New lines of research with the MAGNEX large-acceptance spectrometer

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Abstract: A new design of magnetic spectrometer, MAGNEX, is under construction for the INFN-LNS, Catania. It is primarily intended for use with the Tandem-accelerated radioactive beams from the EXCYT facility. Both projects are expected to be completed by early 2004. The unique features of MAGNEX are its solid angle of acceptance (51 msr), momentum acceptance (±10%), overall momentum resolution of 1/2000 and mass resolution of 1/200, together with a focal plane detector having a low detection threshold (0.5 MeV/A). The spectrometer is based on a 55° bend angle dipole magnet with mean radius of 1.6 m. It is designed for a maximum rigidity of 1.8 Tm. Despite the large acceptance, a good momentum resolution is achieved by a combination of careful ion-optical design and software ray-reconstruction. The latter depends on three things: the availability of detailed field maps, the precise measurement of position and angle by the detection system, and the solution to high order of the equation of motion based on, in our case, the program COSY INFINITY. The MAGNEX spectrometer, connected with the broad choice of both stable and radioactive beams at the LNS, will provide new opportunities for, e.g., spectroscopy of weakly-bound nuclei by direct reactions, reaction mechanisms with large isospin and nuclear astrophysics.

Introduction

Historically the technique of magnetic spectrometry for nuclear physics experimentation has enjoyed enormous advantages with beams from Tandem accelerators. The coupling to the excellent emittance of these beams allows the full exploitation of the high energy and mass resolving power of a magnetic spectrometer. In addition the possibilities to measure at very forward angles (including zero degrees), to compensate for the energy dependence of the reaction products with scattering angle, and to suppress part of the background through a Bρ analysis strongly enhance the attraction of such devices. Benchmark examples like the Enge Split-Pole [1] or the Q3D [2] of the 1960s and '70s, and many others, indicate the durability of magnetic spectrometers for studies of nuclear spectroscopy and reaction mechanisms at low bombarding energy. A limitation of these devices has been the low acceptance (not more than 10 msr solid angle), mainly due to the high order aberrations generated for large solid angles and momentum bites. Recently, with the advent of the ray-reconstruction techniques, the performances of magnetic spectrometers in terms of acceptance have been upgraded (~20 msr for the Osaka LAS [3] and the NSCL S800 [4]) and new scenarios have been consequently opened.

The concept and layout of the MAGNEX spectrometer has been described in refs. [5-7]. In brief, it is a large-acceptance device (50 msr) based on a vertically-focussing quadrupole and 55° bend-angle dipole. The angles and profiles of the dipole entrance and exit pole faces are used to correct partly the aberrations in the ion-optics. Further corrections are performed in software by a ray-reconstruction technique, resulting in an expected average momentum resolution of about 1/2000.

The ray-reconstruction is based on a solution to high orders of the equation of motion using, in our case, the program COSY INFINITY of Berz [8]. Detailed measured field maps in five vertical planes are used. A position-sensitive timing detector (PSD) between the target and quadrupole gives both the angle of the scattered particles and a start signal for the time-of-flight. The focal plane detector (FPD) measures positions and angles as well as providing particle identification information [9].

Presently the spectrometer is in an advanced step of construction, the end of which is foreseen for the beginning of 2004. In this paper we focus on some of the experimental opportunities opened by the advent of MAGNEX at the LNS, including its use with radioactive ion beams (RIB) from the ISOL-type EXCYT facility [10]. In Section 1 an overview of the type of experiments accessible with the spectrometer is given. Of course it is only our own view of the use of the device and does not necessarily reflect the type of experiments that will be performed. In Section 2 a deeper analysis of the MAGNEX capabilities is shown in reference to a specific RIB experiment simulated with our Cosymag routine libraries [11]. In Section 3 the conclusions and future prospects are discussed.

