Intermediate Energy Physics Experiments at γ-ALBA, the Proposed Photon Laser Backscattering Facility for Spain.

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We review the experiments of interest in intermediate energy nuclear physics that would be suitable for the proposed nuclear physics line in the synchrotron at Barcelona. We propose to measure Compton scattering and pion photoproduction on protons, deuteron, ^{3}He, and ^{4}He using polarised photons in order to make high precision measurements of all the necessary observables to describe the photoproduction amplitudes. With this kind of measurements the analysis initiated by other laboratories in the region of the first baryon excitation, $\Delta(1232)$, would be completed. Also a deeper knowledge of the nucleon resonance properties in light nuclei would be achieved. We also suggest to study the role of the pion in the nuclear medium. In the longer term we envision the possibility to study also higher line resonances like the Roper resonance or even the pentaquark if enough energy is available. As a guide, figures are given showing the minimal photon energy required for meson production and resonance excitations on the proton and on different nuclei.

I. MOTIVATION

The first proposal for a photo-nuclear physics facility in Spain, taking advantage of the planned synchrotron at Laboratorio de Luz Sincrotrón (LLS) near Barcelona, was presented almost ten years ago [1]. At present, when the details of the facility are known, the proposal has been reactivated and a working group has been organised to discuss its various aspects [2].

This document is a first attempt to convey the deliberations of the group concerning *Intermediate Energy Physics* of the planned photon-nucleus (γ-ALBA) proposal that focusses on the loosely defined region of energy for the incoming photons approximately between 50 MeV and 2 GeV.

The intermediate energy physics (IEP) community of Spain – borderline with the particle and high energy physics community on one side, and with the nuclear structure and nuclear reactions communities on the other – is very active and well represented on the theoretical part. There are internationally well known groups in the most important universities and at CSIC. However, the experimental part of the spanish IEP community is severely under-represented. Particularly so if compared to the high energy physics community of Spain. At any instance we are quite far from the experimental and theory staff ratios of the most developed countries in this field.

The energy range and intensity accomplishable at γ-ALBA are on line with the other few facilities existing around the world, while resolution and polarisation degree of the photons would be in general also not worse than at most of them [3]. It must be noted that gamma-installations are often available at synchrotron radiation centers and at many electron-positron colliders not only due to the interest in research of gamma photons with nuclei, but also because Compton sources are the most useful tools for the diagnosis of the operating rings themselves. Compton scattering is applied in measuring transverse and angular distributions of beams, for determining the position and stability of the beam orbit and for measuring the polarisation of the electrons (if available) inside the storage ring [3]

At present, there are no – and have never been – intermediate energy physics facilities in Spain, of any kind. As we shall see in the present document, the proposed photon-nuclear facility represents the most versatile and cost effective means of putting Spain in the selected league of countries with advanced nuclear physics facilities. There are just a handful of installations capable of intermediate energy studies of photo-nuclear and photo-nucleon processes, while the physics cases that can be addressed are, probably, among the most interesting and numerous that we can deal with. This region of physics has been 'discovered' but certainly has not been fully explored. There are just too few facilities of this

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kind around the world compared to the large number of physics experiments to be performed. hence, the importance of the planned facility cannot be overemphasized, even at the international level.

In what follows we briefly review the type of intermediate energy experiments that could be performed at γ-ALBA but first of all a few considerations are in order. We will put a little bit more detail on the studies that can be achieved with the present design goal of 530 MeV maximum photon energy, but we should keep in mind that this limit represents just the state of the art of laser technology. This area of research is fastly evolving and we cannot close the issue of the actual maximum energy of the incident photons without taking into account the improvements that, for sure, laser technologies will experiment in the next 24 months. Owing to these considerations, we also pay attention to a region of energy that could only be reached if a considerable increase in the maximum photon energy is finally achieved. This would open the possibility to perform a full study of the recently discovered pentaquark state, as well as a deep exploration of as many nucleon resonances as the facility would allow.

To finish this section we would like to state that having the opportunity to perform experiments at such a facility is the dream of any intermediate energy physicist, and having it in Spain is undoubtly the best opportunity that the IEP community of Spain has ever faced.

