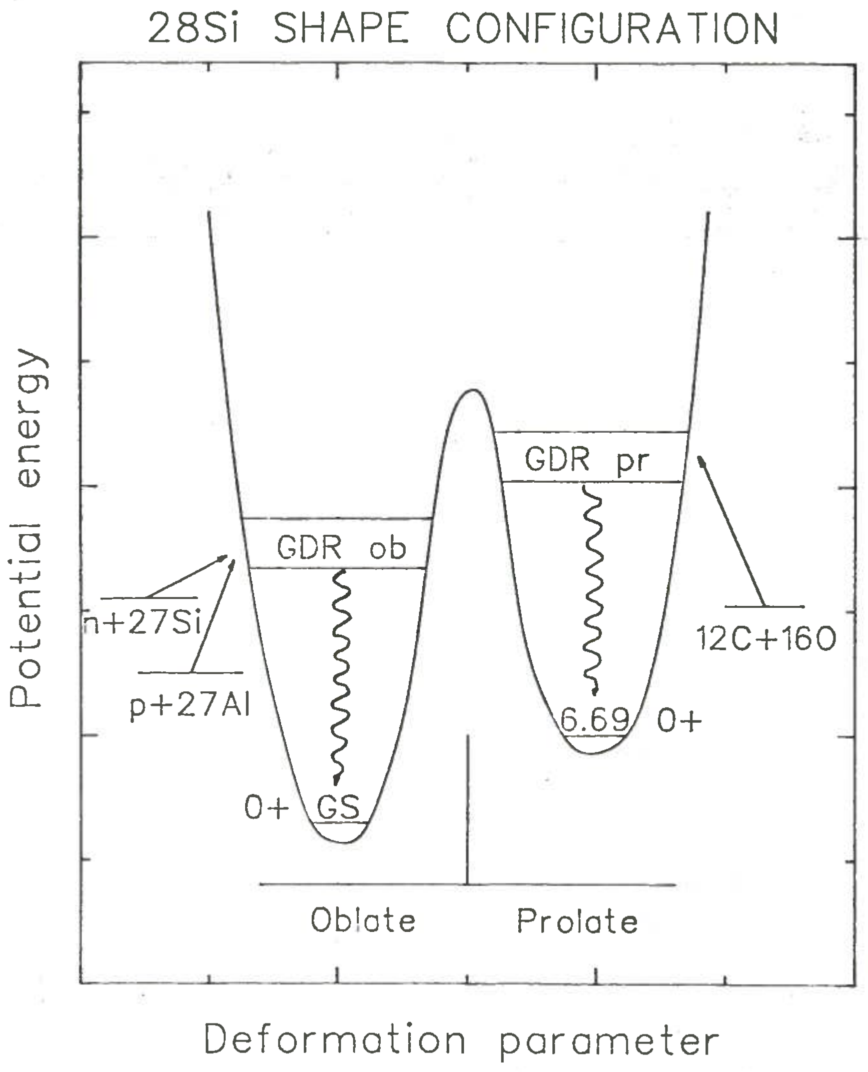

FIG. 6 - Schematic model of the selective excitation of GDR built on excited states of the prolate band of ^{28}Si.

the possibilities offered by the NAC cyclotron ion beams with immediate effort and in an obviously valuable way.

4.- THE HIGH ENERGY GAMMA DETECTOR

With the available current technology the gamma spectrometer for this kind of experiment has a conventional configuration, and despite efforts towards a new generation of solid state detectors(14) this configuration is still highly recommended since its performance is continuously subject to appreciable further improvement.

The detector assembly includes a large volume NaI(Tl) crystal, a plastic scintillator anticoincidence detector both around and in front of the NaI(Tl) crystal to cut off the contribution due to energy escapes from the crystals boundaries, as well as large parts of the cosmic ray contribution which is expected typically to have a count rate comparable to that of the true events.