1. *Direct reactions with Tandem stable beams*

Recent studies have shown how the (^{7}Li,^{7}Be) reaction at Tandem energies is a powerful tool to explore the excited states of light neutron rich nuclei [12]. In ref [13] an energy resolution of 50 keV has been obtained in the excitation energy spectrum of ^{11}Be by detecting the ^{7}Be ejectiles with the Split-Pole magnetic spectrometer at IPN-Orsay. The observation of narrow resonances embedded in the continuum (BSEC), well beyond the ^{11}Be neutron emission threshold, has raised the question whether this phenomenon is connected to the exotic properties of the ^{11}Be structure. It has stimulated similar studies for different ions such as ^{12}B, ^{14}B, ^{15}C and ^{7}He. A clear indication of the BSEC has been obtained [14,15] for the ^{15}C nucleus, which presents many similarities with ^{11}Be. It is worthwhile to note that both ^{11}Be and ^{15}C have a structure of 3 neutrons coupled to an integer number of α particles. The analysis of the data for ^{7}He, which also has an Nα + 3n structure, is in progress. Such results have determined the development of sophisticated microscopic theories based on QRPA. The calculated response functions have shown how these narrow resonances cannot be explained as 2 quasi-particle (2QP) excitations and need a broader phase space including at least 4QP configurations. The microscopic model of Dynamical Core Polarisation (DCP) of refs. [16,17], which accounts for the correlation of 4QP core phonons with single particle excitations of the external neutron, predicts the existence of narrow resonances at low excitation energy for light neutron rich odd nuclei. This is due to the presence of a weakly bound, and thus easily polarizable core, e.g., ^{10}Be for the ^{11}Be nucleus and ^{14}C for the ^{15}C, that effectively exchange energy with the unpaired single neutron. Consequently the energy produced in a collision, proceeding through a direct mechanism, can be directly transferred to the core, the valence neutron being weakly influenced. In the extreme case of BSEC the valence nucleon remains bound to the core even when the energy transferred to the whole nucleus by the direct process would be enough to extract it.

A systematic study of the Nα + 3n nuclei up to the Iron-Nickel region via the (^{7}Li,^{7}Be) reaction at Tandem energies would allow us to follow the evolution of this phenomena as a function of the mass, charge and binding energy. This would greatly help to understand the microscopic origin of the BSEC and to clarify whether this phenomenon can be described within the general framework of mean field theory or many-body correlations are unavoidable. This study has been hindered up to now by the reduction of the cross sections for heavier systems at the low incident energy necessary for achieving the high resolving power in the energy spectra. The use of the MAGNEX spectrometer with its large solid angle (more than 25 times the Split-Pole) will open new opportunities in this field. The energy resolution achievable will be of the order of 50 keV, thus allowing a clean separation of most of the excited states.

2. *DCX and transfer reactions with ^{14}C beam.*

A ^{14}C beam from the Catania Tandem or Superconducting Cyclotron could be used for the study of (^{14}C,^{14}O) double charge exchange (DCX), as well as for multinucleon transfer reactions such as (^{14}C,^{16}O) and (^{14}C,^{10}C). Example cases are given below.

The 2-proton pickup reaction (^{14}C,^{16}O) could be used to study neutron-rich nuclei, making use of the favourable Q-values (no less than –2 MeV in most cases). Potentially-interesting light targets would be ^{40}Ar, ^{30}Si, ^{26}Mg, and ^{18}O, leading to ^{38}S, ^{28}Mg, ^{24}Ne and ^{16}C, respectively.

The DCX reaction might be used with, e.g., ^{7}Li, ^{9}Be, ^{11}B, ^{13,14}C, ^{22}Ne targets to study ^{7}H, ^{9}He, ^{11}Li, ^{13,14}Be, ^{22}O, respectively. The expected cross sections are in the range 0.1 to 0.5 μb [18]. Realistic simulations for the ^{11}B(^{14}C,^{14}O)^{11}Li reaction at 105 MeV have shown that an energy resolution of 140 keV is achievable in energy spectrum of ^{11}Li and a counting rate of 1.5 events per hour. In the simulations we assumed a beam intensity of 10^{10} pps , a target thickness of 100 μg/cm^2, solid angle of 50 msr and a cross section of 100 nb/sr. The 50 msr solid angle means that the ^{14}O ejectiles are detected over the full acceptance of the spectrometer, which can be done with MAGNEX because of its effective capability to compensate even severe kinematic effects. It should be emphasized that, using MAGNEX, high resolution spectra are accessible for ^{11}Li even in the regime of 100 nb/sr.

