Search for new resonant states in $^{10}$C and $^{11}$C and their impact on the cosmological lithium problem

F. Hammache, A. Coc, N. de Séréville, I. Stefan, P. Roussel, S. Ancelin, M. Assié, L. Audouin, D. Beaumel, S. Franchoo, B. Fernandez-Dominguez, S. Fox, C. Hamadache, J. Kiener, A. Laird, B. Le Cron, A. Lefebvre-Schuhl, L. Lefebvre, I. Matea, A. Matta, G. Mavilla, J. Mrázek, P. Morfouace, F. de Oliveira Santos, A. Parikh, L. Perrot, A. M. Sanchez-Benitez, D. Suzuki, V. Tatischeff, P. Ujic, M. Vandebrouck

1 Institut de Physique Nucléaire d’Orsay, UMR8608, IN2P3-CNRS, Université Paris Sud, 91406 Orsay, France
2 CNRSIN2P3-CNRS, Université Paris Sud, 91405 Orsay, France
3 Universidad de Santiago de Compostela, E-15786 Santiago, Spain
4 Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom
5 Nuclear Physics Institute ASCR, 250 68 Rez, Czech Republic
6 GANIL, CEA/DSM-CNRS/IN2P3, Caen, France
7 Departamento de Física Aplicada, Universidad de Huelva, E-21071 Huelva, Spain
8 Departamento de Física e Engenheira Nuclear, Universitat Politècnica de Catalunya, E-08036 Barcelona, Spain

(Dated: 07/11/2013)

The observed primordial $^{7}$Li abundance in metal-poor halo stars is found to be lower than its Big-Bang nucleosynthesis (BBN) calculated value by a factor of approximately three. Some recent works suggested the possibility that this discrepancy originates from missing resonant reactions which would destroy the $^{7}$Be, parent of $^{7}$Li. The most promising candidate resonances which were found include a possibly missed 1 $\pm$ 2 narrow state around 15 MeV in the compound nucleus $^{10}$C formed by $^{7}$Be+$^{3}$He and a state close to 7.8 MeV in the compound nucleus $^{11}$C formed by $^{7}$Be+$^{4}$He. In this work, we studied the high excitation energy region of $^{10}$C and the low excitation energy region in $^{11}$C via the reactions $^{10}$B($^{4}$He,$^{7}$Li)$^{10}$C and $^{11}$B($^{4}$He,$^{7}$Li)$^{11}$C, respectively, at the incident energy of 35 MeV. Our results for $^{10}$C do not support $^{7}$Be+$^{4}$He as a possible solution for the $^{7}$Li problem. Concerning $^{11}$C results, the data show no new resonances in the excitation energy region of interest and this excludes $^{7}$Be+$^{4}$He reaction channel as an explanation for the $^{7}$Li deficit.

PACS numbers: 26.35.+c, 25.55.Kr, 24.30.-v, 29.30.-h, 29.30.-h

The primordial nucleosynthesis of light elements $^2$H, $^3$He and $^7$Li, together with the expansion of the Universe and the cosmic microwave background (CMB) are the three observational pillars of the standard Big-Bang model where the last free parameter was the baryonic density of the Universe, $\Omega_b$. A precise value for this free parameter has been deduced from the analysis of the anisotropies of the CMB as observed by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite ($\Omega_b h^2 = 0.02249 \pm 0.00056$) [1] and more recently by the Planck mission ($\Omega_b h^2 = 0.02207 \pm 0.00033$) [2].

A comparison between the calculations of the primordial abundances of the light nuclei and the observations reveals a good agreement for helium and an excellent agreement for deuterium. In contrast, the theoretical predictions show a discrepancy by a factor of $\approx 3$ for $^7$Li abundance [3,4]. Indeed, at the baryonic density of the Universe, $\Omega_b h^2$, derived from the CMB anisotropies, the predicted BBN abundance of $^7$Li is: $(^7$Li/$H)_{BBN} = (5.12 \pm 0.71) \times 10^{-10}$ [3] when using WMAP data or $(4.89 \pm 0.41) \times 10^{-10}$ [5] with the Planck data. On the other hand, the observed $^7$Li abundance, derived from the observations of low-metallicity halo dwarf stars, was found to be $(^7$Li/$H)_{halo} = (1.58 \pm 0.31) \times 10^{-10}$ [6]. This significant discrepancy between the observations and the BBN predictions is known as the “lithium problem” [7].

