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SCATTERING OF PHOTONS AT THE 15.11 MeV ENERGY LEVEL IN ^{12}C*

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The 15.11 MeV energy level in ^{12}C was excited by bremsstrahlung. The scattered photons were detected with a total γ absorption NaI(TI) spectrometer set at 135° to the bremsstrahlung beam. The following level parameters were obtained: $\sigma_a^0 = (17.9 \pm 0.6)$ barn, $\Gamma_{tot} = (69 \pm 4)$ eV and $\sigma_{int} = (1.86 \pm 0.12)$ mb MeV. The branching ratio to the first excited state and the ground state is $\Gamma_{\gamma 1}/\Gamma_{\gamma 0} = (3.6 \pm 1.0)\%$.

Introduction

Scattered photons from the 15.11 MeV energy level in ^{12}C have been studied using high energy bremsstrahlung (end point energy 108 MeV). Although subsequent fluorescence experiments were performed [1—6], considerable uncertainty remained about the level parameters.

The first $T = 1,1^+$ energy level in ^{12}C at 15.11 MeV is of particular interest because it is an isobaric analogous state of several low-lying states in the neighbouring odd-odd nuclei. Scattered photons are easily observed since the integrated scattering cross section is rather large (1.86 mb MeV), the level is narrow (69 eV) and situated in an energy region which is free of other scattering processes. It is, therefore, desirable to have available an accurate determination of the parameters of this level for calibration purposes.

This level disintegrates to the 0^+ ground state of ^{12}C and to the first 2^+ state at 4.43 MeV. ALMQUIST et al. [7] measured a branching ratio of $\Gamma_{\gamma 1}/\Gamma_{\gamma 0} = 3\%$. An α-disintegration to the 0^+-ground state of ^8Be is strongly momentum and parity forbidden and α-particle emission to the 2^+ state at 2.9 MeV of ^8Be does not occur if the 15.11 MeV level is a pure $T = 1$ state. REISMAN et al. [8] reported that the Γ_α width of that state amounts to 2% of the total width Γ_{tot}. Because the experimental errors described in this paper are of the same order, this contribution can be neglected, and

$$\Gamma_{tot} = \Gamma_\gamma + \Gamma_\alpha \approx \Gamma_\gamma = \Gamma_{\gamma 0} + \Gamma_{\gamma 1}\,.$$

* The experiment was performed at the 300 MeV electron linear accelerator at Mainz.
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The level parameters σ_α^0 and Γ_{tot} were determined through a resonant absorption experiment. This experiment consists of two independent measurements:

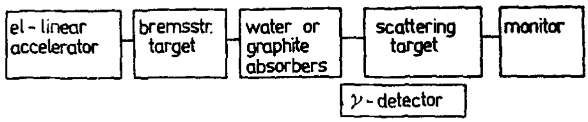
in the first — the production experiment — the yield of scattered photons from a target of thickness T is measured;

in the second — the self-absorption experiment — an absorber is placed into the incident beam to attenuate the 15 MeV photons.

Experimental arrangement

The experiment was performed using the bremsstrahlung beam from the 300 MeV electron linear accelerator at Mainz.

The experimental set-up is shown below:



The bremsstrahlung beam is produced by electron bombardment of a 0.1 mm thick tantalum target. A narrow beam of 2.4 mrad is defined by conical lead collimators. At the scattering target, situated 12.5 m from the bremsstrahlung target, the beam was 5 cm in diameter. A sweep magnet and vacuum pipe maintain an electronfree beam up to the target. As target a 2 cm thick (3.31 g/cm^2) disc of reactor graphite was used.

For the "self-absorption" experiment, a 7 cm thick (11.6 g/cm^2) graphite absorber was placed in the primary beam. The absorber and scatterer thicknesses were measured along the direction of the photon beam, thus eliminating cosine factors from the formulae given below.

The scattered photons are detected at 135° and analysed in a total γ-absorption NaI(Tl) spectrometer (9″ diameter $\times$15.5″ length). The detector was placed 1.20 m from the scatterer. The resolution of the spectrometer for 15 MeV was 5.5%. The number of scattered photons $N(T)$ was obtained by summation over the peak shown in Fig. 1. All runs were monitored in terms of the charge collected from a calibrated thick aluminium ionization chamber of the NBS type P2—4 [9]. A detailed description of the bremsstrahlung beam production, the total γ-absorption spectrometer, the electronics and the neutron background subtraction is given elsewhere [10—13].