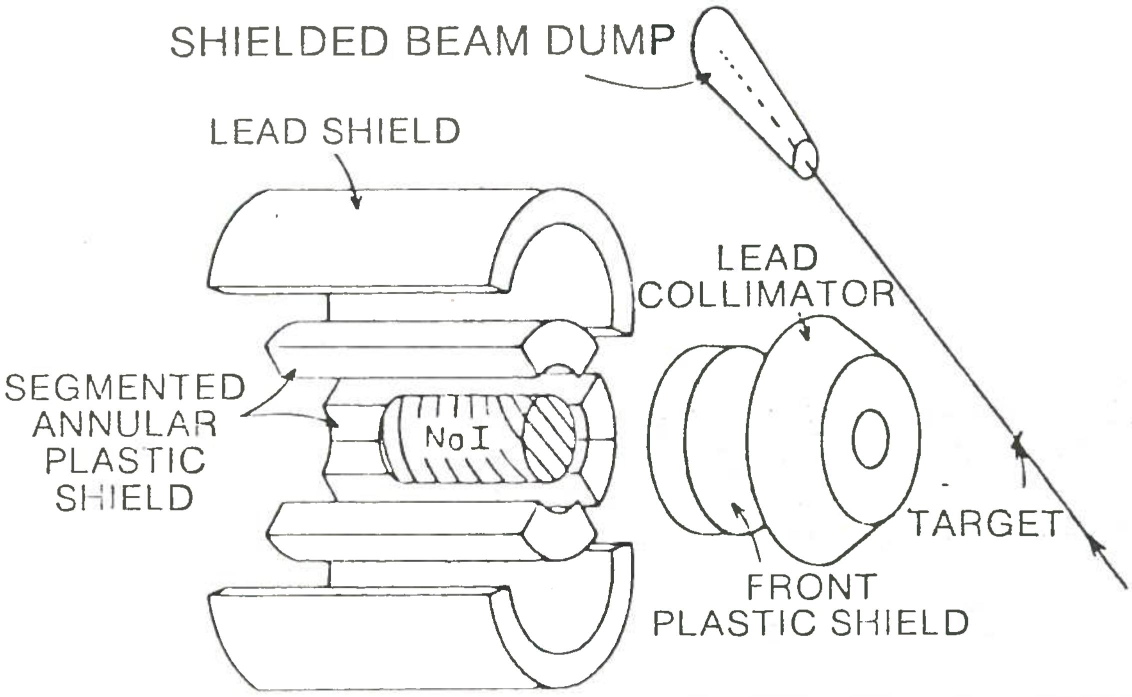

FIG. 7 - Typical design of a large anticoincidence detector for high energy photon spectrometry. This configuration assures high efficiency, good resolution and large solid angle.

Extensive lead shielding and collimation will define the solid angle, reduce the room background and convert the hard muon component of the cosmic radiation. The thermal and diffused neutron background may necessitate additional layers of moderator (paraffin) and neutron absorber (LiH).

From the discussion presented and from the example cited therein it is evident that we have to design a photon detector for energies up to 100 or 120 MeV.

Crirical parameters of the NaI(Tl) crystal are the length and diameter since they determine both the resolution and efficiency. Critical parameters for the anticoincidence shield are the extension and the thickness since they determine the efficiency of rejection of the energy escapes from the crystal boundaries as well as the efficiency of rejection for the cosmic component. A Monte Carlo programme which takes into account all the processes involved in the formation of the electromagnetic shower and its development into various part of the detector permits a reliable estimate for any of this parameters. One of these Monte Carlo codes(15) already tested with real monochromatic photon data up to 60 MeV is available at NPRU and has helped to fix the detector dimension to a diameter not less than 24 cm, and length not less than 35 cm, the anticoincidence thickness of 9-10 cm a length for 6 of the anticoincidence shield of about 60 cm.

The collection efficiency is strongly dependent on the rejection energy threshold which in turn affects sensitively the overall energy resolution, but 40 to 50% efficiency and 2 to 3% resolution should be achieved by such a detector. A remarkable example of the technical improvements achieved in such a detector is that of the BNL MKIII model developed recently in a joint collaboration between the Bicron Corporation and the Brookhaven National Laboratories. With respect to the previous standard design this presents a series of original refinements resulting in an appreciable improvement of the overall performances(14). In particular:

a) The NaI(Tl) is grown as a single ingot, Bicron being the builder of the largest single ingot crystals in the world. An accurate polishing of the crystal surface is made imposing uniformity constraints at 6.13 MeV (average penetration depth 8 cm) with a ^{244}Cm-^{13}C source, instead than at 0.667 MeV as usually (penetration depth less than 1 cm). This iterative technique leads to a final spread of only ± 0.4% and to an improvement of the 6.13 MeV resolution from 4.2% to 3.2% in the anticoincidence mode.

