INFLUENCE OF ^{13}C ON PROTON-INDUCED ^{13}N PRODUCTION FROM NATURAL CARBON TARGET

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Two recent measurements of the $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$ reaction on natural carbon were performed by detecting β^+ decay of the ^{13}N residue. It is argued that the measurements at energies above the $^{13}\mathrm{C}(p,n)^{13}\mathrm{N}$ reaction threshold of 3.24 MeV proton kinetic energy can be interpreted as a consequence of 1.06% admixture of the ^{13}C isotope in natural carbon, as the cross section for ^{13}N production raised by 3 orders of magnitude with respect to the measurements of $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$ at lower energies.

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1. Introduction

The radiative capture reaction $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$ has been recently studied via the detection of β^+ decay of the ^{13}N isotope. These measurements were performed on natural carbon targets in the astrophysical proton energy range below 2 MeV [1] and in the range of 2–22 MeV [2]. The cross sections measured by Rodríguez-González *et al.* [2] at proton energies of 2–22 MeV are three orders of magnitude above those reported in measurements performed at ATOMKI [1]. We argue that this unexpected increase might be due to the (p,n) reaction on ^{13}C nuclei, since the target was natural carbon. The cross section of the $^{13}\mathrm{C}(p,n)^{13}\mathrm{N}$ reaction leading to the formation of ^{13}N is relatively high, which might compensate for the small 1.06% [3] content of ^{13}C in natural carbon.

2. Analysis

The ^{13}N nucleus can be produced in two proton-induced reaction channels on natural carbon, namely $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$ and $^{13}\mathrm{C}(p,n)^{13}\mathrm{N}$. The first one on the most abundant ^{12}C isotope (about 99% [3]) is exothermic. The second one on the $f_{13} = 1.06\%$ abundant ^{13}C [3] is endothermic with $Q = \left(M(^{13}\mathrm{C}) + M(p) - M(^{13}\mathrm{N}) - M(n)\right)c^2 = -3.003$ MeV. The corresponding proton beam energy threshold is $E_p^{\mathrm{thr}} = 3.236$ MeV. The cross section of the radiative proton capture reaction is reduced by the electromagnetic vertex. This is not the case of the (p,n) reaction, where all vertices are strongly coupled. The natural carbon target for protons below $E_p^{\rm thr}$ can be treated as monoisotopic, while at higher energies, the (p,n) reaction may start to play a role, particularly as the cross section is significantly higher. This factor might compensate for the low abundance of the ^{13}C isotope.

Recently, two experimental groups measured the ^{13}N production via the detection of β^+ decay [1, 2]. Both groups used natural carbon targets and measured the decay curve of ^{13}N by the detection of 511 keV γ quanta from the β^+ annihilation. A single HPGe detector was used to detect the off-beam 511 keV radiation in the ATOMKI measurements [1], while a PET scanner was used off-beam to detect coincident events in the measurements by Rodríguez-González *et al.* [2]. The half-life of ^{13}N is equal to $T_{1/2} = 9.951 \pm 0.003$ min. [4], making it very distinct from other β^+-active nuclei of similar mass — half-life of ^{11}C is twice longer, while half-life of ^{15}O is five times shorter (unexpected presence of oxygen in a BN sample irradiated with protons was observed this way [5]). The measurement of the ^{12}C$(p,\gamma)^{13}$N reaction at astrophysically important energy range below 2 MeV was performed at ATOMKI [1]. The results obtained by detecting the ^{13}N decay agree well with the measurements employing other methods. As the energy range in ATOMKI measurements [1] is below the threshold energy for the ^{13}C$(p,n)^{13}$N reaction, the process is only the radiative capture. However, in the case of measurements by Rodríguez-González *et al.* [2], the proton energies were up to 22 MeV, which is well above $E_p^{\rm thr}$. Comparison of the cross section values reported for the three highest proton energies of [1] and the three lowest energies of Rodríguez-González *et al.* [2], summarized in Table 1, shows a sudden rise of three orders of magnitude, from μb to mb range.

Table 1. The cross section of the ^{12}C$(p,\gamma)^{13}$N reaction on natural carbon targets obtained by the detection of β^+ decay of ^{13}N . Three results at the highest energies of ATOMKI measurements [1] and three results at the lowest energies from [2] are listed.