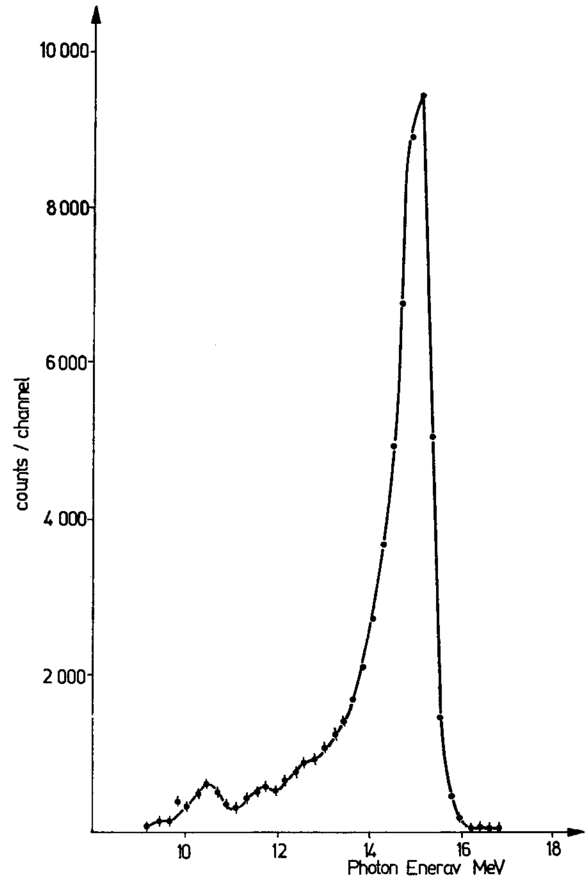


Fig. 1. The pulse-height distribution produced in the NaI(TI) crystal at 135° to the bremsstrahlung beam

Procedure and results

For a target of thickness T the yield of photons scattered by a single level is given:

$$N(T) = C \cdot I_g(T) = C \cdot \frac{I_s(T)}{S(T)} = C \cdot \int_{\text{res}} \sigma^*(E, T)\, dE\,, \tag{1}$$

$$\sigma^*(E, T) = \frac{\sigma_s}{nT\left(\sigma_a(E) + b\sigma_e(E)\right)}\left(1 - e^{-nT(\sigma_a(E) + b\sigma_e(E))}\right).$$

$N(T)$ — yield of scattered photons;

C — includes scattering and solid angle, dipole-distribution of the scattered photons, detector efficiency, number of incident 15 MeV photons, and absorbers in the scattered beam;

T — target thickness;
$S(T)$ — target self-absorption factor;
$I_g(T)$ — measured integral scattering cross section;
$I_s(T)$ — integral scattering cross section;
$\sigma_s(E) = \sigma_a(E) \frac{\Gamma_\gamma}{\Gamma_{tot}}$ — resonant scattering cross section;
$\sigma_a(E)$ — resonant absorption cross section;
$\sigma_e(E)$ — absorption cross section due to pair production and Compton scattering;
b — mean path of photons in the target.

It is assumed that the bremsstrahlung spectrum is constant in the energy interval where σ_s and σ_a are not zero and, therefore, the number of incident 15 MeV photons could be placed before the integral. It is clear that for such a narrow level photon selfabsorption occurs and the number of scattered photons is no more proportional to the target thickness.

Here we obtained

$$I_g(T = 3.31 \text{ mg/cm}^2) = (1.16 \pm 0.068) \text{ mb MeV}.$$

With an absorber of thickness Δ in the incident beam the attenuated scattered yield is

$$N(T, \Delta) = C_1 \int_{res} \sigma^*(E, T)\, e^{-\sigma_a(E) n \Delta}\, dE. \tag{2}$$

$N(T, \Delta)$ — yield of scattered photons with absorber of thickness Δ in the incident beam.

In the production experiment a water absorber was placed in the incident beam of equivalent thickness to the graphite absorber.

This absorber modifies the bremsstrahlung spectrum in the same way as does the graphite absorber, except for the filter effect at 15 MeV.

Therefore C is identical with C_1.

