MAGNEX: an innovative magnetic spectrometer for nuclear physics studies

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An innovative magnetic spectrometer has been recently installed at the INFN-LNS laboratory of Catania (Italy). Thanks to a powerful technique of trajectory reconstruction based on differential algebraic algorithms and on the use of a sophisticated focal plane tracker detector, it allows to guarantee good energy, mass and angular resolution in a large solid angle and a broad range of explored momenta. An array of 36 Ne213 liquid scintillators (EDEN) from IN_2P_3-IPN Orsay (France) laboratory has been installed around the scattering chamber of the spectrometer. In this way it is possible to detect, in coincidence with MAGNEX, the neutrons emerging from the reactions in a broad range of energies and with rather high efficiency. The facility, designed for an open nuclear physics community, makes it possible to face old and new challenges of experimental nuclear physics, often producing data of unprecedented quality. Example of new data are shown as connected to the exploration of multi-neutron transfer reactions induced by ^{18}O projectiles, charge exchange reactions and nuclear rainbow in heavy ion collision.

1. Introduction

The study of the motion of charged particles through a magnetic field is a well established technique to explore the microscopic structure of the matter. Early in the study of nuclear physics, magnetic spectrographs were used to analyze electron conversion line and alpha particle spectra from naturally occurring radioactivity. Since 1922, when F. W. Aston discovered the existence of isotopes, six Nobel Prizes have been awarded in the field of magnetic spectrometry.

Also nuclear physics has taken profit by the use of magnets to select and detect the charged particles emitted in a nuclear reaction. In such a context, the magnetic spectrometry offers several advantages compared to other detection techniques. One of these is the strong selection of the reaction products based on their mass over charge ratio which determines the reduction of the background. As a consequence, the use of magnetic spectrometers allows to detect the reaction products at very forward scattering angles. There, due to the proximity of the particle beam, the reaction yields are typically beyond the acceptable rate of the common particle detectors. One should notice that the clearest part of the spectroscopic information is normally expected at such small scattering angles. Another important advantage is that the measurements with magnetic spectrometers are usually characterized by a high achievable mass and momentum resolution, thus permitting accurate studies of nuclear spectroscopy.

On the other hand the magnetic spectrometers have been usually designed with small overall acceptance. In fact, the presence of large optical elements produces unavoidable aberrations determining a sensitive reduction of the above mentioned properties. The treatment of the high order aberrations is a long standing issue, that has found a solution scheme only with the recent advent of sophisticated mathematical approaches based on the differential algebra [1-4]. Nevertheless the application of such approaches to practical cases has required a consistent supplementary effort in the last few years. This has mainly been driven by the increasing interest that modern experimental nuclear physics is giving to large acceptance detection systems.

Fig. 1. MAGNEX at the INFN-LNS, Catania, Italy.

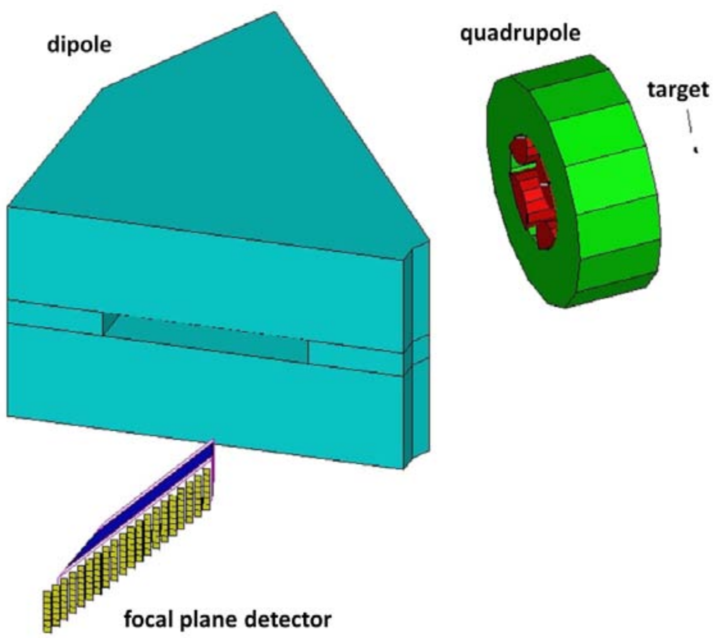

Fig. 2. Schematic view of the MAGNEX spectrometer.

