EFDA–JET–CP(10)03/20

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** See annex of F. Romanelli et al, "Overview of JET Results", (Proc. 22 nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).*

Preprint of Paper to be submitted for publication in Proceedings of the
18th High Temperature Plasma Diagnostics, Wildwood, New Jersey, USA.
(16th May 2010 - 20th May 2010)

ABSTRACT.
Cross section data for the $^{12}C(^{3}He, p)^{14}N$ reaction of relevance for g-ray spectrometry of fusion plasmas are evaluated. Available data for the population of excited states in ^{14}N up to the 8th level are assessed in the range E_{3He} = 0-5MeV. Discrepancies and gaps in the database have been solved by means of interpolations and consistency analysis. The evaluated cross section data are used to predict the intensity ratio of characteristic 2.31MeV and 1.63MeV g-rays.

1. INTRODUCTION

Gamma-ray spectrometry is in use at the JET fusion experiment as a diagnostics of energetic ions with energies in the 0.5-5.0MeV range [1]. Typical measurements involve the observation of g-ray emission peaks due to reactions between light plasma impurities and energetic ions driven by Ion Cyclotron Resonance Heating (ICRH). A good example is the $^{12}C(^{3}He, p\gamma)^{14}N$ reaction. Emitted γ-rays have typical energies of $E_{\gamma 1}$ = 2.31MeV and $E_{\gamma 2}$ = 1.63MeV that are well within the range of available spectrometers. Somewhat more challenging is the interpretation of the measurements. The $^{12}C(^{3}He, p)^{14}N^{*}$ reaction is exothermic, with a Q value of 4.78MeV, which exceeds the energy of the first two ^{14}N excited states at 2.31MeV and 3.95MeV. Gamma ray emission is negligible for E_{3He} < 1MeV. At ^{3}He energies in the MeV range, ^{14}N excited states higher than the 2nd contribute to the peaks at $E_{\gamma 1}$ and $E_{\gamma 2}$ through cascade transitions (Fig.1 and Table 1). A good knowledge of the reaction cross sections for the population up to the 8th excited state of ^{14}N is required for accurate simulations of the I_1/I_2 intensity ratio in the range E_{3He} = 0-5MeV. However available data [2-6] show discrepancies and gaps in the database that are solved here by means of interpolations and consistency analysis. The evaluated differential cross section data $d\sigma_i/d\Omega$ (i=1-8) are used to predict the intensity ratio of characteristic γ-rays at $E_{\gamma 1}$ = 2.31MeV and $E_{\gamma 2}$ = 1.63MeV.

2. CROSS SECTION DATA AND INTERPOLATIONS

Available cross section data for the $^{12}C(^{3}He, p)^{14}N$ reaction were obtained at accelerators with ^{3}He beams in the energy range E_{3He} = 1.1–5.5MeV (laboratory system). The available data can be divided into two groups. The first group [2-4] contains data from experiments aimed at a systematic investigation of O^{15} nuclear structure and decays. Data on the proton angular distributions (differential cross sections $d\sigma_i/d\Omega$) at selected angles are provided as a function of $E^{3}He$ for several excited states of $1^{4}N$, as well as $d\sigma_i/d\Omega(q)$ data provided. for the full angular range 0°-180° at selected energies. A second, more recent set of measurements [5,6] was motivated by the interest in an alternative technique for profiling ^{12}C below a surface. The differential cross section $d\sigma_i/d\Omega(q=90°)$ was measured in the energy range E_{3He}=1.5-3MeV for the ground, 1st and 2nd ^{14}N excited state, and in the range E_{3He}=2-3MeV for the 3rd and 4th excited state. No information is provided by the more recent measurements on higher excited states, nor on the angular dependence of the cross section.

The available data set above E_{3He} = 3MeV is complete and consistent and does not require corrections or interpolations. The situation is less satisfactory in the range 1MeV < E_{3He} < 3MeV. This is illustrated in Fig.2, where some cross section data from [2] and [6] are shown. The main observations are

i) Above E_{3He} = 1.8MeV, data for dσ1/dΩ (q=90°) from [2] are systematically underestimated if compared to those of [6], whose values are however in agreement with [5]. The same is also true when comparing data for dσ2/dΩ (q=90°).

ii) Data at E_{3He} = 2MeV indicate that dσ4/dΩ (q=90°) is higher than dσ1/dΩ(q=90°) and dσ2/dΩ (q=90°) for E_{3He} < 2 MeV; however no dσ4/dΩ (q=90°) values are available below E_{3He} < 2MeV.