From these two independent measurements the ratio V was experimentally determined

$$V = \frac{N(T)}{N(T, \Delta)} = 3.75 \pm 0.1. \tag{3}$$

However, V can be also determined by numerical calculation with σ_a^0 and Γ_{tot} as variables:

$$V = \frac{\int_{res} \sigma^*(E)\, dE}{\int_{res} \sigma^*(E)\; e^{-\sigma_a(E) n \cdot \Delta}}. \tag{4}$$

For the calculation of (4) the nuclear absorption cross section $\sigma_a(E)$ is given by folding a Gaussian distribution for thermal motions of the scattered nuclei with the Breit—Wigner one-level formula:

$$\sigma_a(E) = \sigma_a^0 \frac{1}{2\sqrt{\pi t}} \int \frac{\exp[-(x-y)^2/4t]}{1+y^2}\, dy\,,$$

where $x = 2\dfrac{E-E_0}{\Gamma}\,,\quad t = \left(\dfrac{\delta}{\Gamma}\right)^2,$

σ_a^0 — peak absorption cross section at the resonance energy;
E_0 — the resonance energy;
E — the actual energy;
Γ — the full level width at half maximum;
δ — the "Doppler width".

For photons of energy E incident on a nucleus of mass M, the Doppler width may be given by

$$\delta = E\left[\frac{2kT'}{Mc^2}\right]^{1/2},$$

where k — the Boltzmann constant;
c — the velocity of light;
T' — the effective temperature which takes into account the vibration of the scatterer atoms due to their binding in a chemical lattice.

As a lower level for δ SCHMIDT [4] suggested 31.6 eV (for carbon gas at room temperature) and as an upper level 40 eV (for diamant crystals). In our calculation a value of 33 eV was used.

Calculations for various values of $t = (\delta/\Gamma_{tot})^2$ and σ_a^0 were carried out on a computer at the University of Mainz.

The best fit with the experimental data was obtained for the values

$$\Gamma_{tot} = (69 \pm 4)\ \text{eV}\,,$$
$$\sigma_a^0 = (17.9 \pm 0.6)\ \text{b}.$$

The obtained data are summarized in the following Table together with the results of other authors.

The integrated cross section I_s was obtained from these values to be:

$$I_s = \int_{res} \sigma_s(E)\, dE = \frac{\pi}{2}\sigma_\alpha^0 \Gamma_\gamma = (1.86 \pm 0.12)\ \text{mb. MeV}.$$

Table I

Parameters of the 15.11 MeV level

Reference	I_S [mb. MeV]	σ_a^0 barn	Γ_{tot} [eV]	$\frac{\delta}{\Gamma_{tot}}$	$\frac{\Gamma_{4.43\,MeV}}{\Gamma_{tot}}$ %
FULLER [1]	1.90±0.27	22.2±2.2	79±16	1	7
GARWIN [2]	2.33±0.19	29.7±1.1	64±10	0.62±0.1	5±4
BUSSIERE [3]	2.45±0.5	32	60±8	0	11±5
SCHMID [4]*	1.82±0.12	32	45±10	1	—
GUDDEN [5]*	1.79	32	35.5	—	—
KÜHNE [6]*	1.8±0.2	32	39±5	0.9±0.3	—
present work	1.86±0.12	17.9±0.6	69±4	0.48±0.1	3.6±1.0

Discussion

The authors marked by an asterisk used for σ_a^0 the value obtained from perturbation theory for a single level formula $6\pi\lambda\!\!\!^{-2} = 32b$. In this case the level width is no longer a free parameter, it follows directly from formula (1).

The influence of the following systematic errors on the ratio V should be considered:

- after bremsstrahlung beam reduction by a factor of 4 the ratio does not change. This means that errors due to detector dead-time are negligible;
- the bremsstrahlung spectrum was modified by a 1.3 cm thick lead absorber, and no change in the ratio was observed. It follows that the 15.11 MeV level is not populated by inelastic scattering from levels above the giant resonance;
- the 15.11 MeV level could be reached by the $^{13}C(\gamma, n)^{12}C^*$ reaction. The isotopic abundance of ^{13}C is about 1%, but the (γ, n) cross section is rather high [14].

If all ^{12}C nuclei populate the 15.11 MeV state, the ratio would change so that $\sigma_a^0 = 6\pi\lambda\!\!\!^{-2}$. This is extremely unlikely. But if σ_a^0 is smaller than $6\pi\lambda\!\!\!^{-2}$, the extrapolation made in the perturbation theory is not valid for this level. It is also possible that there are two levels very close to each other and the level broadening could be explained. The resolution of our apparatus was not enough to check this possibility. In Fig. 1 at 10.68 MeV the small peak represents the transition from the 15.11 MeV level into the 2^+ level at 4.43 MeV. The obtained branching ratio $\Gamma_{\gamma 1}/\Gamma_{\gamma 0} = (3.6 \pm 1)\%$ is in good agreement with reported data [7].

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