Such devices are essential when the measurement conditions are characterized by low detection yields as when dealing with low intensity radioactive ion beams or with investigation of suppressed reaction channels. An example of such a device is the new magnetic spectrometer MAGNEX, developed and built at the INFN - Laboratori Nazionali del Sud (LNS) in Catania (Italy) [5-7]. The spectrometer shown in Fig. 1 and Fig. 2 is characterized by a large angular (about 50 msr) and momentum (-14.3%, +10.3%) acceptance. It basically consists of two large aperture magnets, (a quadrupole and a dipole) and of a focal plane detector (FPD) [8-10] for the detection of the emitted ions. The problem of the aberrations is faced by an accurate design of the spectrometer layout, which minimizes their content [5-6], an efficient ray-reconstruction technique [11] based on the differential algebraic methods of COSY INFINITY [12] and the use of a specialized focal plane detector for the measurement of the optical phase space parameters. The method is powerful enough to treat the problem up to high order (10th order in the case of MAGNEX) and general enough to be extended to other fields of magnetic spectrometry and transport lines.

2. An overview of the MAGNEX spectrometer

Many details of the spectrometer characteristics, working principles and performances can be found in literature [13]. In particular the capabilities of the device to get particle identification is reported in ref. [14], where a mass resolution of about 1/160 is achieved by the simultaneous measurement of the ions kinetic energy, momentum modulus and electric charge. Similarly the reconstruction of the full momentum vector of the detected particle is discussed in ref. [11]. A resolution as high as 1/1800 is obtained for the momentum modulus and up to 0.2° for the scattering angle as result of the high order reconstruction algorithms. Finally the possibility to perform measurements of the absolute cross section of nuclear reactions was tested against Rutherford scattering [15]. A relevant accuracy and precision within a few percent are demonstrated.

In Table 1 the main features of MAGNEX are listed.

Table 1. Main features of MAGNEX.

Optical characteristics	**Measured values**
Maximum magnetic rigidity	1.8 T m
Solid angle	50 msr
Momentum acceptance	-14.3% +10.3%
Momentum dispersion for k= - 0.104 (cm/%)	3.68
Momentum resolution	1/1800
Mass resolution	1/160
Angular resolution	0.2°

The performances of the spectrometer make it possible its application in a very large range of nuclear physics studies, where the large acceptance and momentum bite are requested, without serious drawbacks in terms of energy, mass, angular resolutions and cross section accuracy. The instrument has been conceived for a broad community of nuclear physics researchers, allowing its user friendly use and fast data reductions.

3. Some example of nuclear physics experiments

The MAGNEX spectrometer has been used to study several nuclear physics experiments using Tandem Van de Graaff beams at the INFN-LNS laboratory. Such experiments span many fields of interest in nuclear spectroscopy and reaction mechanism studies and have in common the necessity to exploit the advantages of the combined high resolution and large angular and momentum acceptance. The major part of them have been prohibitive since the advent of MAGNEX, due to the low yields and the poor signal to noise ratio. In the following some results from one of these experiment is briefly shown and discussed, without concentrating on the physical results but stressing on the features and advantages of a typical data analysis with MAGNEX.

3.1 Two-neutron transfer reactions

The experiment proposes the study of light neutron-rich nuclei via multi-nucleon transfer reactions at energies above the Coulomb barrier [16]. Such a research is of great importance to describe the evolution of the nuclear structure from the β-stability valley towards the neutron drip-line. From the theoretical point of view the description of these nuclei represents a crucial benchmark to probe advanced microscopic theories of nuclear structure beyond the mean field approximation and toward the ambitious goals of “ab initio” approaches. Some of these nuclei can be experimentally accessed via multi-neutron transfer reactions using intense stable beams, thus allowing the collection of accurate and statistically significant datasets.