II. INTRODUCTION

Research on nuclei, nucleons and their excitacions through photon beams have been of great interest over the last decades for the nuclear and particle physics community. From the experimental point of view, one of the main problems lies in that photon facilities had to compromise among achieving either good energy resolution, high degree of polarisation or high photon flux. This has been a very important difficulty in the development of experimental programmes. Development of experimental techniques like laser backscattering allow to gather these three designing goals in the same experiment, measuring interference phenomena and polarisation observables in photonuclear processes [4]. With this kind of measurements pion photoproduction amplitudes can be fully characterized.

Research on baryon excitations through pion photoproduction is of great interest – from both theoretical [5–7] and experimental [8, 9] points of view – due to new available data, specially in the $\Delta(1232)$ region. The main difficulty is the isolation of each resonant contribution from the background due to other resonances and the non-resonant contributions (v.g. light meson exchange). The new generation of high precision experimental facilities are of great importance in this research area. Because of its energy range, the future γ-ALBA facility will be an excellent tool to study $\Delta(1232)$ and possibly the Roper N(1440) nucleon resonances by means of Compton scattering and pion photoproduction on free protons and light nuclei. Also, it would greatly increase our ability to determine physical properties of excitations of free and bound nucleons.

Precise determination of $\Delta(1232)$ and N(1440) properties in a broad energy range, and a correct separation of the non-resonant contributions is very important for theoretical descriptions of pionic effects in nuclei, such as *Meson Exchange Currents* (MEC) [10] or models based upon chiral perturbation theory [11]. Because of the energy range γ-ALBA will be covering, many effects under study will be strongly affected by MEC, and their correct description becomes of great interest.

III. EXPERIMENTAL STATUS

Experiments on pion photoproduction are performed in two different kind of facilities. Those where photons are produced by *bremsstrahlung* – i.e. MAinz MIcrotron (MAMI) in Mainz [12] – and those which produce photons through laser backscattering like γ-ALBA, much more suitable for polarisation measurements. There are several laboratories with photon beams in the energy range that allows the study of the lowest energy nucleon excitations by means of Compton scattering and pion photoproduction. For example, LEGS (Laser Electron Gamma-ray Source, up to 470 MeV)[1] [13] and HIGS (High Intensity Gamma Source, from 2 to 50 MeV) [14] in USA, G.R.A.A.L. (GRenoble Anneau Accelerateur Laser) in France [15] that will be able to study resonances beyond the $\Delta(1232)$ region and meson production because of its operation energy range between 550 and 1500 MeV. Higher energy experiments are carried out at LEPS (Laser Electron Photon Experiment at SPring-8) [16] which operates from 500 MeV up to 2400 MeV. Table I summarizes the characteristics of main laser backscattering facilities around the world.

The most complete experiments on pion photoproduction in the $\Delta(1232)$ region have been performed at Mainz [17] and Brookhaven[2] [18]. Details on LEGS experiments are valuable for γ-ALBA proposals due to the similar energy range of both facilities. Actually, some of the experiments here proposed on free protons and ^{4}He have been carried out at Brookhaven (Refs. [18] and [19] respectively), but it is convenient to repeat them with higher statistics and better resolution as would be achieved in γ-ALBA, in order to confirm and complete their results.

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[1] All energies are in laboratory frame.
[2] A second part of the experiment is currently running and new experimental data are expected by the end of 2004.

	Taladon	ROKK-1	ROKK-2	ROKK-1M	LEGS	GRAAL	LEPS
Location	Frascati	Novosobirsk	Novosobirsk	Novosobirsk	Brookhaven	Grenoble	Harima
Storage Ring	Adone	VEPP-4	VEPP-3	VEPP-4M	NSLS	ESRF	Spring-8
Energy definning method	int.tg.	tagging	tagging	tagging	ext. tg.	int. tg.	int. tg.
Electron energy (GeV)	1.5	1.8-5.5	0.35-2.0	1.4-5.3	2.5	6.04	8
Laser Photon Energy (eV)	2.45	2.34-2.41	2.41-2.53	1.17-3.51	3.53	3.53	3.5
γ-ray Energy (MeV)	35-80	100-960	140-220	100-1200	180-320	550-1470	500-2400
Energy Resolution (%)	5	-	1.5	-	2	1.1	1.25
Electron Current (A)	0.1	0.2	0.2	0.1	0.2	0.2	0.1
FWHM (MeV)	4-2	1.5-2	4	-	0.2	0.2	0.1
γ Intensity (s^{-1})	$5 \cdot 10^5$	$2 \cdot 10^5$	$2 \cdot 10^6$	$2 \cdot 10^6$	$4 \cdot 10^6$	$2 \cdot 10^6$	10^7
Date of operation	1989	1982	1987	1993	1987	1996	1999

TABLE I: Laser backscattering facilities around the world [15] (int. tg. stands for internal tagging and ext. tg. for external tagging).