Several ideas were addressed to try to explain this $^7$Li problem [8]. Some conceived the idea that the $^7$Li deficit points toward physics beyond the standard model such as decay of super-symmetric particles [8]. Others have suggested that the problem could be due to $^7$Li stellar destruction in the atmosphere of the halo stars [9]. However, a uniform destruction of $^7$Li over the so-called Spite-plateau region seems difficult [10]. Finally, several authors investigated the nuclear aspect of the problem concerning the $^7$Li abundance [11,13]. The main process for the production of the BBN $^7$Li at $\Omega_b h^2$ is the decay of $^7$Be which is produced in the reaction $^3$He($^4$He,$^7$Be). Direct measurements of this reaction cross-section were performed by several groups resulting in a significant reduction of the thermonuclear reaction rate uncertainty [13], but no solution to the $^7$Li problem. More generally, the experimental nuclear data concerning the 12 main BBN reactions are sufficient to exclude a solution in this region, so that one has to extend the network to

---

* Corresponding author: hammache@ipnno.in2p3.fr
1 Present address Department of Physics, University of Surrey, Guildford, GU2.5XH, United Kingdom
2 Present address GANIL, CEA/DSM-CNRS/IN2P3, Caen, France
3 Present address Vinča Institute of Nuclear Sciences, University of Belgrade, Serbia

$^7$Li abundance, derived from the observations of low-metallicity halo dwarf stars, was found to be $(^7$Li/$H)_{halo} = (1.58 \pm 0.31) \times 10^{-10}$ [6]. This significant discrepancy between the observations and the BBN predictions is known as the “lithium problem” [7].

Several ideas were addressed to try to explain this $^7$Li problem [8]. Some conceived the idea that the $^7$Li deficit points toward physics beyond the standard model such as decay of super-symmetric particles [8]. Others have suggested that the problem could be due to $^7$Li stellar destruction in the atmosphere of the halo stars [9]. However, a uniform destruction of $^7$Li over the so-called Spite-plateau region seems difficult [10]. Finally, several authors investigated the nuclear aspect of the problem concerning the $^7$Li abundance [11,13]. The main process for the production of the BBN $^7$Li at $\Omega_b h^2$ is the decay of $^7$Be which is produced in the reaction $^3$He($^4$He,$^7$Be). Direct measurements of this reaction cross-section were performed by several groups resulting in a significant reduction of the thermonuclear reaction rate uncertainty [13], but no solution to the $^7$Li problem. More generally, the experimental nuclear data concerning the 12 main BBN reactions are sufficient to exclude a solution in this region, so that one has to extend the network to
up to now neglected reactions. For instance, it was found
that if the $^7\text{Be}(d,p)^2\alpha$ reaction rate was significantly
higher, the $^7\text{Li}$ abundance would be brought down
to the observed level. However, subsequent experiments
ruled out this possibility.

Very recent works have extended this search and suggested the possibility of partially or totally solving
the $^7\text{Li}$ problem if additional destruction of A=7 isotopes occurs via missed resonant nuclear reactions in-
volving $^7\text{Be}$. The most promising candidates are possibly
missed resonant states in $^7\text{Be} +^3\text{He} \to^{10}\text{C}$, and in $^7\text{Be} +^4\text{He} \to^{11}\text{C}$ compound nuclei.

According to Ref. [19], the presence of any narrow
$^{10}\text{C}$ states with $J^\pi = (1^- \text{or} 2^-)$, allowing s-wave capture,
close to the $^7\text{Be} +^3\text{He}$ reaction threshold ($Q=15.003$
MeV), could bring a solution for the $^7\text{Li}$ problem (see Figure 8 in Ref. [19]). Unfortunately, the excitation energy
range of $^{10}\text{C}$ between 10.0 and 16.5 MeV is very poorly
known; the investigated excitation energy region in ref [23],
where $^{10}\text{C}$ was populated via $^{10}\text{B}(^3\text{He},t)$ reac-
tion, was limited to the region between the ground state
and 8 MeV while in ref. [24], where it was studied via
(p,n) reaction up to 20 MeV excitation energy, the energy
resolution of about 1 MeV and the important background
doesn’t allow to draw any conclusions on the absence or
presence of a narrow 1$^-$ or 2$^-$ state close to 15 MeV exi-
tation energy. $^{10}\text{C}$ was also studied via $^{12}\text{C}(p,t)$ reaction
but this favors the population of 0$^+$ and 2$^+$ states.