In the experiment performed at the INFN-LNS a ^{18}O beam was accelerated by the Tandem at 84 MeV incident energy. Various targets were used from ^{9}Be up to ^{208}Pb in order to study the systematic evolution of the energy spectra and angular distributions. A 50 μg/cm^2 self supporting ^{12}C foil was one among the used targets. The Oxygen isotopes produced in the collisions were momentum analyzed by the MAGNEX spectrometer and detected by its FPD. The magnetic fields were set in order to accept the Oxygen ions with charge between 6$^+$ to 8$^+$ at the maximum kinetic energy. These were identified using the technique described in ref.[14]. Once the ^{16}O^{8+} ejectiles are selected, the horizontal and vertical positions and angles at the focal plane are analyzed, thus providing the constraints for the application of the high order algorithms of trajectory reconstruction, implemented in the spectrometer. This procedure does allow the reconstruction of interesting physical quantities like the scattering angle θ_{lab} and the excitation energy of the target residual E^*. An example of the (E^*, θ_{lab}) bi-dimensional plot is shown in Fig. 3 for the angular setting where the MAGNEX optical axis was θ_{opt} = 12°. Since the spectrometer was in the full acceptance mode, ejectiles with 7° < θ_{lab} < 19° were detected in a single run. The ^{14}C ground and several excited states are well visible as vertical and straight loci, as expected since the E^* parameter is not depending on the scattering angle for transitions to the ^{14}C states.

A projection of the data on the E^* axis provides a typical excitation energy spectrum for the ^{14}C nucleus as shown in Fig. 3 for 9.5° < θ_{lab} < 10.5°. The FWHM for the ground state peak is 150 keV resulting in a momentum resolution of about 1/1100 mainly limited by the energy straggling of the oxygen particles in the target.

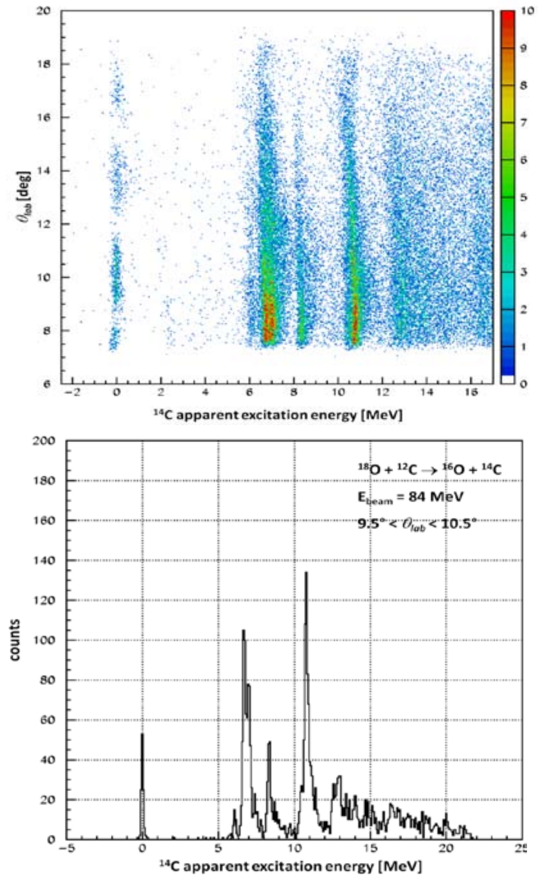

Fig. 3. Left: two-dimensional plot of the reconstructed θ_{lab} against the ^{14}C apparent excitation energy E^* for the ^{12}C(^{18}O, ^{16}O)^{14}C reaction at 84 MeV and θ_{opt} = 12°. Right: Projection of the energy spectrum for 9.5° < θ_{lab} < 10.5°.

The angular distribution of the absolute cross-section was deduced for the transitions to the ^{14}C ground and excited states. The results for the ^{18}O + ^{12}C $\rightarrow$ ^{16}O + ^{14}C$_{g.s.}$ channel in the angular range covered by the θ_{opt} = 6°, 12°, 18°

MAGNEX setting are shown in Fig. 4. Thanks to the large angular acceptance, an angular range of about 7° < θ_{CM} < 52° in the center of mass reference frame was explored with only three largely overlapping setting of the spectrometer. The differential solid angle for the full acceptance was carefully determined taking into account the overall transport efficiency as described in ref. [15]. An angular bin of 0.56° in the center of mass reference was chosen (corresponding to 0.24° in the laboratory) in order to achieve a good compromise between the statistical uncertainties in the number of counts for each bin and the angular resolution. The error bars include both the statistical contribution and a component due to the uncertainty on the solid angle determination. An oscillating pattern, characteristic of the L = 0 ^{12}C(g.s., 0^+) → ^{14}C (g.s., 0^+) transition, is observed. This confirms the achieved angular resolution in a typical experiment of nuclear physics interest. The capability to measure an angular distribution with unprecedented quality in terms of continuity and resolution is evident.