The 4-neutron stripping reaction (^{14}C,^{10}C) potentially would allow the study of neutron rich nuclei even further from the stability line. Of course, due to the rather negative Q-values (around –20 MeV at best) and to the complex transfer mechanisms, the cross sections are anticipated to be very low (perhaps a few hundred nb/sr). For that reason, similar to the DCX reactions, a large solid angle and the compensation of the kinematic effect are expected to be crucial for such experiments, for which MAGNEX is thus a unique tool.

Another interesting use of a ^{14}C beam would be in the search for giant pairing resonances through the (^{14}C,^{12}C) reaction as an alternative to the (t, p) reaction. The pairing resonances are $2\hbar\omega$ 0^+ collective excitation of a pair of particles (or holes) coupled to the continuum, predicted by Broglia and Bes in 1977 [19]. The predicted excitation energy range is 15 to 25 MeV, with a width of 2 to 3 MeV. The best probes would be weakly-bound n-rich projectiles on “open-shell” n-rich targets. Previous experimental searches were done with the Orsay SC in 1989 using the ^{208}Pb(p,t)^{206}Pb and ^{116}Sn(p,t)^{114}Sn reactions [20]. The latter was compared with exisiting ^{116}Sn(α,^{6}He)^{114}Sn data. The results in terms of the pairing resonance were not definitive, although the authors were able to deduce stretched (Valence+Deep) hole configurations near E_x = 8 MeV in ^{114}Sn.

3. *Direct reactions with EXCYT RIB’s*

The precise plan for future experiments is obviously dependent on what RIB’s are developed for EXCYT. One interesting nucleus that may be studied with a ^{9}Li beam and the (d,p) reaction in inverse kinematics is the unbound ^{10}Li. The interest is in the location of the $2s_{1/2}$ and $1p_{1/2}$ resonances, which is an important stepping-stone to a better understanding of the classic 2-neutron halo nucleus ^{11}Li. Further details may be found in the contribution by Angela Bonaccorso [21]. As another example, we consider a first the use of an ^{14}O beam for the two-proton stripping reaction (^{14}O,^{12}C). This reaction has a typically small negative, or even positive, Q-value, and would be a powerful spectroscopic tool to investigate proton-rich nuclei. The idea is that the favourable Q-value matching [22] would enhance the reaction cross section sufficiently to overcome the inherently weak beam intensity and possibly excite previously-unobserved states. To illustrate the

Q-value advantage of the (^{14}O,^{12}C) reaction, one may compare it with other charged-particle reactions which have been used to study the weakly-bound proton-rich ^{8}B nucleus in the past:

Reaction	Q-value (MeV)
^{6}Li(^{14}O, ^{12}C)^{8}B	**-0.829**
^{11}B(^{3}He,^{6}He)^{8}B	-16.92
^{10}B(p, t)^{8}B	-18.53
^{7}Li(^{7}Li,^{6}H)^{8}B	-34.97

One disadvantage of the (^{14}O,^{12}C) reaction compared with the lighter ion reactions is the loss of energy-resolution because of straggling and energy-loss differences in the target. However, preliminary simulations for the MAGNEX spectrometer show that a target thickness of 250 μg/cm^2 would lead to a resolution of about 300 keV in the excitation spectrum. Even with such a relatively thin target, one might still obtain an acceptable count rate: a few per hour in a peak for which the cross section were ~ 0.5 mb/sr, with a ^{14}O beam intensity of 10^5 pps.

