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X-Spam-Flags: <.ABUSE-RFC-IGNORANT.WHOIS-RFC-IGNORANT.@mailbox.univie.ac.at>[168.96.66.10:hydra.cnea.gov.ar] <tandar.cnea.gov.ar>
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X-Mailer: QUALCOMM Windows Eudora Light Version 3.0.5 (32)
Date: Mon, 10 May 2004 22:47:15 -0300
To: Alfred Priller <alfred.priller@univie.ac.at>
From: Jorge Fernandez Niello <fniello@tandar.cnea.gov.ar>
Subject: Re:
X-DCC-ZID-Univie-Metrics: mailbox 4244; Body=0 Fuz1=0

Alfred,
ich habe das Attachment vergessen.
Jorge

At 05:56 AM 11/05/04 +0200, you wrote:
>Lieber Jorge,
>
>Ich hoffe, bei euch ist alles in Ordnung.
>Ich schreibe dir wegen der ECCART in Paris. Da muessen wir bis 31. Mai 2004
>ein Abstract abliefern. Wenn ich das schreiben soll, dann brauche ich ein
>solides Geruest von dir. Besser waere, wenn du eine Abstract Version
>schicken koenntest. Die Namen deiner Koautoren brauche ich dann auch noch.
>
>Ich haette auch geren ein paar Satze ueber den Stand unseres Experiments
>gewusst. Du kommst ja im Juli nach Wien zu uns, und da heatten Peter und
>ich uns gerne ein bisschen vorbereitet.
>
>Herzliche Gruesse
>
>
>_____
>Dr. Alfred Priller
>
>Institut für Isotopenforschung und Kernphysik
>der Universität Wien
>Währinger Str. 17
>A-1090 Wien
>Austria
>
>Tel.: +43-1-4277-51703/51720
>FAX: +43-1-4277-9517
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>_____
>
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Introduction and theoretical background

In this work we attempt to understand the CN cycle by investigating the $^{12}C+p$ and $^{13}C+p$ capture reactions at very low energies. The CN burning process, which occurs in stars somewhat more massive than the sun, consists of the following sequence of reactions:

$$^{12}C(p, \gamma)^{13}N(e^{+},\nu)^{13}C(p, \gamma)^{14}N(p, \gamma)^{15}O(e^{+},\nu)^{15}N(p,\alpha)^{12}C$$

The net effect of this sequence is the conversion of four protons into helium, like in the proton-proton chain. Note that if the cycle begins, for example, with ^{12}C and since it also ends with this isotope, the ^{12}C can be used over and over again. This cycle presents a slow leak at ^{15}N, since at this point the $^{15}N(p, \gamma)^{16}O$ branch occurs 0.4% of the time.

The total energy released in the cycle is Q = 26.73 MeV. The rate of the energy production is governed by the slowest reaction, which in this cycle corresponds to the $^{14}N(p, \gamma)^{15}O$ reaction.

Although the total energy released in this cycle is Q = 26.73 MeV, this is not the primary energy source of the sun. The solar mass is too small to provide a sufficiently high temperature in its interior for this cycle to dominate. However, this reaction sequence plays a dominant role in the production of energy in more massive stars as well as in the nucleosynthesis of the various isotopes of the light elements carbon and nitrogen.

The energy production and nucleosynthesis of the elements are governed by the nuclear reaction rates $<\sigma v>$, whose magnitudes are very sensitive to the Coulomb barrier of the interacting nuclei. These rates depend strongly on stellar temperatures, and its analytical expression is determined by the energy dependence of the cross section $\sigma(E)$. In the domain of interest, the available hydrogen temperatures restrict the Coulomb penetrability and the corresponding extremely low cross sections $\sigma(E)$ impose several difficulties in the experimental determination of their reaction rates.