b) The plastic shell is divided into six optically isolated sections each seen by two photomultipliers. This insures a better light collection for each single piece (20% resolution with a ^{137}Cs source) thus allowing a better definition of the rejection threshold (within ± 10% of the average for the whole annulus) and subsequently a better rejection of peak tail events.

c) A very good gain stabilisation is achieved through the use of active transistor stabilized photomultiplier bases and a LED calibration system correlated to the 1.275 MeV gamma line of a built-in ^{22}Na source. This improves the resolution by a further 0.3%.

The resolution curve for the BNL MKIII detector(14) has been measured up to 46 MeV and is presented in Fig. 8. The excellent value of 3.2% at 6.13 MeV is improved to an estonishing 1.96% at 46 MeV thus indicating the very high performance obtainable by a detector so designed.

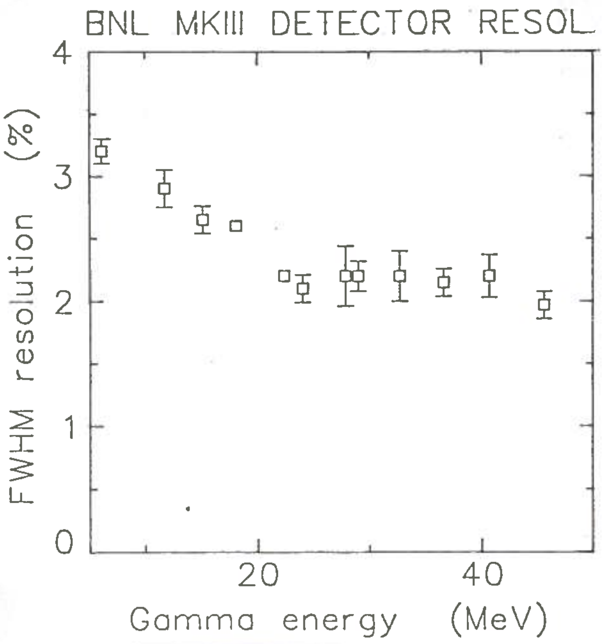

FIG. 8 - Measured FWHM resolution of the BNL MKIII photon spectrometer.

5.- ELECTRONICS

The data handling is an important part of the experiment since most of the functions involved contribute significantly to the final resolution of the apparatus and than to the quality of the information that can be extracted from the high energy photon spectra.

The electronic chain should follow closely the scheme of Fig. 9 to perform the following functions:

i) NaI(Tl)-plastic anticoincidence.

In both scintillators the anode pulses are summed over a 50 Ohm load; RC shaping is used to warrant a better risetime uniformity over a wide dynamic range; timing is provided by constant fraction discriminators; a fast coincidence (20 nsec resolving time) and a gate and delay generator supply the veto logic pulse.