The (^{7}Li,^{7}Be) studies described in Section 1 may be extended to the use of RIBs from the EXCYT facility. Inverse kinematic reactions and the large acceptance of MAGNEX would be used to overcome the low secondary beam intensity. One of the first beams from EXCYT will be ^{8}Li [23]. We can use this beam to study the neutron-rich nucleus ^{8}He. The proposed experiment is ^{7}Li(^{8}Li,^{7}Be)^{8}He, i.e., the ^{8}Li beam bombards a ^{7}Li target and ^{7}Be reaction products are detected in the focal plane of the spectrometer. Pure (self-supporting) lithium targets are generally difficult to make, but by doing the reaction in inverse kinematics carbon or oxygen impurities or backing material in the target are not important because they would be unlikely to produce ^{7}Be nuclei from a ^{8}Li beam. One of the interests in ^{8}He is that the ground state has a significantly extended matter distribution compared to ^{4}He, and is considered [24,25] to have an α-like core surrounding by 4 neutrons. The current consensus is that ^{8}He is not a halo nucleus, but instead has a *neutron skin* [24, 26]. Besides the possibility of exciting bound states in the continuum, in a similar manner as for ^{11}Be, the low-lying level structure of ^{8}He could be more firmly established. In the most recent evaluation of mass 8 nuclei, three excited states in ^{8}He (S_{2n} = 2.14 MeV) are listed at ~ 3.1, 4.36 and 7.16 MeV [27] with evidence for another at 6.03 MeV [28]. In fact, it is not clear whether the 2^+ first-excited state at ~ 3.1 MeV is a single state or two states: some groups have reported a level near 2.7 MeV [29,30], others give the excitation energy as about 3.6 MeV [31-33] (in addition, Belozerov et al. [29] report a level at 1.3 MeV). With a high resolution spectrum from a generally unselective reaction as (^{7}Li,^{7}Be), one might expect either to excite both levels (if there are two) or determine a more precise energy of a single level.

For the above ^{8}He experiment a complete simulation accounting for the ray reconstruction technique [11] is presented in the following. In the simulation a beam of 57 MeV incident energy and of 1.6 × 10^6 pps intensity is assumed, according to the preliminary predictions for the EXCYT facility [23]. From the systematics for light nuclei of the (^{7}Li,^{7}Be) reaction at 57 MeV, the cross section for the Gamow-Teller transition from the ^{8}Li$_{gs}$(2^+) ground to the ^{8}He(2^+) excited state is estimated to be about 100 μb/sr at forward angles. The weak intensity of the beam and the low value of the cross section put severe constraints on the solid angle and target thickness, in order to perform the experiment in a reasonable time. For this purpose the large solid angle (50 msr) of MAGNEX, connected to the precise reconstruction of the scattering angle and the effective compensation of the kinematic effect, are key elements for the feasibility of this experiment. The kinematic broadening of the peaks in the energy spectra due to the large scattering angle interval (from 1° to 15°) is more than 2 MeV when the spectrometer aperture is fully open. Under these conditions the counting rate per each micron of target thickness is about 0.8 counts / 1 μm × hour, while the effect of target on the energy resolution is about 28 keV / 1 μm. To limit this contribution to the energy resolution to within 200 keV a counting rate of about 6 counts / hour is achievable. This leads to the necessity to fix the spectrometer in the same conditions for at least 100 hours to get enough counts in the GT transition peak. In Fig. 1 the initial conditions of the simulations are shown for a sample of 20000 particles distributed over 12 simulated levels, which corresponds to about 300 hours of measurement. The ground and the known excited states at 2.7, 3.6, 6.03, 7.16 MeV are visible. A broad resonance known at 4.5 MeV is also included. In the simulation the 2.7 and 3.6 MeV states are both considered to exist, and the experimental goal is to resolve them. For each ^{8}He excitation two lines are present in the spectra, arising from either the population of the ground or the 0.429 MeV bound excited state of the ^{7}Be ejectiles. The strong kinematic effect is evident in the plot, appearing as a noticeable curvature of the kinetic energy lines as a function of the scattering angle. In the right panel of Fig. 1 the projected kinetic energy spectrum is shown, emphasizing the need to measure the scattering angle with good precision. It is important to bear in mind that any possible angular segmentation of the data is hindered by the very low counting rate of this experiment.