In order to obtain the complete differential cross section in the range E_{3He}=0–5MeV, data on dσi/dΩ (q) (i=1-8) were completed with suitable interpolations and extrapolations. To fill in the gap in the data for dσ4/dΩ (q=90°) below 2MeV, an exponential extrapolation with slope taken from data in the range E_{3He} = 2.0–2.5MeV was performed down to E_{3He}=1.4MeV. A second exponential extrapolation was used to produce data in the range E_{3He}=0–1.4MeV with a slope chosen so as to have dσ4/dΩ (q=90°)=dσ1/dΩ (q=90°) at E_{3He} = 1.1MeV. Below this value, dσi/dΩ (q=90°) was assumed to be the same for i=1,2,4. The latter choice is based on the observation that dσ1/dΩ (q=90°) and dσ2/dΩ (q=90°) are almost equal in the range E_{3He} < 1.8MeV (Figure 2). For higher excited states (i=5-8) dσi/dΩ = 0 was assumed in the energy range up to E_{3He} = 2MeV where no experimental data are available. Data from [2] were used for dσ1/dΩ (q=90°) and dσ2/dΩ (q=90°) only in the range E_{3He}=1.1–1.6MeV, while data from [6] were used wherever available below E_{3He} = 3MeV. Above this energy data availability was sufficiently adequate for all levels to avoid interpolations for dσi/dΩ (i=1-8). In this way dσi/dΩ (q=90°) was determined at all energies up to 5MeV.

The total cross section si for populating the ith excited level was calculated by assigning the angular dependence of the differential cross sections as a function of E_{3He}. This was available (e.g. from [2]) for a number of E_{3He} energies. Available information was completed by linear interpolation from values at the nearest neighbor points, including a point at E_{3He} = 0MeV where cross section isotropy was assumed.

The resulting cross section values are shown in Fig. 3. For E_{3He} < 2MeV, only the cross sections for the population of the 1^{st}, 2^{nd} and 4^{th} excited states contribute to g-ray emission (the 3rd excited state is disregarded here because it does not yield γ-rays of $E_{\gamma 1}$ = 2.31MeV or $E_{\gamma 2}$ = 1.63MeV). The general trend is that of an exponential, but for a resonance in the cross section for the 1^{st} and 2^{nd} excited states at E_{3He} = 1.3MeV, followed by a second broader resonance for the 2^{nd} excited state at E_{3He} = 1.6MeV. Above E_{3He} = 2MeV higher excited states start to be populated and contribute to γ-ray emission. This is particularly true for the 5^{th} and 7^{th} excited states with a cross section about half of that for the 2^{nd} state, which is the largest in this energy range.

3. REACTIVITY AND PEAK INTENSITIES

The evaluated σ_i database can be used to predict the intensity of characteristic γ-rays in fusion plasmas. The effective cross sections $s_{\gamma 1}$ and $s_{\gamma 2}$ for production of γ-rays with $E_{\gamma 1}$ = 2.31MeV and $E_{\gamma 2}$ = 1.63MeV are determined as a weighted sum of σ_i values with the branching ratios for the relevant transitions as weights.

The reactivities for γ-ray emission in the plasma are

$$Y_{\gamma 1} = \int y_{\gamma 1} dE_{3He} \quad Y_{\gamma 2} = \int y_{\gamma 2} dE_{3He} \tag{1}$$

where $y_{\gamma 2}$ and $y_{\gamma 2}$ are the differential reactivities given by

$$\begin{aligned} Y_{\gamma 1} &= f(E_{3He})\, \sigma_{\gamma 1} (E_{3He}) \nu \\ Y_{\gamma 2} &= f(E_{3He})\, \sigma_{\gamma 2} (E_{3He}) \nu \end{aligned} \tag{2}$$

The differential reactivities reflect the combined energy dependence of the cross sections and of the ^{3}He distribution. For Maxwellian ^{3}He ions $y_{\gamma 1}$ varies as illustrated in Fig.4 for temperatures T_{3He} = 250keV and 400keV. At T_{3He} = 250keV $y_{\gamma 1}$ is practically negligible above E_{3He} = 3MeV, i.e. most of the γ-ray emission comes from the lower excited states L1, L2 and L4. As T_{3He} = is raised to 400keV, ^{3}He energies up to 5MeV contribute to γ-ray emission and levels up to L8 need to be included in the calculation. The qualitative behavior of $y_{\gamma 1}$ is similar. Our evaluation of cross section data was limited to E_{3He} < 5MeV; therefore one should expect to accurately predict γ-ray emission for ^{3}He temperatures up to about 500keV. There is some systematic uncertainty in the calculations, especially at lower T_{3He} values, due to the use of evaluated σ_i values. This can be reduced if new cross section measurements become available for E_{3He} < 3MeV.