Concerning the $^7\text{Be} +^4\text{He} \to ^{10}\text{C}$ reaction channel, Civitarese et al. [21]
claimed also that any isolated state between 7.79 and 7.90 MeV excitation energy of $^{11}\text{C}$ having a to-
total width between 30 and 160 keV and corresponding to
a resonant energy between 250 and 350 keV respectively
would solve the $^7\text{Li}$ problem (see Figures 5, 6 and 7 in
Ref. [21]). The excited states of $^{11}\text{C}$ up to 9 MeV were
studied in the past via various indirect reactions [26] and
no state between 7.79 and 7.90 MeV is reported. How-
however, no dedicated measurement in this narrow energy
region was carried out in the previous works, so it can
not be excluded that a weakly populated state in this
energy region has been missed.

In the present work, we report on an experimental
study of the excited states of $^{10}\text{C}$ and $^{11}\text{C}$ where the
high excitation energy region of $^{10}\text{C}$ and the low
one of $^{11}\text{C}$ were investigated using $^{10}\text{B}(^3\text{He},t)^{10}\text{C}$ and
$^{11}\text{B}(^3\text{He},t)^{11}\text{C}$ charge-exchange reactions respectively.
We have chosen to use the $(^3\text{He},t)$ reaction because: i) it is
less selective than (p,t) reaction where odd parity and
odd spins are strongly inhibited by the selection rules and
ii) it has much better resolution and detection efficiency
than the (p,n) reaction.

The $^{10}\text{B}(^3\text{He},t)^{10}\text{C}$ and $^{11}\text{B}(^3\text{He},t)^{11}\text{C}$ reactions were carried out at an energy of 35 MeV using a $^3\text{He}$ beam
from the Tandem accelerator of the Orsay - ALTO fa-
cility. The targets consisted of a 90(9) $\mu g/cm^2$ enriched
$^{10}\text{B}$ with a gold backing of 200 $\mu g/cm^2$ thickness and a
self-supporting natural boron (80.1% $^{11}\text{B}$) of 250 $\mu g/cm^2$
thickness. Elastic scattering measurements were per-
formed at 40$^\circ$ in order to evaluate the contaminants
present in the two targets. A non-negligible contamination
of $^{12}\text{C}$ and $^{16}\text{O}$ was observed in $^{10}\text{B}$ and $^{10}\text{B}$
targets (Fig.1). Hence, for background contaminant eva-
ulation, we performed $(^3\text{He},t)$ measurements also on an
80(4) $\mu g/cm^2$ $^{12}\text{C}$ target and a 75(4) $\mu g/cm^2$ Si$_2$O$_4$
target. Target thicknesses were determined by $\alpha$-energy loss
measurements. The beam current was measured with a
Faraday cup and the intensity was about 200 enA.

The reaction products were momentum analyzed by
the Split-pole magnetic spectrometer and were de-
tected at the focal plane by a position-sensitive gas cham-
ber, a $\Delta E$ proportional gas-counter and a plastic scintil-
lator. The light fragments emitted by the $^{10}\text{B}(^3\text{He},t)^{10}\text{C}$
reaction were detected at 7$^\circ$, 10$^\circ$, 13$^\circ$ and 15$^\circ$ in the
laboratory system while those coming from $^{11}\text{B}(^3\text{He},t)^{11}\text{C}$
were detected at 7$^\circ$ and 10$^\circ$. Well known excited states
of $^{11}\text{C}$ from 2 MeV to 8.655 MeV excitation energy were
used to calibrate the focal plane position detector.

The energy resolution obtained in this experiment was
about 70 keV (FWHM) in the laboratory frame for the
low excitation energy region ($E_x \leq 8$ MeV) and around
37 keV(FWHM) for the high excitation energy region
($E_x \geq 12$ MeV) of $^{10}\text{C}$ and $^{11}\text{C}$.

Typical spectra obtained for the $^{10}\text{B}(^3\text{He},t)^{10}\text{C}$ reac-
tion at 10$^\circ$ (laboratory) is shown in Fig.2 for the exita-
tion energy region from 0 to 7 MeV in $^{10}\text{C}$ and in Fig.3 for
the excitation region of astrophysical interest from 14 to 16.6
MeV in $^{10}\text{C}$. Peaks not explicitly labeled in the figures
are assigned to unidentified impurities and peaks of $^{10}\text{C}$
are only labelled by their excitation energy.