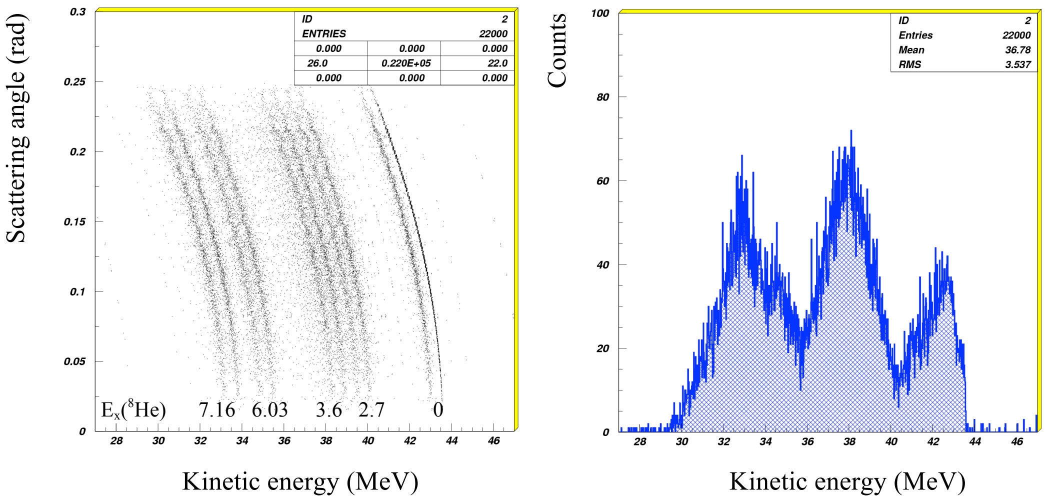

Figure 1. Left panel; initial conditions (after the target) for the simulation of the ^{7}Li(^{8}Li,^{7}Be)^{8}He reaction at 57 MeV. Right panel; initial energy spectrum.

The distribution of particles along the focal plane after tracking through the spectrometer is shown in Figure 2. In the simulations all the active and dead layers are included realistically. To reduce the kinematic effect, the detector has been shifted to the predicted location of the focal plane (as allowed by MAGNEX), and the quadrupolar and sextupolar surface correction coils are used. The scatter plot and the one dimensional spectrum give an idea of the difficulties with the large acceptance condition if trajectory reconstruction is not employed, even with an optically-refined spectrometer such as MAGNEX [7]. The position resolution is obviously not enough to distinguish the peaks at 2.7 and 3.6 MeV.

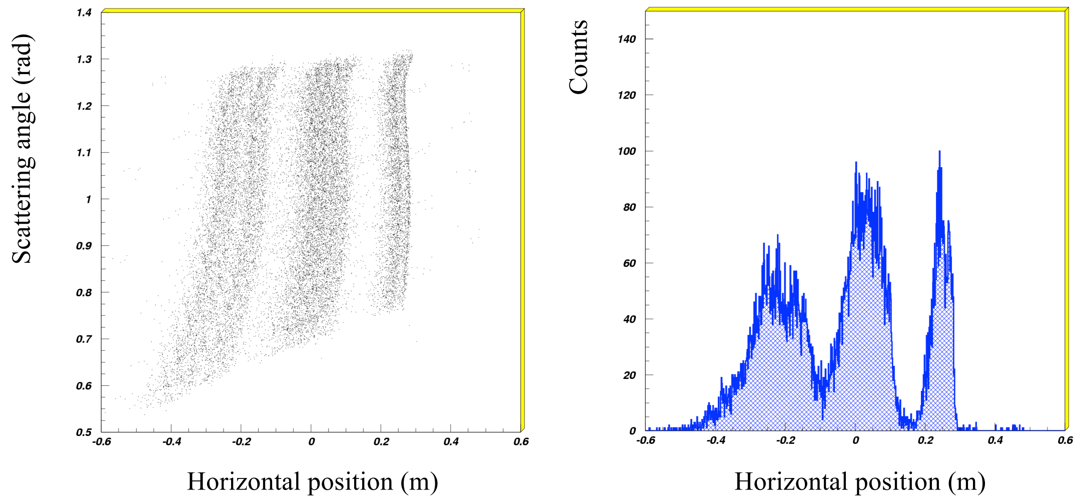

Figure 2. Left panel; scatter plot at the focal plane for the ^{7}Li(^{8}Li,^{7}Be)^{8}He reaction at 57 MeV. Right panel; focal plane position spectrum.