It is useful to express the cross section in the form of two terms, $\sigma(E) = \pi\lambda^{2}e^{-2\pi\eta}S(E)$, where the exponential factor resembles the tunneling dependence and S(E) is the

astrophysical S-factor containing all the strictly nuclear effects. In this expression, $\eta = Z_1 Z_2 e^2/(\hbar v)$ is the Sommerfeld parameter, Z_1 and Z_2 are the atomic number of the colliding nuclei, and v is the velocity of the impinging projectile. The advantage of this way of expressing the cross sections is that, in several cases, the S-factor does not depend on the energy (or it varies very slowly), and, therefore, it is easy to extrapolate it to lower energies.

Moreover, for the evaluation of the reaction rate one has also to consider the velocity distribution of the particles $\phi(v)$. This is described by a Maxwell-Boltzmann distribution:

$$\phi(v) = 4\pi v^2 \left(\frac{m}{2\pi kT}\right) e^{-mv^2/2kT} \propto E\, e^{-E/kT}. \qquad (1)$$

Therefore, the reaction rate per particle pair $\langle \sigma v \rangle$ can be written in the form

$$\langle \sigma v \rangle = \int_0^\infty \sigma(v)\phi(v) v\, dv = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) e^{-E/kT} E\, dE \qquad (2)$$

If the S-factor varies very slowly with the energy (which is the case for non-resonant reactions) the energy dependence of the integrand is given by two exponential terms. One of them, the velocity distribution of the particles, decreases with the energy after reaching a maximum at $E = kT$. The other term, given by the probability of tunneling through the Coulomb barrier, vanishes at low energies and grows exponentially with the square root of the energy. In the overlap region both exponential functions are small. Their convolution leads to a peak of the integrand, the Gamow peak, whose maximum value and width (E_0 and ΔE, respectively) indicate the energy region wherein most of the nuclear reactions that generate energy and synthesize elements take place inside stars. This energy window clearly depends on the temperature and Coulomb barrier of the nuclear involved:

$$\begin{aligned} E_0 &= 1.220 (Z_1^2 Z_2^2 \mu T_6^2)^{1/3} \text{ keV} \\ \Delta E &= 0.749 (Z_1^2 Z_2^2 \mu T_6^5)^{1/6} \text{ keV}, \end{aligned} \qquad (3)$$

where μ is the reduced mass and T_6 is the temperature expressed in 10^6 K. In the case of the sun, $T_6 = 15$, this energy is about 26 keV for the p+C reactions. So, if one is interested in the reaction rate for this process in the sun, one has to measure the corresponding cross sections at center of mass energies of around 20 keV.

The cross sections that we aim to investigate have been already measured down to energies of about 100 keV. These capture reactions are usually studied in the

laboratory by detecting the emitted gamma rays. However, if the capture cross sections are small, competing reactions produce a high background posing a very difficult task for the usual prompt gamma-ray detection method. Besides, the target should be rather thin (or a gas target) in order to avoid energy loss or energy straggling of the incoming particles or of the recoil nuclei in the target.

In order to overcome the problems arising from a very low counting rate and from the interfering background we propose to use the accelerator mass spectrometry (AMS) technique for the determination of extremely low reaction rates. The idea is to produce a nuclear reaction in the gas stripper of a tandem accelerator and to tune the recoil nuclei up to the detection system following the AMS procedure.

Experimental considerations

The idea of producing a nuclear reaction in the gas stripper and detecting the formed nuclei via AMS was first proposed by Michael Paul. In our case we add a second ingredient, which is the formation of the compound nuclei using the inverse kinematics. In the case of the proton-carbon system, a center of mass energy of about 100 keV corresponds to impinging carbon projectiles of around 1.3 MeV.

This is the way we produce our reaction: Setting the terminal voltage of a tandem accelerator at a value of U MV, carbon ions produced in a sputtering ion source will be accelerated to this terminal voltage up to an energy of $(U+PA)$ MeV, where PA is the injection voltage expressed in MV. In this part of the accelerator we have to provide hydrogen nuclei to act as targets. This is done using H_2 as gas stripper. Figure 1 shows the performance of this gas as stripper (p = 2 μbar) when a carbon beam is accelerated by a high voltage of 3 MeV. Once the nuclear reaction takes place, the produced captured nuclei, having an energy E_{PN} and charge state q at the terminal voltage position, will be also accelerated in the high-energy part of the accelerator. The charge state distribution of the formed nuclei depends not only on the properties of the gas stripper but also on the nuclear reaction itself. It would not necessarily follow the charge state distribution that the same isotope accelerated at the energy E_{final} had when traversing the same gas stripper. The final energy reached by these nuclei will depend, of course, on the ionic charge state q that they have after leaving the target