IV. TYPICAL EXPERIMENTAL PROPOSAL

We propose the measurement of Compton scattering $(\vec{\gamma},\gamma)$ and pion photoproduction $(\vec{\gamma},\pi)$ on free protons, deuteron, ^{3}He, and ^{4}He. To reduce uncertaities we suggest to measure in the same experiment the reactions (γ,γ) and (γ,π). In this way, the systematic error is similar for all data and Compton scattering can be used for pion photoproduction analysis. Measurements of different channels contribute to a better determination of multipoles [18]. The expected maximum energy of the photons is 530 MeV with existing laser technology in use in other facilities. Heavier targets will increase the energy available to excite nucleon resonances (see figures 1 and 2). Pion photoproduction experiments are an excellent way to test the quality of the experimental facility and perform beam calibration.

The ^{4}He experiment is specially interesting for γ beam polarisation calibration because the ^{4}He spin ensures a zero contribution to the cross section from photons with parallel polarisation to the scattering plane. Thus $\Sigma = -1$ for any energy [18, 19]. The experiments proposed are developed in the following subsections in somewhat more detail.

A. Compton scattering and pion photoproduction on free protons: $\mathbf{p}(\vec{\gamma},\gamma)$, $\mathbf{p}(\vec{\gamma},\pi^0)$ and $\mathbf{p}(\vec{\gamma},\pi^+)$.

This kind of experiments constitute a first step in the development of an experimental pion photoproduction programme. We suggest to repeat the experiments performed over the last years, specially at LEGS [18], and to complete the experimental analysis by increasing the database of multipoles and polarisation observables in order to solve discrepancies among results of different laboratories. It has to be said that there are important discrepancies between the last analysis at Brookhaven and experimental data obtained at Mainz over the last decade[3].

Detailed experimental study of multipoles is critical. The $E_{1+}^{3/2}$ multipole is dramatically affected by final state interactions between the outgoing pion and the proton. There are great uncertities in this multipole and a lack of experimental knowledge between 300 and 400 MeV that the last experiment at LEGS has started to fill in [18]. It would be of great interest to increase the experimental database for several multipoles in the low energy region (v.g. E_{0+}^p, E_{1+}^p and M_{1+}^p below 200 MeV, M_{2-}^p below 400 MeV and M_{1-}^p and $M_{2-}^{3/2}$ in the whole energy range of the synchrotron). New experimental techniques would be needed to achieve these measurements.

The latest theoretical analysis of Compton scattering [20] do not agree with those performed for pion photoproduction [6], specially with regards to the E2/M1 ratio (EMR) of $\Delta(1232)$ and helicity amplitudes. These observables are of great importance because theoretical models predict values between -0.5% and -6% depending on the existence of a pion cloud around the nucleon. Experiments performed in the last years favour models with the pionic cloud, although EMR is not quite well known, $EMR = -2.5 \pm 0.5\%$ in Ref. [21] and $EMR = -3.07 \pm 0.26$ (stat.+syst.) $\pm$ 0.24 (model) % in Ref. [18]. The solution of the theoretical-experimental puzzle about the $\Delta(1232)$ is one of the aims of this proposal. If enough photon energy is available also the Roper resonance could be studied. The Roper resonance is of great interest for MEC descriptions and its structure and properties are not clear. The recent claims of a pentaquark antidecuplet would seem to require an $N(1650)$ to satisfy the Gell-Mann-Okubo rule with the known $\Sigma(1770)$ and the reported $\Theta(1540)$, $\Xi(1860)$. This resonance has been identified with the $N(1710)$ mixed with the $N(1440)$ and split by level repulsion. If ideal mixing is

[3] A detailed comparison among different experimental data can be found in Ref. [18]