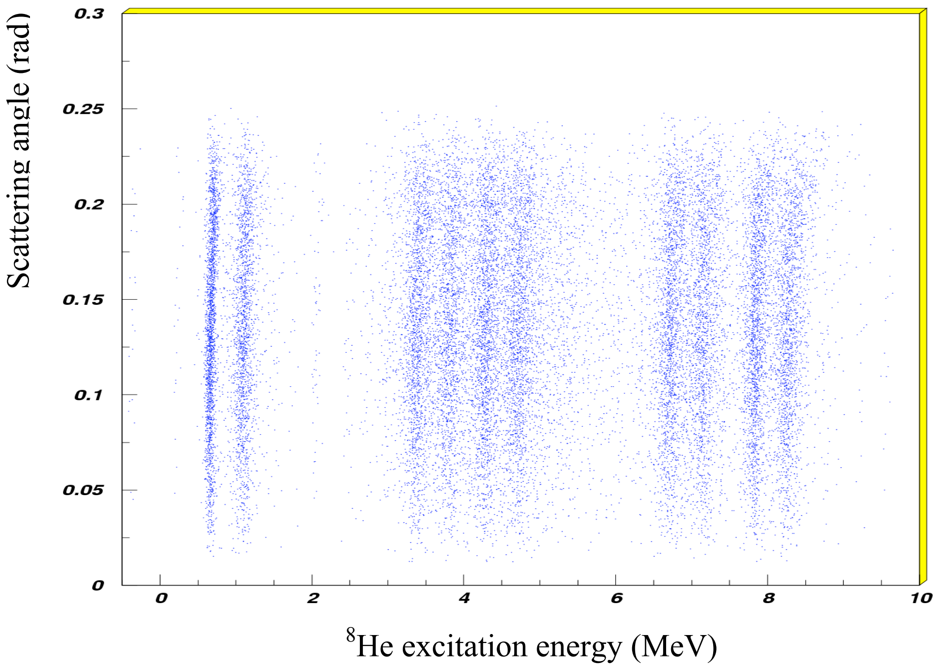

Figure 3. Reconstructed scatter plot at the target for the ^{7}Li(^{8}Li,^{7}Be)^{8}He reaction at 57 MeV. The 11th order algorithm of Cosymag has been used.

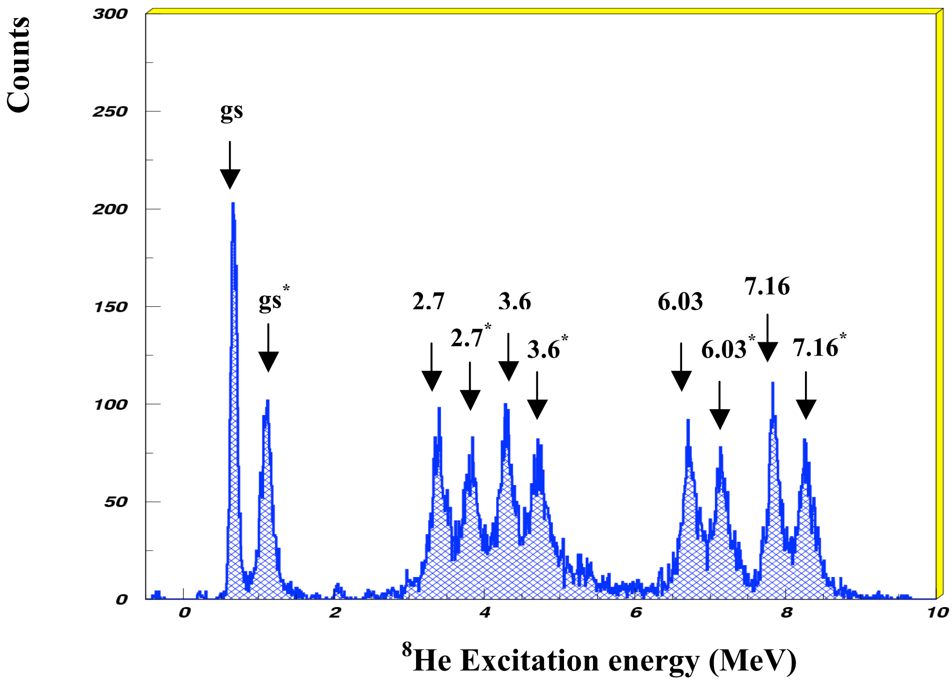

Figure 4. Reconstructed energy spectrum at the target for the ^{7}Li(^{8}Li,^{7}Be)^{8}He reaction at 57 MeV. The 11th order algorithm of Cosymag has been used.