$$E_{final} = E_{PN}+qU. \qquad (4)$$

In the case of the ^{12}C + p reaction, this technique involves the tuning of a ^{13}N beam of charge state *q* through the high-energy part of the accelerator, and from there, with an energy E_{final}, through the analyzing magnet and the beam optics devices up to the detection system.

The background of this method arises from ^{13}C ions with the same energy and charge state as the ^{13}N ions. Most probably these ^{13}C ions stem from a tail of the mass 13 accepted in the injection magnet. They are accelerated together with the ^{12}C projectiles, suffer a stripping process in the gas stripper of the accelerator and another charge exchange with a residual gas molecule at a given place of the high energy part of the accelerator in such way that acquire the same energy and charge state as the ^{13}N. Although the probability of having a ^{13}C ion when tuning the mass twelve, stripping this ion to a charge state (to a determined charge state) an suffering again another charge exchange in the accelerator, may be rather low, one has to consider that the cross sections of our wanted reactions are also extremely low. Since both ions ^{13}N and ^{13}C have the same mass, energy and charge state, both are accepted by the different electrostatic and magnetic selectors of the beam line and both are tuned in the same way.

The only way we have to separate these isobars is with an appropriate detection system. In this case we use an E - ΔE telescope detector, consisting of an ionization chamber (acting as a ΔE) followed by a solid state Si detector. Since the ion energies involved in this work are rather low (approximately 10 MeV), especial care was taken in the choice of the entrance window (a 100 nm thick Si_3N_4 foil) as well as the gas pressure (25 mbar isobutane).

Analysis of the measurements

Since this work aims to address the viability of the proposed experimental technique, our first attempt was to reproduce measured cross section values for the ^{12}C+p reaction. Therefore, we studied this reaction at E_{CM} = 229.5 keV and at E_{CM} = 206.8 keV. Both values have known cross sections of 1.3×10^{-7} barn and 5.4×10^{-8} barn, respectively. The idea was to use these known reactions in order to *calibrate* our technique.

For this purpose, the preaccelerator voltage was fixed at *PA* = 68.8 kV, whereas the terminal voltage was set at *U* = 2915.3 kV and 2619.3 kV for the higher and lower

energies, respectively. The E - ΔE bidimensional spectra corresponding to both bombarding energies are shown in Fig. 2. In these measurements the charge state q=3 were selected. The spectra show events accumulated during approximately 17 hours (see Table 1). As it can be seen from this Figure, the achieved resolution is good enough to identify unambiguously the ^{13}N nuclei from the isobar contamination ^{13}C.

The cross section for a reaction is given by

$$\sigma = N_R / (N_P N_T) \qquad (5)$$

where N_R is the number of the in the reaction produced particles, and N_P and N_T are the number of incoming and target particles, respectively.

The $^{12}C^{q+}/^{12}C^-$ transmissions through the accelerator were calculated from particle currents, which were measured after the analyzing and the injection magnets. Taking into account this transmission, the total number of projectiles N_P was evaluated by integrating the ^{12}C current measured at an offset Faraday cup after the analyzing magnet, in bins of approximately 180 s.

On the other side, the number of target nuclei N_T follows from a measurement of the gas pressure in the middle of the stripper channel (60 cm large). This is the parameter with the largest uncertainty.

Moreover, since the value of N_R can be expressed as the product of the number of the detected particles times the transmission from the target position to the detector, $N_R = N_D T$. Therefore, *calibrate* the method means the knowledge of the transmission T, or better the factor F,

$$F = T/N_T = \sigma N_P / N_D \qquad (6)$$

(see discussion in Outlook).

It should be also pointed out, that the nuclei leave the gas stripper (in our case the target) with different ionic charge states. And indeed the tuning of the beam through the different electromagnetic devices (or the beam optic components) depends on the ionic charge state of the beam.