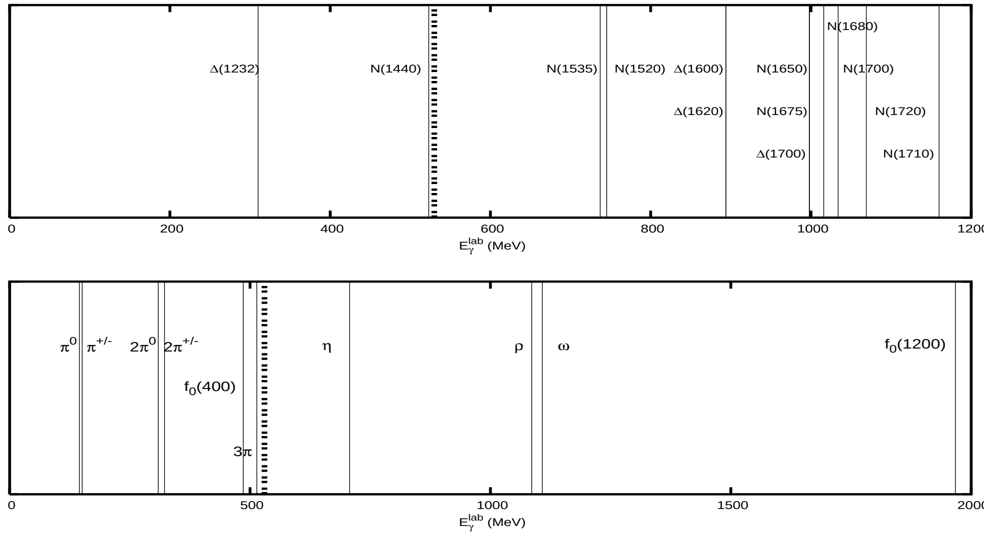

FIG. 1: Upper panel: Spectrum of nucleon resonances on free protons depending on the incident photon energy in laboratory frame. We show resonances with three and four stars in Ref. [21]. Resonance masses are taken from the pole position data of reference [21]. Lower panel: Spectrum of meson production on free protons depending on the incident photon energy in laboratory frame. Because of the large energy range for f_0 we show its value for both maximun and minimun masses. The dashed line stands for the preliminar γ-ALBA maximun energy.

supposed, the lightest resonance (the Roper) has a significant pentaquark component with no hidden strangeness, that is, it can be viewed as largely a baryon with an additional light quark-antiquark pair. The $N(1710)$, carrying the hidden strangeness, would remain out of the reach of γ-ALBA.

B. Compton scattering and pion photoproduction on nuclei.

The use of nuclear targets instead of free protons reduces the energy transferred to the recoiling system and thus increases the energy available to excite nucleon resonances. Furthermore, the Fermi motion of nucleons inside nuclei widens up even more the range of kinematically allowed processes, for a given photon energy. Additionally, targets as ^{3}He are easily polarised, what adds new observables to p study. On the other hand, the recoiling system being complex, many different reaction channels can happen, but suitable coincidence techniques should help isolating the particular channel. For instance, at the kinematics we are considering in this document, detection of the recoiling nuclear system with high resolution in energy can be achieved with the use of fully depleted thin silicon detectors, employing the silicon nuclei in the detector as target.

Furthermore, the study of the indicated processes in complex nuclei will certainly shed light on the behaviour of nucleons, pions and other mesons inside the nuclear medium.

1. Compton scattering and pion photoproduction on deuteron: $d(\vec{\gamma},\gamma)$, $d(\vec{\gamma},\pi^0)$, $d(\vec{\gamma},\pi^+)$ and $d(\vec{\gamma},\pi^-)$.

The aim is to use deuteron as a first step to study pion photoproduction on light nuclei [22] and to establish the influence of $\Delta(1232)$ in its structure. Combination with previous analysis on protons allow to obtain information about the neutron. We need to measure differential and total cross sections as well as polarisation observables. The amount of experimental information is really small and the majority of the experiments were performed many years ago [9]. Thus, a large reduction of the error bar for the observables is expected. The role of other resonances, such as the Roper, is also of great interest.

2. Compton scattering and pion photoproduction on ^3He: $^3He(\vec{\gamma},\gamma)$, $^3He(\vec{\gamma},\pi^0)$, $^3He(\vec{\gamma},\pi^+)$ and $^3He(\vec{\gamma},\pi^-)$.