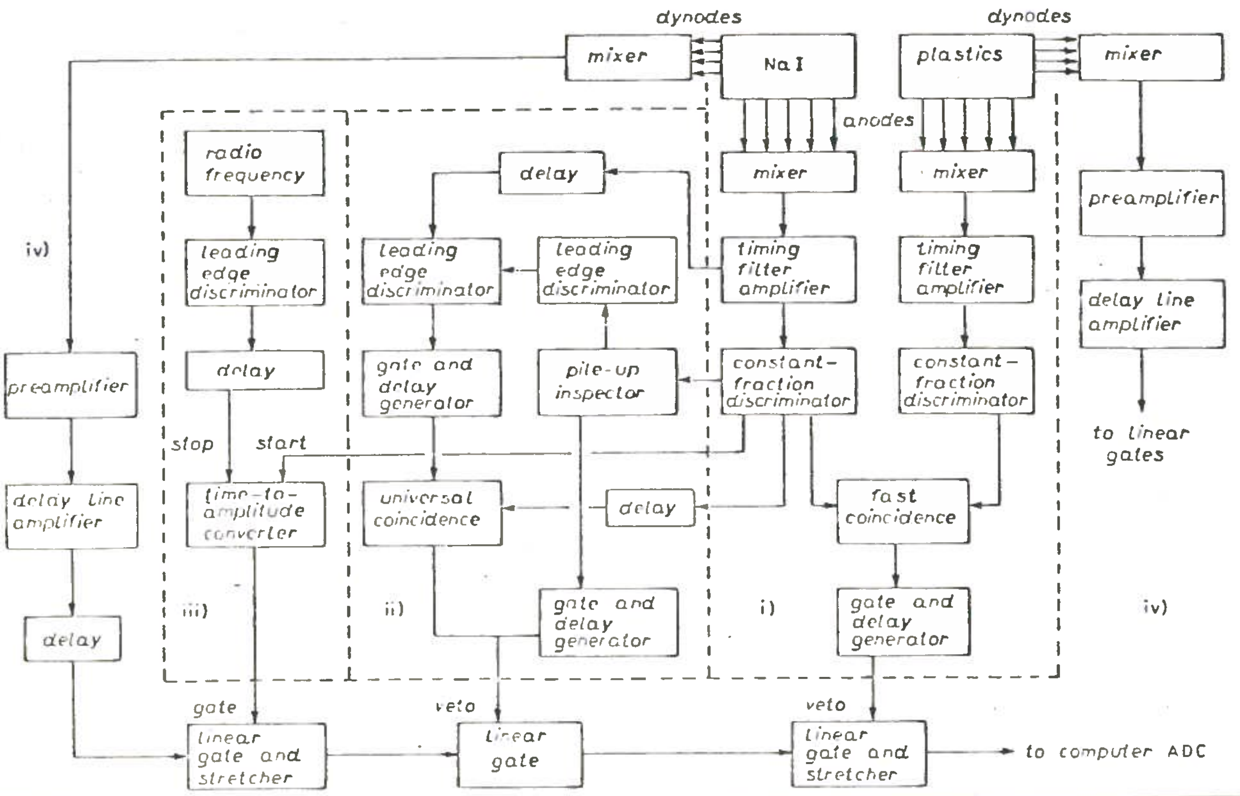

FIG. 9 - The proposed electronic chain to be associated to the detectors. Dashed lines separate the different chain functions. (i) Anticoincidence, (ii) Pile-up rejection, (iii) Neutron TOF discrimination, (iv) Linear analysis.

ii) Pile-up rejection.

If E_{th} is the energy threshold in the NaI crystal, the chain rejects events above E_{th} when piled-up with a pulse occurring either in the energy range $E \geq E_{th}$ or in the interval $E_{low} < E < E_{th}$. The value E_{low} will be chosen comparable with the energy resolution of the spectrometer to prevent peak broadening.

The first rejection is provided by a pile-up inspector; the second one by a coincidence between the NaI(Tl) timing pulse (having already selected the anticoincidence function), and a second one generated by a couple of leading edge discriminators in the range E_{low}-E_{th}.

iii) Neutron gammas time-of-flight discrimination.

The radiofrequency pulses, conveniently processed by a fast discriminator, provide one of the timing pulses, the other coming from the NaI crystal events above E_{th}. To limit the frequency of the events analysed by the window time-to-amplitude convereter the start signal will be the event pulse. If we assume a flight path of 115 cm with a cyclotron period of 40 nsec we will be able to discriminate with an estimated FWHM resolution of 5-6 nsec, photons (3.8 nsec) from neutrons in the range between 100 MeV (9 nsec) down to 4.3 MeV (40 nsec) the low energy ones being normally below the NaI(Tl) threshold.

iv) Linear analysis.

This is as usually performed by a preamplifier and a shaping amplifier (possibly a delay line one) in order to have better definition of the pulse differentiation and consequently a better and more stringent matching between linear and gate pulses.

6.- CONCLUSIONS

We have examined in this proposal the results of the more recent experiments in proton and ion radiative capture reactions.

The perspectives opened by the rather unexspected results in the field of the spectroscopy of excited states are promising and interesting in relation to possible future investigations at the National Accelerator Centre.

The new cyclotron facility at NAC offers indeed great opportunities to exploit, since the beginning of its activity, the prominent characteristics of its beams with a series of competitive experiments both in proton and ion radiative capture reactions.

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