The well known levels of $^{10}\text{C}$ [23] at 3.35, 5.22, 5.38 and
6.58 MeV excitation energy as well as the ground state

![FIG. 1. (Color online) The black, red, yellow and blue solid lines represent the results from $^3\text{He}$ elastic scattering at 35 MeV measured at 40° for $^{10}\text{B}$, $^{10}\text{B}$, Mylar and Si$_2$O$_4$ targets respectively. The contamination from $^{12}\text{C}$ and $^{16}\text{O}$ can be easily identified in $^{10}\text{B}$ and $^{10}\text{B}$ targets.](image-url)
are observed in this experiment (Fig. 2). The 5.22 and 5.38 MeV states are not separated because their natural width (225 and 300 keV respectively) is much larger than their separation energy. A small contamination by the 6.905 MeV state of $^{11}$C coming from a small $^{11}$B contamination of the target or a deuteron contamination of the selected reaction products.

The $^{10}$C excitation energy region from 7 to 14 MeV (not displayed in this paper) was also investigated but no other peaks except those coming from $^{16}$O($^3$He,t)$^{16}$F and $^{12}$C($^3$He,t)$^{12}$N contaminant reactions were identified at the four measured angles. The two states at 9 and 10 MeV excitation energy in $^{10}$C weakly populated in the $^{10}$B(p,n)$^{10}$C work [24] are not observed in this experiment.

In Fig. 3, the background becomes much more important because of the triton continuum. The well populated and separated peaks belong to unbound states of $^{16}$F and bound states of $^{13}$N coming from ($^3$He,t) reactions on $^{16}$O and $^{12}$C contamination, respectively. A dominant peak corresponding to an excitation energy of 16.46 MeV in $^{10}$C is observed at the angles $7^\circ$ and $10^\circ$ and follows well the $^{10}$B($^3$He,t)$^{10}$C reaction kinematic. From the peak analysis of this state, we deduced a peak position of $E_\gamma$=16.46±0.01 MeV and a peak width of about 150±19 keV. Note that a state at the energy of about 16.5 MeV was already observed in the $^{10}$B(p,n)$^{10}$C experiment [24].

Concerning the excitation energy region between 14.9 and 15.2 MeV in $^{10}$C, no unknown state is observed. The only observed peaks in this energy region are the unbound states of $^{16}$F at 3.758 and 3.87 MeV excitation energy due to $^{16}$O contamination in the target. The absence of a new $^{10}$C state at the four measured angles may have three non exclusive explanations: first, the state of interest is too large and can not be distinguished from the triton continuum. Second, the charge exchange ($^3$He,t) reaction cross section is too small, or third, there is no isolated state of $^{10}$C in this excitation energy region.

The choice among these explanations is thus dependent on the width of the peak of interest and the ($^3$He,t) cross-section. In order to visualize the effect of these quantities for our particular experimental conditions a numerical simulation has been performed of an assumed state at 15.1 MeV on top of the measured ($^3$He,t) spectrum at $\theta_{lab}$=10$^\circ$ once the $^{16}$O contamination is subtracted from a spectrum obtained with the Si$_2$O$_4$ target. The assumed state is given different widths and is populated with different charge-exchange cross-sections. For these simulations, we considered a $^{10}$B thickness of 90 $\mu$g/cm$^2$, a number of incident $^3$He nuclei similar to the one measured in the experiment and the measured experimental resolution of 37 keV (FWHM) in the considered excitation energy range. The excitation energy region of interest is fitted with a linear function well describing the triton background ($\chi^2=0.85$ with dof=96, where dof denotes degree of freedom) and the parameters of which are left free.

The presence of the assumed state with the chosen properties lead to an increase of the $\chi^2$ value, and the null hypothesis ”there is a $^{10}$C state in the region of interest” can be rejected at the usual significance level of 5% when $\chi^2 > 1.25$ for 96 degrees of freedom (goodness-of-fit test). An exclusion zone can then be drawn in the plane.
of the charge-exchange cross-section versus the width of the assumed state as shown on Fig. 4. We conclude that if a state is present in this region, a peak would have been identified with a probability larger than 95% confidence level in the red exclusion zone.

