wand gegen die Auffassung von EINSTEIN und LAUB erhoben werden.

Die Diskussion zeigt, daß die Frage nach dem Energie-Impulstensor im wesentlichen auf das Problem zurückgeführt werden kann, wie das elektromagnetische System vom mechanischen System abzugrenzen ist. Bei der hier vorgenommenen Abgrenzung folgt nach dem Noetherschen Theorem der von MINKOWSKI eingeführte Energie-Impulstensor. In anderem Zusammenhang kann sich eine andere Abgrenzung als zweckmäßig erweisen.

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Direct Photodisintegration of ^{13}C below 17 MeV. Reaction $^{13}C(\gamma,n)^{12}C$

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A nuclear model where the single-particle states of the valence neutron are vector coupled to the ground (0^+) and first excited (2^+) ^{12}C-core states, is considered. The model is applied to calculate total photodisintegration cross sections of the reaction $^{13}C(\gamma, n)^{12}C$ for energies below the Giant dipole resonance. The radial wavefunctions in initial- as well as final states are of the Saxon-Woods type.

Most nuclei possess what is called a dipole state[1], a state strongly excited by γ-rays and assumed to be responsible for the familiar Giant dipole resonance. In the light $4n$ nuclei this state, or the Giant dipole resonance, is exhausting almost entirely the electric dipole sum-rules. An exception from this are some lighter nuclei like ^{12}C where the Giant dipole resonance is carrying only about 60% of the "dipole sum"[2], the rest is due to an extraordinary large high-energy tail.

The addition of an extra nucleon to these nuclei seems to have profound effects on their cross sections. In that to ^{12}C neighbouring nucleus ^{13}C, there appear in the (γ, n) cross sections below the Giant dipole resonance a secondary resonance of the same order of magnitude. The total cross section of ^{13}C integrated over these resonances comes closer to the sum-rule limit than the ^{12}C case, as the high-energy tail disappears. This secondary maximum, usually named the Pygmy resonance, is mainly attributed to the added valence neutron (nucleon) and its ability to polarize the core.

This resonance which has importance in revealing the structure of light $4n+1$ nuclei, has been studied by several authors[3–6]. The numerical analyses are, however, accomplished with wavefunctions of incorrect asymptotic behaviour and may not give quantitative correct results.

In a previous paper[7], further referred to a I, the cross sections of the reaction $^9Be(\gamma, n)^8Be$ were studied in the energy range from threshold through the Pygmy resonance. The nuclear model applied, was a core possibly with internal excitation and an outher valence neutron approximated to be in a spherical-symmetric field. In the present work it is intended to extend this model to the ^{13}C case, and to calculate within this frame the electric-dipole cross sections of the reaction $^{13}C(\gamma, n)^{12}C$. As in I the radial wavefunctions in initial and final states are of the Saxon-Woods type.

In Section 1 the formulae from I are, without mathematical rigour, adapted to the actual problem. In Section 2 the obtained results, depicted in Fig. 1, are discussed and analysed. Section 3

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includes a general discussion of the (γ, n) cross section and conclusions.

1. Mathematical Survey

The symmetry character of the ^{13}C ground state wavefunction is deduced from that of ^{9}Be by inserting the third α-cluster as an additional 4-row in the Young diagrams. The ^{13}C ground state wave function is then characterized by the quantum numbers.

$$\Psi[(1s)^4(1p)^9[4\,4\,4\,1], \quad S=\tfrac{1}{2}, T=\tfrac{1}{2}, L=1, J^{\pi}=\tfrac{1}{2}^-]. \tag{1.1}$$

Using the formalism applied in I, the state-function (1) can be decoupled into products of core and valence nucleon wavefunctions. We obtain:

$$\begin{aligned}\Psi^{\mathrm{i}}_{\mathrm{g.s.}}(^{13}\mathrm{C}) = \frac{1}{\sqrt{84}} \sum_{\substack{L'\\ \mathrm{magn.}}} \Big\{ &\langle p^9[4\,4\,1]\,1 \,|\, p^8[4\,4]\,L'\rangle \cdot (1\,M_L\,\tfrac{1}{2}\,M_S \,|\, 1\,\tfrac{1}{2}\,\tfrac{1}{2}\,M_J) \cdot (L'\,M'_L\,1\,m_l \,|\, L'\,1\,1\,M_L) \\ &\times \sum_{(r')=1}^{n_{\lambda'}} \Phi^{\mathrm{i}}_{\mathrm{c}}(p^8[4\,4], (r_8 \cdots r_1), L'\,M'_L) \cdot \Phi^{\mathrm{i}}_{\mathrm{c}}(\gamma^8[\widetilde{4\,4}], (\tilde{r}_8 \cdots \tilde{r}_1), T=0, S=0) \\ &\times \Phi^{\mathrm{i}}_{\mathrm{v.n.}}(p_q\,1\,m_l) \cdot \Phi^{\mathrm{i}}_{\mathrm{v.n.}}(\gamma_q\,\tfrac{1}{2}\,m_s) \cdot \Phi^{\mathrm{i}}_{\mathrm{v.n.}}(\gamma_q\,\tfrac{1}{2}\,m_\tau) \Big\}.\end{aligned} \tag{1.2}$$