As far as we know, there are no pion photoproduction experiments on ^{3}He with polarised photons in the energy range of γ-ALBA. Nevertheless, this process is of great interest at the present thanks to realistic three-body models [23] developed in the last years and Compton [20] and pion photoproduction models [7] with consistent $\Delta(1232)$ description. In this way we would be able to perform an acceptable theoretical analysis of the influence of the $\Delta(1232)$ in systems like ^{3}He and few body systems. In addition, availability of polarised ^{3}He and polarised photon beams allow the determinationof many helicity asymmetries which can provide information about models.

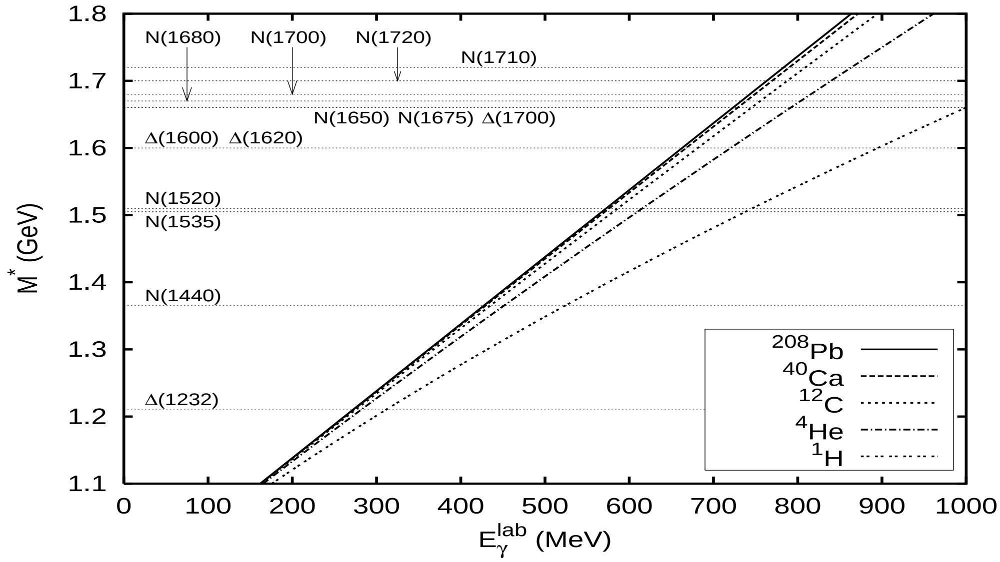

FIG. 2: Available energy for resonance excitations with different targets depending on the incident photon energy in the laboratory frame. Pole masses of nucleon resonances are marked in the figure as horizontal lines.

3. Compton scattering and pion photoproduction on ^{4}He: $^4He(\vec{\gamma},\gamma)$, $^4He(\vec{\gamma},\pi^0)$, $^4He(\vec{\gamma},\pi^+)$ and $^4He(\vec{\gamma},\pi^-)$.

^{4}He is a high density and highly bound nucleus, compared to any other light nuclei. With only four nucleons, ^{4}He is strongly bounded and the role of the pion is emphasized. Thus, pion photoproduction appears as an excellent mechanism to study the pion in the nuclear medium. The role of the $\Delta(1232)$ and final state interactions may be also important, being of great interest for physicist who are developing few body models. Because of ^{4}He spin ($J = 0$), the contribution of photons with polarisation parallel to the scattering plane is zero and the asymmetry $\Sigma = -1$ for any energy. There are experimental data in the energy range of 200 to 300 MeV [19] where no violation of $\Sigma = -1$ was found. High precission measurements of possible violations of this asymmetry in a broad energy range seems to be a suitable mechanism to search for internal structure effects in ^{4}He.

C. Further experiments:

a. Further meson production. In the energy range expected for γ-ALBA the production of further mesons can be envisioned. By looking at figure 1 we observe that the threshold for two-pion production is well below 500-600 MeV. This channel has been studied in the past, but precision studies are possible. One goal of such studies would be the narrowing of error bands for the parameters of the standard chiral lagrangians. An exotic channel is readily available through double-charged pion production $\gamma Z \to (Z-2)\pi^+\pi^+$. This isospin $I = 2$ channel cannot hold a molecular-type resonance as the strong interaction is repulsive [24], but γ-ALBA could exclude the presence of any intrinsic narrow state (automatically a tetraquark) such as the much debated pentaquark in a flavor-exotic KN wave. Exotic spectroscopy is expected to come to the forefront of research in the upcoming years [25].