According to the literature \cite{27, 28}, typical (³He,t) differential charge exchange cross sections to 1⁻ or 2⁻ states at energies close to our incident energy are generally much larger than 25 µb/sr at 10° in the laboratory system. Therefore, if we assume comparable cross sections, we can conclude from the 95% CL exclusion zone that any 1⁻ or 2⁻ state of ¹⁰C in the excitation energy region around 15 MeV should have, if present, a total width larger than 590 keV in order to not be observed in this experiment.

To check the consistency of our simulations and conclusions concerning a hypothetical existing ¹⁰C state, we used the same procedure for states of ¹²N populated by the ¹²C(³He,t)¹²N reaction and using 10 µg/cm² of ¹²C which is the amount of contamination present in our ¹⁰B target. In this case, the total width limit of observation of any 1⁻ or 2⁻ existing state of ¹²N is found to be lower, Γ_T = 300 keV, at the expected cross section of 60 µb/sr \cite{29}. This result is in agreement with the observation in our experiment of the 1.191 MeV (J^π = 2⁻) state of ¹²N which has a total width of 118 keV and the lack of observation of the known 1.8 MeV (J^π = 1⁻) state of ¹²N which has a total width of 750 keV.

Concerning the ¹¹B(³He,t)¹¹C measurements, spectra obtained at 7° (lab) and 10° (lab) are shown in Fig. 5 and 6.

In Fig. 5, we do not observe any triton peak in the excitation energy region between 7.79 and 7.90 MeV of ¹¹C corresponding to the energy resonance between 250 and 350 keV. Owing to the very large signal to background ratio observed in the spectrum which is ten times better than in ¹⁰C case, it is very unlikely that a new state of ¹¹C exists in this energy region. This result is strengthen by the fact that all the known states in the mirror nuclei ¹¹B \cite{29} have their counterpart in ¹¹C at energies lower than 12 MeV.

The reactions ⁷Be(³He,p)⁹B and ⁷Be(³He,α)⁸Be are the only possible open channels for the reaction ⁷Be+³He→¹⁰C, so calculations of their reaction rates were performed for the lower limit derived from our experiment concerning the study of resonant state in the compound nucleus ¹⁰C. Hence, we assumed a 1⁻ state in the compound nucleus ¹⁰C with a total width equal to the experimental lower limit of Γ_T = 590 keV in one case and also with Γ_T = 200 keV in the case where the (³He,t) differential charge exchange cross section to this state is a factor of three smaller than the expected minimum one. The resonance position was varied so that the corresponding resonance energy E_R would take the values of 10, 100 and 500 keV, spanning the range of interest for BBN, for such a broad state. In these calculations, the Wigner limit value of 1.842 MeV was used for the reduced partial width in the entrance channel. This leads, at the three resonance energies mentioned above, to partial widths, Γ_t(He), of respectively 5.70×10⁻⁴³, 6.25×10⁻⁹ and 2.38 keV at a channel radius of 4.026 fm.

Since Γ_t(He) ≪ Γ_T, the total width is dominated by the

![FIG. 4. (Color online) Exclusion zone in the plane of the charge-exchange cross section vs the width of the state. The red hatched area corresponds to a 95% confidence level (CL) exclusion zone of an isolated ¹⁰C state when using a ¹⁰B target. In this case, the total width limit of observation of any 1⁻ or 2⁻ state is present in this region, a peak would have been identified with a probability larger than 95% confidence level in the red exclusion zone.](image-url)

![FIG. 5. (Color online) ¹¹B(³He,t)¹¹C Bρ spectra measured at the laboratory angles, θ=7° (a) and 10° (b) in the excitation energy region from gs to 9 MeV. Excitation energies (MeV) of ¹¹C levels are indicated. The unlabeled peaks correspond to unidentified contamination.](image-url)
and were found to have no effect on the primordial rates were included in a BBN nucleosynthesis calculation each case to the maximum possible rate. The calculated nuclei exchange reactions are irrelevant for the abundance. Thus, we can conclude that this channel is absence of any state of the presence of a large triton continuum background, the conclusion we could assert is that any state of C nuclei put an end to the various discussions concerning the missing resonant states in these nuclei which were thought to partially or totally solve the 7Li problem [19–21] and exclude 7Be+ 3He and 7Be+ 4He reaction channels as responsible for the observed 7Li deficit. With our conclusion and those of previous works concerning the other important reaction channels 3He+ 4He and 7Be+d, the 7Li problem remains unsolved. The solution has very likely to be found outside of nuclear physics.