The core angular momentum L' can take the values $L'=0$ and $L'=2$. The summation over (r') extends over all allowed Yamanouchi symbols ob tainable from the Young diagram $[\lambda']=[4\,4]$.

Due to the spin-independence of the electric-dipole operator the symmetry of the final state wavefunction is fixed. The summation over (r') then turns out as a multiplicative factor equal to the dimension of the representation $[4\,4]$. The result is:

$$\begin{aligned}\Psi^{\mathrm{i}}_{\mathrm{g.s.}}(^{13}\mathrm{C}) = \frac{1}{\sqrt{6}} \sum_{\substack{L'\\ \mathrm{magn.}}} \{ &\langle p^9[4\,4\,1]\,1 \,|\, p^8[4\,4]L'\rangle \cdot (1\,M_L\,\tfrac{1}{2}\,M_S \,|\, 1\,\tfrac{1}{2}\,\tfrac{1}{2}\,M_J) \cdot (L'\,M'_L\,1\,m_l \,|\, L'\,1\,1\,M_L) \\ &\times \Phi^{\mathrm{i}}_{\mathrm{c}}(p^8[4\,4], L'\,M'_L) \cdot \Phi^{\mathrm{i}}_{\mathrm{c}}(\gamma^8[\widetilde{4\,4}], T=0, S=0) \cdot \Phi^{\mathrm{i}}_{\mathrm{v.n.}}(p_9\,1\,m_l) \cdot \Phi^{\mathrm{i}}_{\mathrm{v.n.}}(\gamma_9\,\tfrac{1}{2}\,m_s) \cdot \Phi^{\mathrm{i}}_{\mathrm{v.n.}}(\gamma_9\,\tfrac{1}{2}\,m_\tau)\}.\end{aligned} \tag{1.3}$$

The actual final state wavefunction can be written:

$$\begin{aligned}\Psi^{\mathrm{f}}(^{13}\mathrm{C}) = \sum_{\substack{L''\\ \mathrm{magn.}}} \{ &\alpha_{L''} \cdot (L''\,M''_L\,l'\,m'_l \,|\, L''\,l'\,L\,\bar{M}_L)\,(L\,\bar{M}_L\,\tfrac{1}{2}\,m'_s \,|\, L\,\tfrac{1}{2}\,J\,M_J) \\ &\times \Psi^{\mathrm{f}}_{\mathrm{c}}([4\,4], L''\,M''_L) \cdot \Psi^{\mathrm{f}}_{\mathrm{c}}([\widetilde{4\,4}], T=0, S=0) \cdot \Psi^{\mathrm{f}}_{\mathrm{v.n.}}(l'\,m'_l) \cdot \Psi^{\mathrm{f}}_{\mathrm{v.n.}}(\tfrac{1}{2}\,m'_s) \cdot \Psi^{\mathrm{f}}_{\mathrm{v.n.}}(\tfrac{1}{2}\,m_\tau)\}.\end{aligned} \tag{1.4}$$

Following the procedure in I the general equation of the integrated cross section is established.

$$\sigma_J(\mathrm{E\,1}) = K \cdot \sum_{\mu=0,2} \{(A_\mu \alpha_1^4 + B_\mu \alpha_1^2 \alpha_2^2 + C_\mu \alpha_2^4) \cdot I^2_\mu\}. \tag{1.5}$$

The symbols used in Eqs. (1.3), (1.4) and (1.5) have all the same significance as in I. The constants, however, have different values as the fractional parentage coefficients as well as some Clebsch-Gordan coefficients are different. The channel spin J can have the possible values $J=\frac{1}{2}, \frac{3}{2}, \frac{5}{2}$.