The transmission from the gas stripper to the detector, however, depends not only on the charge state distribution of the produced ^{13}N nuclei but also on the emittance properties of the different ionic states. In fact, when a nucleus is produced at an excited

state E^*_{PN}, due to the momentum $p_\gamma = E_\gamma/c$ of the capture gamma rays, the recoil nuclei are emitted in a cone of half angle $\theta/2 = E_\gamma/p_1 c$, where p_1 is the momentum of the projectile. In the case of the p(^{12}C, gamma)^{13}N reaction, its Q-value is Q = 1.944 MeV. Since the first excited state of ^{13}N has an energy of 2.365 MeV, it is expected that only one gamma will follow the deexcitation of the captured nucleus, with an energy $E_\gamma = Q + E^{CM}$.

Moreover, depending on the direction of the emitted gamma ray, the energy E_{PN} of the produced nucleus in the laboratory system

$$E_{PN}^{lab} = \tfrac{1}{2} M_{PN} [(v^{CM}+v^{CM}_{PN} \cos\theta)^2 + (v^{CM}_{PN} \sin\theta)^2] \qquad (7)$$

takes maximum (for $\theta = 0$) and a minimum (for $\theta = \pi$) values. In Eq. (7) M_{PN} and v^{CM}_{PN} refer to the mass and center of mass velocity of the produced captured nucleus. Therefore, it follows that for higher final energies (higher charge states), the relative difference in the energy of the ions conforming the beam will be smaller. Beam optic calculations performed for the extreme conditions in angle and energy described above, for the E_{CM} = 229.5 keV, $q = 3^+$ case, show that neither any slits nor other devices limit the transport of the captured nuclei from the target to the detector.

In order to learn about the dependence of the transmission on the tuned charge state, measurements at E_{CM} = 229.5 keV for $q = 2^+$ and $q = 4^+$ were carried out (see Fig. 3). Contrary to the charge state distribution shown in Figure 1, the transmission shows a maximum at $q = 3^+$, which evidences the fact that the capture products acquire a higher charge state than the charge state of the projectiles.

A summary of the measurements is listed in Table 1. At the two bombarding energies, the transmission took a maximum value of about 2% for the charge state q = 3 of the captured products. It should be pointed out that the transmission may be affected by a common factor which stem from the uncertainty on the absolute value of the gas pressure. Nevertheless, it allows us to get a confident trend of the transmission.

Outlook

In this work we explored an alternative method for the determination of extremely low astrophysical reaction rates. It is based on the merit of the AMS technique for identifying small amounts of isotopes. Although the measurements reported here show

the viability of the proposed method, there are still some improvements and/or developments to implement.

- As noted above, no absolute value of the gas-stripper pressure is available. In order to estimate the number of detected particles, we assume a steady gas-stripper pressure, whose value was half of its value at the middle of the stripper channel. This magnitude should be better known.

  Nevertheless, there are here two points to remark: Firstly, the uncertainty of the pressure can be overcome endorsing it to the transmission T, see Eq. 6. In the evaluation of the cross section, the product $F = T/N_T$ is the only unknown magnitude. A misestimation of the pressure leads to a misestimation of the target nuclei N_T, and, therefore, it will affect the transmission by the same factor. In this way, the value F can be extracted from measurements at energies with known cross sections (as did in this work). One has to study then the evolution of this factor F as a function of the energy. It might be possible, that one can extrapolate its value to lower energies, where no cross sections are known. Secondly, the value of the pressure, and therefore the number of target nuclei, could be underestimated at most by a factor of 20. Such value can be inferred analyzing the total transmission, defined as the sum of the transmission obtained for all possible charge states. The total transmission for the case of a carbon beam, about 60%, represents an upper limit for T, and results twenty times larger than the total transmission yielded from these measurements (about 3%, see Table 1).

- As mentioned above, the proposed reactions have been studied down to center of mass energies of around 100 keV. The corresponding cross sections are three order of magnitude lower than the ones measured in this work. It is clear that much research and technical development are needed to address these reactions. In the future it might be possible to achieve this goal increasing the intensity of the carbon beam, the pressure of the gas stripper and the measuring time.