Energy [MeV]	Cross section	Ref.
1.7977	(2.98 ± 0.25) μb	
1.8478	(1.85 ± 0.15) μb	[1]
1.898	(1.54 ± 0.13) μb	
2.0 ± 1.2	(0.79 ± 0.06) mb	
4.2 ± 1.0	(1.89 ± 0.15) mb	[2]
5.9 ± 0.8	(2.09 ± 0.17) mb	

We argue that the results of Rodríguez-González *et al.* [2] are indeed the cross section for the ^{13}N production on natural carbon, but the responsible reaction is mainly $^{13}\mathrm{C}(p,n)^{13}\mathrm{N}$ and not $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$. This conjecture is based on the experimental results of the $^{13}\mathrm{C}(p,n)^{13}\mathrm{N}$ reaction, performed on isotopically enriched targets [6, 7]. The results of Firouzbakhtl *et al.* [7] were obtained using a well-type NaI(Tl) scintillating detector, a method different from Kitwanga *et al.*, employing coincident measurement in a pair of plastic scintillation detectors [6]. These results are compared to the measurements of Rodríguez-González *et al.* [2] scaled by the $\frac{1}{f_{13}}$, as the correction of the abundance of ^{13}C in natural carbon. The results, shown in Fig. 1, agree quite well, particularly around the broad maximum in the proton energy range of 5–10 MeV.

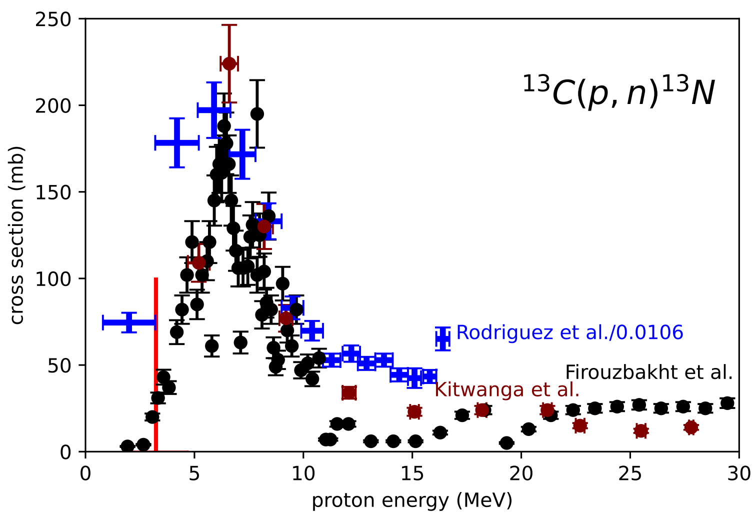

Fig. 1. The cross section of the $^{13}\mathrm{C}(p,n)^{13}\mathrm{N}$ reaction from the measurements with isotopically enriched ^{13}C targets [6, 7]. The production of ^{13}N observed in the measurements of Rodríguez-González *et al.* [2] is scaled with the 1.06% abundance of ^{13}C nuclei in the natural carbon target.

The interpretation by Rodríguez-González *et al.* [2] which attributes the measurements to the radiative process $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$ is, however, supported by the measurements of Cohen [8] performed on an isotopically enriched ^{12}C target at two-proton beam energies of 5 and 11 MeV (the reported cross section is 2.5 mb and 1.8 mb, respectively). The carbon target used in measurements of Cohen, performed more than 70 years ago, was isotopically enriched (^{13}C content was as low as 0.05%). The influence of the (p,n) reaction on the remaining ^{13}C nuclei was accounted to be $\sim 10\%$, however, the total uncertainty of the measured cross section was not provided [8]. It should be noticed that other results of the measurements of (p, γ) by Cohen [8] on ^{54}Fe, ^{60}Ni, ^{64}Zn, and ^{209}Bi are in relatively good agreement with later experiments.

3. Conclusions

The measurement of the $^{12}\mathrm{C}(p, \gamma)^{13}\mathrm{N}$ reaction in the proton energy range between 2 MeV and 22 MeV, performed by Rodríguez-González *et al.* [2], can be interpreted as the production of ^{13}N on the 1.06% abundant ^{13}C isotope. The reported cross section, when corrected for the low abundance of ^{13}C isotope, agrees roughly with the dedicated measurements of the $^{13}\mathrm{C}(p, n)^{13}\mathrm{N}$ reaction on isotopically enriched targets.

The importance of the cross section of proton-induced reactions on carbon, nitrogen, and oxygen targets calls for an intensified experimental activity, as these nuclei are abundant in tissue and proton-therapy procedures cause nuclear reactions on these elements (*e.g.* reactions on oxygen [9]). This activity should cover not only the most abundant light isotopes of these elements, but also all heavier ones, as it is the topic of current astrophysical research [10]. The recent progress in experimental capabilities, in particular radiation detectors of energy resolution superior to those used in the past, should be exploited. The results might also influence the precision of predicted radiation in proton therapy centers, an issue valid for patients and personnel [11].

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