FIG. 6. (color online) 11B(3He,t)11C Bp spectra measured at θ=7° (a) and 10° (b) in the excitation energy region of interest close to 8 MeV. Excitation energies of 11C levels are indicated. The double arrow indicates the astrophysical region of interest.

FIG. 7. (Color online) 7Be(3He,p) 8B and 7Be(3He,α) 8Be reaction rate in (a) and (b) respectively. The red, green and blue solid lines correspond to calculations with E_R=10, 100 and 500 keV respectively and Γ_T=590 keV while the dotted lines correspond to calculations with Γ_T=200 keV.

ACKNOWLEDGMENTS

We thank the Tandem-Alto technical staff and the IPNO target laboratory staff for their strong support during the experiment. This work has been supported by the European Community FP7 - Capacities-Integrated Infrastructure Initiative- contract ENSAR n° 262010, the IN2P3-ASCR LEA NuAG and the French-Spanish AIC-D-2011-0820 project.

[1] E. Komatsu et al., Astrophys. J. Suppl. Ser., 192 18 (2011).
[2] P. A. R. Ade et al. (The Planck Collaboration), arXiv:1303.5076 submitted to Astron. Astrophys.
[3] R.H. Cyburt, B.O. Fulop, and K.A. Olive, J. Cosmology and Astroparticle Phys. 11, 12 (2008).
[4] A. Coc and E. Vangioni, Proc. 4th Int. Conf. on Nucl. Phys. in Astrophysics, J. Phys. Conf. Ser. 202, 012001
[5] A. Coc, J.-Ph. Uzan, E. Vangioni, arXiv:1307.6955
[6] L. Sbordone et al., Astron. Astrophys., 522, 26 (2010)
[7] M. Spite, F. Spite, and P. Bonifacio Proc. "Lithium in the Cosmos" (Paris), Mem. S.A.It. 22 9 (2012).
[8] B. Fields, Annual Review of Nuclear and Particle Science, 61, 47 (2011)
[9] O. Richard, G. Michaud, & J. Richer, Astrophys. J. 619, 538 (2005).
[10] F. Iocco, Proc. "Lithium in the Cosmos" (Paris), Mem. S.A.It. 22 19 (2012).
[11] A. Coc, E. Vangioni-Flam, P. Descouvemont, A. Adahchour, and C. Angulo, Astrophys. J., 600 544 (2004).
[12] C. Angulo E. Casarejos, M. Couder et al., Astrophys. J. 630, L105 (2005).
[13] R. H. Cyburt, B. D. Fields and K. A. Olive, Phys. Rev. D 69, 123519 (2004)
[14] A. Di Leva et al. Phys. Rev. Lett 102, 232502 (2009) and references therein
[15] R.H. Cyburt & M. Pospelov, International Journal of Modern Physics E21, 50004 (2012), [arXiv:0906.4373].
[16] P.D. O’Malley, D.W. Bardayan, A.S. Adekola et al., Phys. Rev. C84, 042801 (2011).
[17] C. Scholl, Y. Fujita, T. Adachi et al., Phys. Rev. C84, 014308 (2011).
[18] O.S. Kirsebom & B. Davids, Phys. Rev. C84, 058801 (2011).
[19] N. Chakraborty, B. D. Fields and K. Olive Phys. Rev. D 83, 063006 (2011)
[20] C. Broggini, L. Canton, G. Fiorentini, F.L. Villante, JCAP 06, 030 (2012)
[21] O. Civitarese and M.E. Mosquera, Nucl. Phys. A 898, 1 (2013)
[22] J. E. Spencer and H. A. Enge, Nucl. Instrum. Methods 49, 181 (1967)
[23] M. J. Schneider et al. Phys. Rev. C 12, 335 (1975)
[24] L. Wang et al. Phys. Rev. C 47, 2123 (1993)
[25] W. Benenson, G. M. Crawley, J. D. Dreisbach and W. P. Johnson, Nucl. Phys. A 97, 510 (1967) and references therein
[26] http://www.nndc.bnl.gov/chart/ and references therein
[27] G. C. Ball et al. Phys. Rev. 155, 1170 (1967)
[28] G. C. Ball and J. Cerny, Phys. Rev. 177, 1466 (1969)
[29] W. A. Sterrenburg, M. N. Harakeh, S. Y. Van Der Werf and Van Der Woude, Nucl. Phys. A 405, 109 (1983).