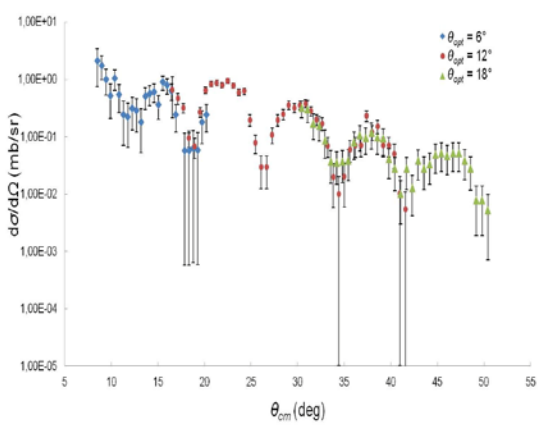

Fig. 4. Angular distribution of the differential cross-section in the center of mass reference frame for the $^{18}O + ^{12}C \rightarrow ^{16}O + ^{14}C_{gs}$ reaction at 84 MeV incident energy.

3.2 The $^{19}F(^{7}Li,^{7}Be)^{19}O$ charge exchange reaction at 52 MeV

The $^{7}Li^{+++}$ beam at 52.2 MeV was accelerated by the Tandem facility of INFN-LNS. The ^{19}F target was a 80μg/cm^2 thick AlF_3 foil evaporated on a gold backing of 250 μg/cm^2 produced at the chemical laboratory of the LNS. A ^{27}Al target (116 μg/cm^2) was also used in order to estimate the background due to aluminum in the target compound and subtract it in the final spectra. Supplementary runs were done also on a WO_3 target (150 μg/cm^2 on 20 μg/cm^2 carbon backing) and on a carbon target (76 μg/cm^2) for the subtraction of the contribution in the final spectra due to the oxygen and carbon impurities in the AlF_3 target. The MAGNEX quadrupole and dipole fields and the α-surface coil, together with the position of the Focal Plane Detector (FPD), were set in order to focus the ^{7}Be ejectiles relative to the $^{19}O_{gs}$ in the focal plane position corresponding to a momentum deviation δ = 0.08 with respect to the reference one. In the data analyzed up to now the spectrometer was located at a central angle of θ_{opt} = 12.2° with respect to the beam incidence direction, corresponding to a covered angular range 7.1° < θ_{lab} < 19.8° in the laboratory reference frame. Measurements at θ_{opt} ~ 0° and θ_{opt} = 6° were also performed and the data analysis is in progress.

A reconstructed spectrum of the ^{19}O excitation energy is shown in Fig.5. The spectrum obtained from the data with the AlF_3 target is shown with superimposed that related to the aluminum target. The background due to the Al-derived reaction is the only one up to about 6 MeV ^{19}O excitation energy. Several excited states are observed and identified in the low excitation energy region. The well isolated peaks are labeled with the relative excitation energy in MeV. Peaks marked with an asterisk refer to the transitions in which ^{7}Be ejectiles are in the first excited state at 0.43 MeV. Most of the ^{19}O states have been observed in the past by one and two neutron transfer reactions [17], thus confirming the capability of the (^{7}Li,^{7}Be) reactions to populate such states. For most of them the shell structure configuration is quite well known as for example for the 1.47 MeV excited state ($1/2^+$) which is mainly a single-particle state with the configuration of one neutron in the $2s_{1/2}$ orbital on a $^{18}O(0^+)$ core. The estimated energy resolution is about 80 KeV (FWHM). In a previous test run, realized with the same experimental setting in order to check the feasibility and study the working conditions, a better resolution was achieved (about 50 KeV) [18]. There are two main reasons causing the lack of resolution in the present experiment. First, the gold backing of the AlF_3 target was thicker (250 μg/cm^2) in the present experiment compared to 120 μg/cm^2 in the test run, thus producing less straggling in the target. In addition, in the test run the magnetic fields were set to focus the ^{7}Be relative to the $^{19}O_{gs}$ in a different focal plane position, closer to the spectrometer optical axis (X_{foc} = 0), where a minor contribution of aberrations is expected.