- The reaction $p(^{13}C, gamma)^{14}N$ posses other challenges. On one side, the isotopic abundance of ^{13}C is two order of magnitude lesser than that of ^{12}C, which directly affects the beam intensity. On the other side, the Q-value for this reaction 7.55 MeV, and contrary to the case of the $^{12}C+p$ reaction, there are several gamma rays that can be emitted in the deexcitation of the captured ^{14}N nucleus, even at the lowest possible energies.

FIGURES

Figure 1: Stripping efficiency for ^{12}C beam using H_2 as gas stripper. The solid circles correspond to a gas stripper pressure of 5.8 μbar, the open circles to 3.3 μbar, and the square to 4.8 μbar.

Figure 2: E - ΔE spectra taken at center of mass energies of a) E_{CM} = 229.5keV and b) E_{CM} = 206.8 keV. The ^{13}N events were tuned with charge state $q = 3^+$.

Figure 3: Bidimensional E - ΔE spectra recorded at E_{CM} = 229.5 keV for a) $q = 2^+$ and b) $q = 4^+$.

Table 1: Summary of the results from this study. The reaction yield is defined as the cross section times the target nuclei, whereas the reactions per second is the product of the reaction yield times the number of projectiles per second. Due to the uncertainty in the target nuclei, no errors are reported.

Energy; charge state	229.5 keV; 3^+	206.8 keV; 3^+	229.5 keV; 4^+	229.5 keV; 2^+
Run duration (approx)	60100 s	61200 s	2700 s	48300 s
Detected particles	123	22	2	4
Cross section [b]	1.3×10^{-7}	5.4×10^{-8}	1.3×10^{-7}	1.3×10^{-7}
Target nuclei [cm^{-2}]	1.3×10^{16}	1.3×10^{16}	1.3×10^{16}	1.3×10^{16}
Reaction yield	1.69×10^{-15}	7.02×10^{-16}	1.69×10^{-15}	1.69×10^{-15}
Mean ^{12}C current [μA]	10	4.5	12	7
Reactions/s	1.1×10^{-1}	2.0×10^{-2}	1.3×10^{-2}	7.4×10^{-2}
Transmission T	1.94×10^{-2}	1.8×10^{-2}	5.8×10^{-3}	1.1×10^{-3}

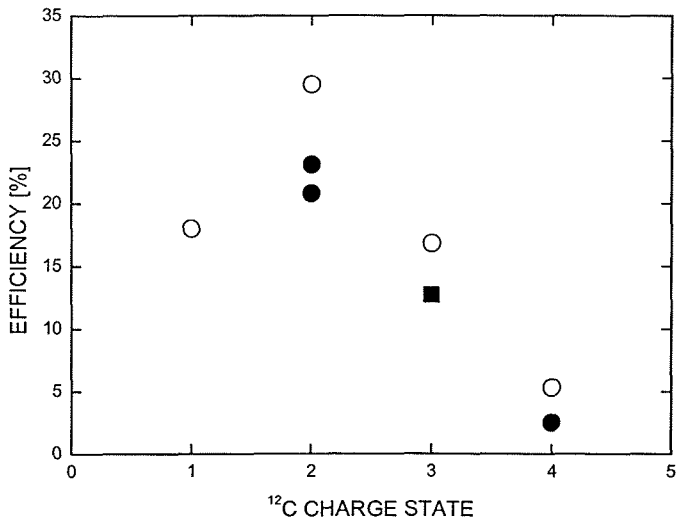
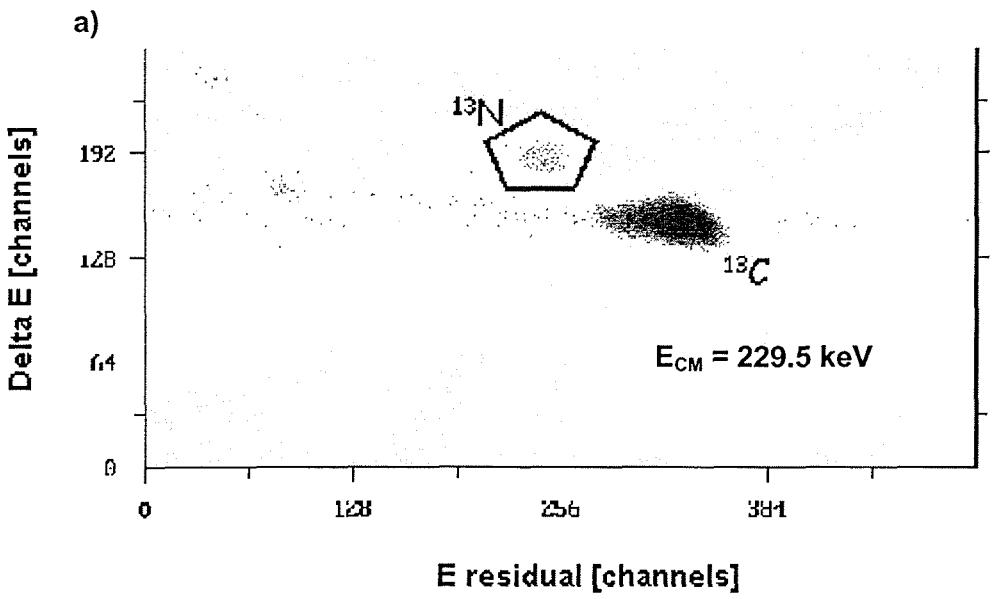