In Figure 3 and 4 the result of the application of the ray reconstruction method is shown. The order of reconstruction has been set to the 11th. In Figure 3 the reconstructed kinematic scatter plot clearly indicates the power of this technique in compensating both the kinematic effect and the effects of residual aberrations that were observed in Figure 2. In Figure 4 the excitation energy spectrum shows the clear separation of the peaks in the region of interest around 3 MeV. The broadening of the peaks is almost entirely due to the effect of target thickness which is unavoidable and not dependant on the instrument itself.

4. *Direct reactions with Cyclotron beams*

The (^{7}Li,^{7}Be) reaction at intermediate energy (i.e., with a cyclotron beam) may be used either for checking the evolution of the reaction mechanism (1-step versus 2-steps, spin transfer, Ikeda sum rules and so on) and/or to excite the IVGMR (IAS and GT resonances) and IVSDR. For the former we need to explore the excitation function with at least 3 different energies (e.g. 15, 30 and 45 MeV/u), e.g., for the ^{11}B(^{7}Li,^{7}Be)^{11}Be reaction. To distinguish between the ^{7}Be ground and excited state at the higher bombarding energies, a γ-ray detection array close to the target should be coupled to MAGNEX (see, e.g., Ref. [34]).

Concerning the IVGMR, we recall that the first clear evidence for this resonance was seen in ^{60}Ni($\pi^{\pm}$,π^{0}) by Erell et al. [35]. Subsequently the IVGMR was investigated by the (^{13}C,^{13}N) reaction [36,37]. However, the angular distribution of the (^{13}C,^{13}N) data indicated an L=2 angular momentum transfer. Nakayama [38], on the other hand, has clearly observed the IVGMR in ^{60}Ni(^{7}Li,^{7}Be), with an L=0 angular distribution and only in the ΔS=0 channel. His method is to subtract the 1° spectrum from the 0° one, which enhances L=0 peaks. A broad "bump" corresponding to the IVGMR is seen at ~20 MeV. A measurement at 0° appears to be crucial, since the IVGMR was not observed by Annakage et al. in ^{208}Pb(^{7}Li,^{7}Be) at 2° [39]. The IVSDR, on the other hand, is readily seen in the previously-mentioned experiments, e.g., in ^{208}Tl at E_x = 5.1 MeV. The IVGMR is important for isospin mixing and symmetry energy. One needs between 10 to 60 MeV/A incident energy, 0.5 MeV resolution, and at least 0.5° angular resolution. A systematic survey of the IVGMR for a range of masses is needed to study, e.g., the excitation energy and width dependence of this resonance. The advantage of using MAGNEX is that it allows to measure the ^{7}Be spectra at very forward angles with a good angular resolution which is fundamental to apply the spectra difference technique. A possible upgrading in this field could arise from the use of a proton ancillary detection system (e.g., Monte [40] or LEDA [41]) in order to observe the proton decay associated to the monopole resonance. In addition, the use of a γ-array would help to disentangle the IVGMR from the ΔS=1 (Gamow-Teller) resonance.

Heavy-ion beams from the Catania SC may be used with MAGNEX to study excitations in target nuclei beyond the reach of Tandem beam energies. One such possibility, stimulated by previous studies of transfer reactions on ^{208}Pb [42-46], is the search for high orbital angular-momentum states (l = 10,11) in ^{208}Pb. It is shown that, surprisingly, single particle configurations look like being a persistent mode of structure for this nucleus also at high excitation energy and high spin. The proposed tool to excite such states is the (^{14}N,^{13}N) reaction with a beam energy/nucleon of about 30 MeV/A. One of the advantages of using MAGNEX in this experiment is represented by the large momentum byte allowing the exploration of energy spectra up to high excitation energy. In addition the large angular acceptance would allow to easily access to angular distributions up to forward angles. For this experiment a neutron array would be a useful complement to the spectrometer: the angular correlations of the decay neutrons and the ^{13}N for given slices of residual nucleus excitation could be compared with different calculations for different l-values.

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