On the contrary, the production of $I = 0$ pion pairs is guaranteed to give a window into the established physics of the σ resonance[4] $[f_0(400-1200)]$, a broad structure in $\pi\pi$ scattering and final states that is expected to have a large molecular-type tetraquark component [26]. The connection of this resonance to the Roper [27] can also be studied for example by the two-pion plus nucleon decay of the Roper.

Another threshold that can be reached is that for three-pion production. The detailed study of this final state is of interest for fundamental problems of the strong interactions, as it allows to undertake studies of several-body problems with chiral lagrangians and the reach of chiral symmetry can be further tested. Multipion states are under active investigation by several high-energy experiments [28] and γ-ALBA would have to provide precision lower-energy studies.

Finally, although photoproduction of $\eta(547)$ requires some 700 MeV on a hydrogen target, its threshold is lowered on heavier nuclei and can be within reach of γ-ALBA depending on its final energy range. Again, precision studies of $SU(3)$ lagrangians are now possible, and topics like hidden strangeness or $SU(3)$ breaking could potentially be addressed. The role of this meson inside nuclei could also be studied from its characteristic two-photon decay. It also provides three-pion final states with very well defined energy.

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[4] Current estimates put it at 500 MeV.

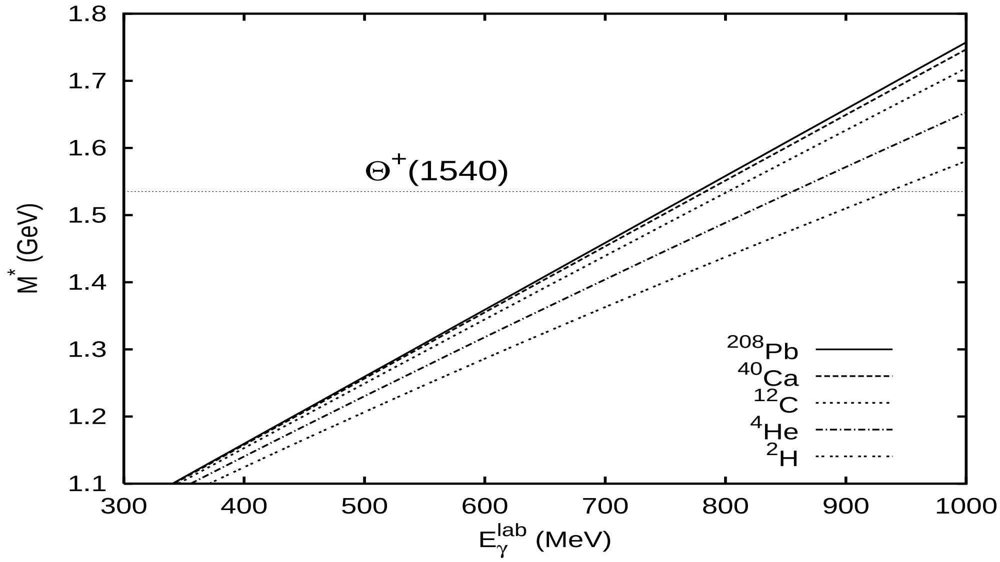

FIG. 3: Pentaquark production on nuclei. The pentaquark mass is marked as an horizontal line at $M^* = 1535$ MeV. The considered reaction is $\gamma A \to \Theta^+(1540) + B \to \ldots$, where B is an hypernucleus.

b. Pentaquark. Since the first experimental traces of its existence [29], the pentaquark, $\Theta^+(1540)$, is undoubtly one of the hottest topics in intermediate energy physics. Due to this interest of the scientific community it should be studied whether γ-ALBA facility gives any possibility to contribute to research on the non-three quark baryons and mesons states. A pentaquark production experiment on free nucleons requires an amount of energy that is far away from γ-ALBA facility, but there are other possibilities that should be considered. For the same reasons as in subsection IV B the threshold energy of pentaquark production is reduced on nuclei. This is presented in figure 3. The energy reduction from the free case is considerable and it would be possible to excite a pentaquark with only 800 MeV on a ^{12}C target. If these kind of experiments could be carried out, γ-ALBA would become one of the first facilities of the world to start an experimental programme on pentaquark excitation in nuclei, begining the study of its properties and effects in nuclear medium.

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