2. Results

Although the nuclei ^{9}Be and ^{13}C are assumed to be of comparable structure, there are certain dissimilarities of some importance as regarding (γ, n) reactions. Presumably due to the additional α-cluster, the (γ, n) threshold energy in ^{13}C is found to be about 3.3 MeV higher than the exceptional low energy-limit for such reactions in ^{9}Be. As a consequence the first two positive parity levels, which structures are assumed to be equal in the two nuclei, in the ^{13}C nucleus are below the (γ, n) threshold [8]. Consequently the two maxima of the (γ, n) cross section found in ^{9}Be in the vicinity of the threshold energy, are not present in the reaction ^{13}C(γ, n) as the corresponding states only can gives rise to scattering effects.

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In the present work we attempt to account for the data of GREEN et al.[9] and EDGE[10] in the low energy region, and the Pygmy resonance data of COOK[11]. The low energy data of the latter experiment are not indicating the resonance peak at 7.7 MeV recently found by GREEN et al.[9], but as seen from Fig. 1, the two data sets are not inconsistent. The best fit obtained was with the following potential parameters:

In the low energy region the initial states are characterized by a radius parameter $r_0 = 1.25$ fm, a diffuseness parameter $a_0 = 0.65$ fm and a potential depth $V \approx 40$ MeV fixed by the neutron binding energy. The final state parameters are constrained to give the elastic scattering phase shifts of the $^{12}C + n$ system as found by WILLS et al.[12] (Fig. 2). The $D_{3/2}$ phase shift is found by adding the tangents of the phase shifts of the two individual $D_{3/2}$ resonances at 7.68 and 8.33 MeV, to give the tangent of the resultant $D_{3/2}$ phase shift, shown in Fig. 2. The actual final state parameters are then: an unchanged radius parameter, a slightly decreased diffuseness parameter and an increased, state dependent potential depth.

In the energy region where the 2^+ core state is of importance the initial states are described by slightly increased parameters, i.e. $r_0 = 1.30$ fm, $a_0 = 0.75$ fm giving $V \approx 45$ MeV. The difference between initial- and final state parameters have to be made a little larger than in the low energy region in order to get the resonance maxima at the right energies.

The effect of a final state spin-orbit term is approximated by applying different potential depths.

The results of the calculations, shown in Fig. 1, can be summarized as follows.

The 6.90 MeV resonance. This resonance which maximum corresponds with a narrow $5/2^+$ level at 6.86 MeV, is probably due to E 1 transitions between the states.

$$(l = 1,\ L = 0,\ J^\pi = \tfrac{1}{2}^-) \rightarrow (l = 2,\ L = 0,\ J^\pi = \tfrac{5}{2}^+)\,. \tag{1}$$

The symbols used have the same significance as in I.

The 7.7 MeV resonance. At 7.68 and 8.33 MeV, respectively, there are two positive parity levels both with spin assignment $3^+/2$. It is therefore

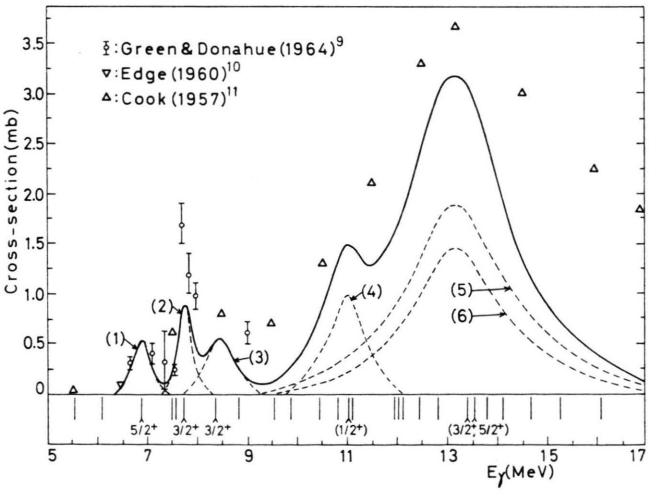

Fig. 1. Upper part: Electric-dipole cross sections for the $^{13}C(\gamma, n)^{12}C$ reaction calculated with Saxon-Woods radial wavefunctions. Solid line represents total photo-neutron cross sections. Dashed lines represent contributions from different reaction channels. The curve-numbers correspond to bracketed numbers written in the text besides the indicated transitions. — Lower part: Experimental energy levels[8]. No. (1)—(6) in the figure belongs to Eqs. (1)—(6) from Sec. 2.