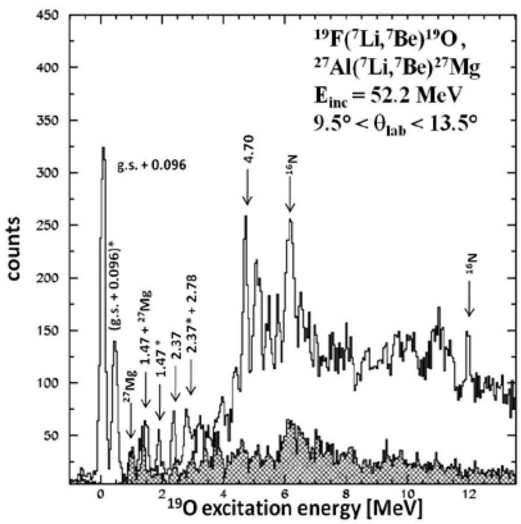

Fig. 5. ^{19}O excitation energy spectrum obtained using the AlF3 target and, superimposed, the normalized spectrum obtained from the aluminum target. The known states of ^{19}O are indicated with their energy. The presence of ^{27}Mg and ^{16}N states is also shown. Peaks marked with an asterisk refer to the transitions in which ^{7}Be ejectiles are in the first excited state at 0.43 MeV.

3.3 Nuclear rainbow in ^{16}O + ^{27}Al elastic scattering

A specific research line searching for coupled channel effects in heavy ion collisions above the Coulomb barrier has recently started with the use of MAGNEX. A detailed analysis based on modern techniques of reaction cross section calculations was developed to this purpose. The main ingredients are the use of Coupled Reaction Channel calculation with an Exact Finite Range approach and of the Sao Paulo potential, i.e. a microscopically derived double folding optical potential with real and imaginary part and the inclusion of Pauli non-locality [19]. Calculations within this framework indicates that a nuclear rainbow pattern should be observed in the ^{16}O + ^{27}Al elastic scattering above the Coulomb barrier. This is a quite uncommon prediction due to the expected role of strong absorption in heavy ion collisions and is explained as the result of the increased role of coupled channel in reducing the absorption. The discussion following this new prediction has opened the doors to a renewed interest in rainbow research, with the set up of a very challenging experiment done at the LNS with MAGNEX.

The ^{16}O + ^{27}Al elastic and inelastic scattering has been successfully measured at 99.2 MeV incident energy. Part of the results, describing the technical details of the experiment and data reduction can be found in ref. [20] and part, focusing on the data analysis are going to be published very soon. The reaction ejectiles have been detected at forward and at backward angles up to θ_{lab} = 52°, corresponding to θ_{CM} = 80° in the center of mass reference frame. All the challenging requirements of the experiment have been satisfied, allowing to clearly identify the ^{16}O ions, to separate the ground from the first excited states of ^{27}Al at 844 keV and to measure accurate absolute cross sections and angular distributions even at backward angles. We emphasize that the cross-section decreases of about 7 order of magnitude in the explored angular region, down to about 100 nb/sr and that a thin target (~ 100 μg/cm^2) must be used to reduce the energy straggling.

4. Conclusion

With the advent of many radioactive nuclear beam facilities throughout the world, considerable effort is directed to new detectors apparatus designed taking into account the peculiar properties of secondary beams. In particular, the low intensities (at least three orders of magnitude lower than the stable ones) need large acceptance devices. Similarly a growing interest is nowadays shown in the study of suppressed reaction channels populated by stable beams induced reactions. As a consequence the detection technology is trying to find appropriate solutions to the general problem of measuring in such unfavorable conditions. While in several laboratories, large segmented arrays of, e.g., silicon detectors are used or planned, the higher energy and mass resolution of a magnetic spectrometer, together with its rejection power of unwanted ion species, makes such devices an attractive choice for charged-particle spectroscopy. This implies to push the ion optics of magnetic spectrometers beyond the limits of the standard ones. In fact, when the count rate is low, a large acceptance is important to save beam time. In addition, one strongly wishes to get the high resolving power achieved by traditional small acceptance spectrometers. This is a partial compensation for low-statistics spectra (improving the signal to noise ratio) as well as an advantage to resolve close-lying states. However, to join large solid angle and momentum acceptance together with high resolving power necessarily means that the ion-optical aberrations must be very carefully treated.

The advent of new computational tools such as those offered by the application of differential algebra to ion optics has offered a clever solution scheme to such problems. The development of a new strategy for first order layout design, of new techniques for large scale field measurements and interpolations, such as of suitable focal plane detectors, has completed the job, renewing the central position of magnetic spectrometry in the nuclear research. In this manuscript, a collection of the main ideas behind this upgraded technology has been presented and referred to for the case of MAGNEX. In addition the possibilities to face old and new puzzles in nuclear science offered by such an instrument have been shown.

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