The ratio of the reactivities $Y_{\gamma 1}$ and $Y_{\gamma 2}$ is $r = Y_{\gamma 1} / Y_{\gamma 2}$. Its value is always above 2 because the 2nd excited state contributes equally to the $E_{\gamma 1}$ = 2.31MeV and $E_{\gamma 2}$ = 1.63MeV peak whereas the 1st and several other levels only contribute to the $E_{\gamma 1}$ peak. An exception is the 8th level that has a resonant contribution to γ_2 at E^3He ≈ 3MeV. Shown in Fig.5 is the variation of r versus T_{3He}. As T_{3He} is raised from 100keV to 200keV r increases from 2.4 to 2.7. It isthen practically independent of T_{3He} up to T_{3He} = 350keV. The slow decrease of r above 350keV is due to the relatively larger contribution of the 2nd excited state σ_2 at higher energies, see Fig.3.

Also shown in Fig.5 is a value for r derived from γ-ray spectrometry measurements at JET. One can see that the measured ratio is of limited use as a T_{3He} diagnostics. On the other hand the measured ratio agrees with the predicted value over a broad range of temperatures. This confirms that the systematic errors on the cross sections should not be too large.

CONCLUSIONS

Cross section values for the $^{12}C(^3He, p)^{14}N$ reaction of relevance for γ-ray spectrometry of fusion plasmas were evaluated in the range E_{3He} = 0-5MeV. Available data for the production of up to the 8th excited state of ^{14}N were assessed and discrepancies as well as missing data were found for E_{3He} < 3MeV. Discrepancies and gaps in the database were solved by means of interpolations and consistency analysis. The evaluated cross section data were used to predict the intensity ratio of characteristic γ-ray peaks at 2.31MeV and 1.63MeV which was found to be in reasonable agreement with the measured value.

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Level	Energy (keV)
L1	2313
L2	3948
L3	4915
L4	5106
L5	5691
L6	5834
L7	6204
L8	6446

Table I: Energies of the first eight ^{14}N excited states.

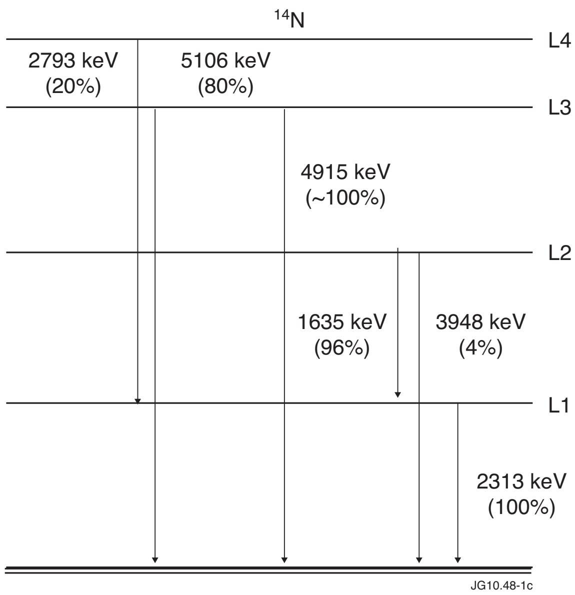

Figure 1: Level scheme for the first four excited levels of ^{14}N nucleus. The branching ratios for allowed transitions are indicated.

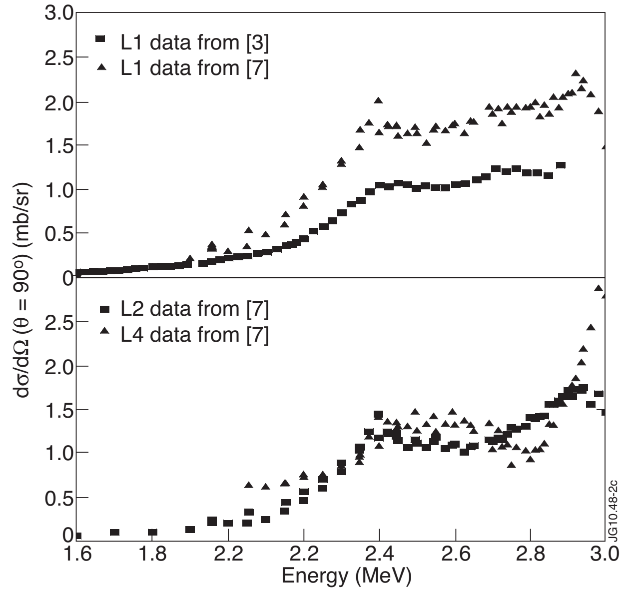

Figure 2: (a) Differential cross section $d\sigma/d\Omega(\theta=90°)$ for the reaction ^{12}C (^{3}He,p)^{14}N populating the 1st excited state of ^{14}N. Data taken from [6]. Cross section data from [2] are als shown for comparison. (b) Same as (a) but for the 2nd and 4th excited state of ^{14}N. Data for the 4th excited state are not available for $E_{^3He}$< 2MeV.