Figure 1


a)
Delta E [channels]
192
128
64
0
0
128
256
384
E residual [channels]
^{13}N
^{13}C
E_{CM} = 229.5 keV

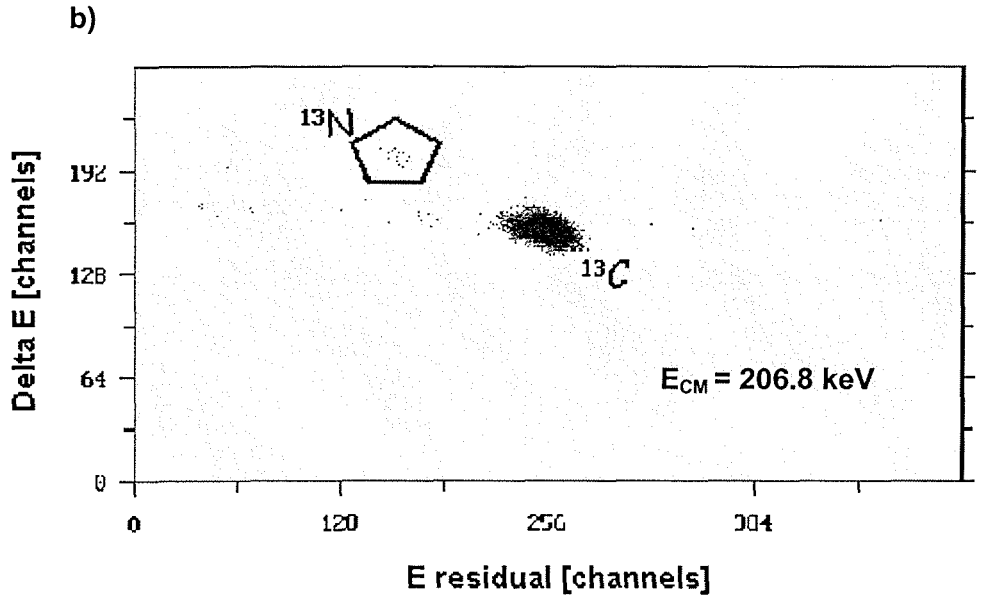

b)
Delta E [channels]
192
128
64
0
0
120
256
384
E residual [channels]
^{13}N
^{13}C
E_{CM} = 206.8 keV