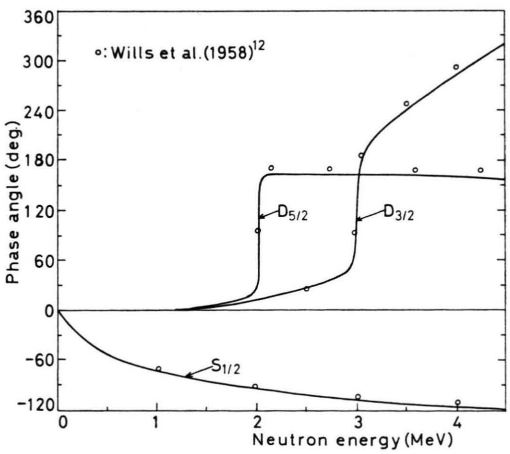

Fig. 2. Phase shifts calculated for elastic neutron scattering on ^{12}C using Saxon Woods wavefunctions.

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natural to consider the reported 7.7 MeV resonance actually as two separate resonances, one due to the narrow 7.68 MeV level and one due to the broader 8.33 MeV level. Both resonances can be explained as E1 transitions of the type.

$$(l = 1,\ L = 0,\ J^\pi = \tfrac{1}{2}^-) \rightarrow (l = 2,\ L = 0,\ J^\pi = \tfrac{3}{2}^+). \qquad (2, 3)$$

The shape of the resonances is very sensitive to small changes in the parameters. It may therefore be possible to get a better fit especially to the very narrow resonance at 7.7 MeV by slightly different parameters.

The Pygmy resonance. The main part of the Pygmy resonance is due to a group of positive parity levels at about 13.4 MeV, assumed strongly excited by electric-dipole γ-rays. In addition there is a narrow, positive parity level of spin $1/2^+$ at 11.02 MeV. The Pygmy resonance is then to be considered as the resultant contribution from these known positive parity levels.

The 11.02 MeV resonance may be explained as E 1 transitions between the states.

$$(l = 1,\ L = 2,\ J^\pi = \tfrac{1}{2}^-) \rightarrow (l = 1,\ L = 2,\ J^\pi = \tfrac{1}{2}^+). \qquad (4)$$

From the spin assignment it is forbidden as S-wave transition.

The supposed spin assignments of the group of levels at about 13.4 MeV are $3/2^+$ and $5/2^+$[13]. The resonance with maximum at this energy can therefore by explained as E 1 transitions

$$(l = 1,\ L = 2,\ J^\pi = \tfrac{1}{2}^-) \rightarrow (l = 2,\ L = 2,\ J^\pi = \tfrac{3}{2}^+) \qquad (5)$$

and

$$(l = 1,\ L = 2,\ J^\pi = \tfrac{1}{2}^-) \rightarrow (l = 2,\ L = 2,\ J^\pi = \tfrac{5}{2}^+). \qquad (6)$$

There is made no effort in splitting the resonances by simulated spin-orbit effects, as the spin assignments of the levels are not definitely verified.

In the energy range here considered the S-wave crosssections calculated with the relevant parameters are vanishing, in good agreement with the sum-rule calculations of OPAT[14]. The non-resonant S-wave phase shifts have their strongest variation for energies lower than 1.5 MeV where the bound $s_{1/2}$ level certainly has some effects.

3. Discussion

In contrast to the situation in ^{9}Be where only a few levels were within the energy range considered, the ^{13}C nucleus has in the same energy region a large number of excited states of which the majority are of unknown structure. The total, theoretical (γ, n) cross section shown as a solid line in Fig. 1, is the resultant contribution from only a few positive parity levels reached by E1 transitions. It is therefore not expected that the calculated cross section can account for the whole area under a curve drawn through the experimental points.

In the low-energy region ($E_\gamma \leqq 9$ MeV) there is reason to believe that the levels of unknown spin are all normal parity states. Assuming these to be reached by M 1 or E 2 transitions, it is from order of magnitude considerations, probable that these levels can account for the remaining area under the experimental curve.

In the energy region $9 \leqq E_\gamma \leqq 13$ MeV only one of the reported levels is assumed to be of positive parity. The most probable structure of this level is ($l = 2$, $L = 2$, $J^\pi = 1/2^+$) as levels decaying to the 0^+ core state would in this energy region, contribute very little to the total cross section as their channel widths (fractional parentage coefficients) are smaller.

At energies beyond 13 MeV there are besides the „dipole„ group at 13—14 MeV, broad levels at 15.25 MeV and 16.1 MeV, respectively, which spin- and parity assignments are not yet verified. These levels are probably able to account for the relative large gap between the experimental- and theoretical values in this energy region. In addition the Giant dipole resonance certainly has some influence on the high-energy part of the region.

The conclusion drawn from the present work is then that the Pygmy resonance or at least the main part, is due to E 1 transitions to positive parity levels all decaying to the first excited 2^+ core state. Due to lack of experimental evidence about the implied nuclear states, further characterization of the Pygmy resonance is so far not possible.

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