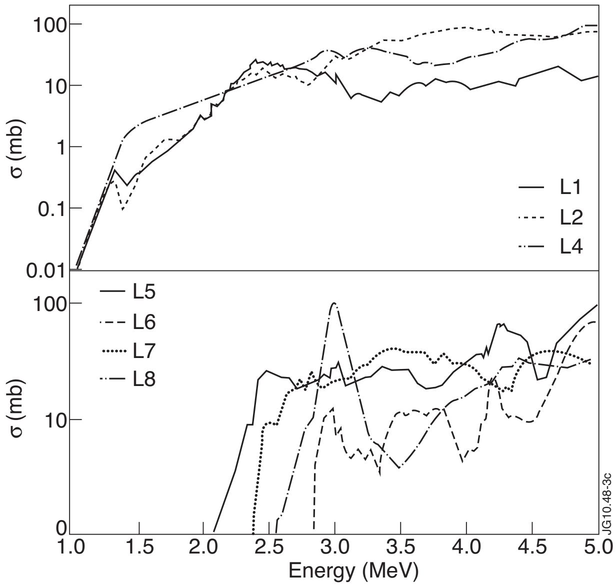

Figure 3: (a) Excitation functions (integral cross sections) for the 1st to 4th ^{14}N states populated in the ^{12}C (^{3}He,p)^{14}N reaction obtained from interpolations of experimental data. (b) Same as (a) but for the 5th to 8th excited state of ^{14}N.

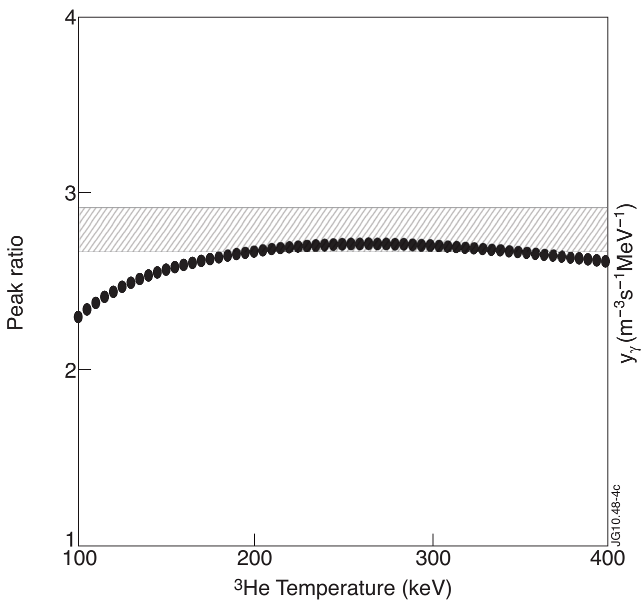

Figure 4: Differential reactivity for the production of 2.31-MeV γ-rays assuming Maxwellian ^{3}He ions with tail temperatures equal to 250keV (solid line) and 400keV (dashed line).

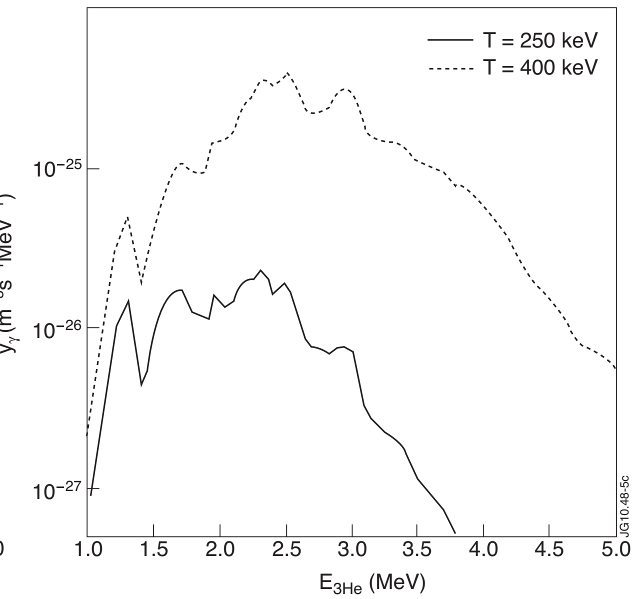

Figure 5: Intensity ratio of 1.63MeV and 2.31MeV γ-rays from the ^{12}C(^{3}He,pγ)^{14}N reaction for Maxwellian ^{3}He ions of different temperatures. The shadowed band is the intensity ratio determined from experimental data.