Figure 2

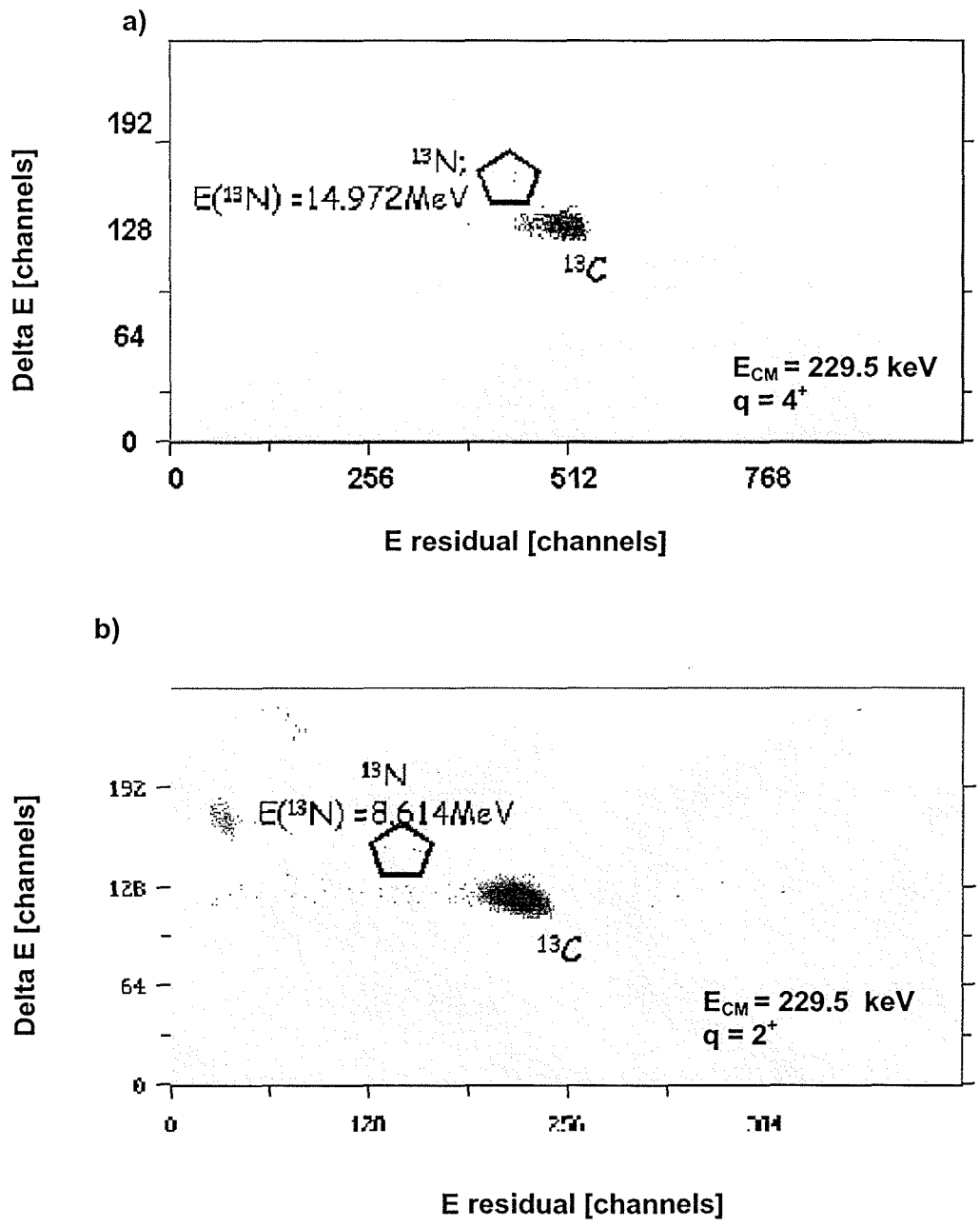

a)
192
128
64
0
Delta E [channels]
^{13}N;
E(^{13}N) =14.972MeV
^{13}C
E_{CM} = 229.5 keV
q = 4^+
0
256
512
768
E residual [channels]
b)
192
128
64
0
Delta E [channels]
^{13}N
E(^{13}N) =8.614MeV
^{13}C
E_{CM} = 229.5 keV
q = 2^+
E residual [channels]

Figure 3