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Experimental Study of Isospin Mixing in $^{12}C + n \longrightarrow {}^{13}C\ (T = 3/2)$ and $^{16}O + n \longrightarrow {}^{17}O\ (T = 3/2)$ Resonances

S. Cierjacks, G. Schmalz, F. Hinterberger, P. v. Rossen
Institut für Kernphysik

Kernforschungszentrum Karlsruhe

KERNFORSCHUNGSZENTRUM KARLSRUHE

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S. Cierjacks, G. Schmalz, F. Hinterberger[+] and P. v. Rossen[+]

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[+] Institut für Strahlen- und Kernphysik der Universität Bonn, Nußallee 14-16, 5300 Bonn

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Experimentelle Untersuchungen von Isospinmischungen in $^{12}C + n \rightarrow {}^{13}C(T=3/2)$ und $^{16}O + n \rightarrow {}^{17}O(T=3/2)$ Resonanzen

Zusammenfassung

Mit Hilfe hochauflösender Messungen der totalen Neutronenwirkungsquerschnitte von Kohlenstoff und Sauerstoff wurden energiescharfe Resonanzen von ^{13}C und ^{17}O im Bereich von 3 - 30 MeV untersucht. Die Verwendung des verbesserten Neutronenflugzeitspektrometers am Karlsruher Isochronzyklotron und spezieller Eichmethoden gestattete Neutronenmessungen mit einer Energieauflösung von 1:2100 bei 10 MeV und Resonanzenergiebestimmungen mit einer Genauigkeit von 10^{-4} bis 10^{-5}. Über Resonanzanalysen wurden Resonanzparameter für zahlreiche energiescharfe Anregungszustände von T=1/2 und T=3/2 Resonanzen bestimmt. Diese Daten zusammen mit früher veröffentlichten Werten von breiten T=1/2 Zuständen boten eine gute Möglichkeit zur Ermittlung von Matrixelementen für die Isospinmischung in niedrig liegenden T=3/2 Zuständen. Die experimentell abgeleiteten Matrixelemente werden mit früheren Messungen und Schalenmodell-vorhersagen für diese Größen verglichen.

Abstract

Narrow resonances of ^{13}C and ^{17}O have been studied by a measurement of the total neutron cross sections of carbon and oxygen between 3 and 30 MeV. Employing the improved time-of-flight spectrometer at the Karlsruhe Isochronous Cyclotron and precise calibration methods, resonance cross sections were measured with an energy resolution of 1:2100 at 10 MeV and energy accuracies between 10^{-4} and 10^{-5}. Resonance analyses of the measured data provided parameters for numerous narrow states of both isospins, T=1/2 and T=3/2. These data in conjunction with information from broad T=1/2 resonances provided a good means to experimentally determine isospin mixing matrix elements. Results were obtained for the first five T=3/2 resonances in ^{17}O and the first T=3/2 resonance in ^{13}C. The obtained mixing matrix elements are compared with previous experimental results and shell-model predictions of this quantity.

EXPERIMENTAL STUDY OF ISOSPIN MIXING IN $^{12}C + n \rightarrow {}^{13}C(T=3/2)$ AND $^{16}O + n \rightarrow {}^{17}O(T=3/2)$ RESONANCES

S. Cierjacks, G. Schmalz

Kernforschungszentrum Karlsruhe
Institut für Kernphysik
Postfach 3640
7500 Karlsruhe
Federal Republic of Germany

and

F. Hinterberger, P. v. Rossen

Institut für Strahlen- und Kernphysik
der Universität Bonn
Nußallee 14-16, 5300 Bonn
Federal Republic of Germany

1. INTRODUCTION

A special feature of the lowest $T = 3/2$ states in light nuclei of mass $A = 4\,n + 1$ is that they are bound with respect to isospin-allowed particle decay. The study of their isospin-forbidden decays provides a good means to investigate the nature of charge-dependent effects in the nuclear states, i.e., the size and the structure of isospin impurities. In principle, a systematics of isospin mixing can provide not only information on the isospin violating Coulomb part of the interaction, but also on the effects of a possible charge assymetry or a charge dependance of the nuclear forces.

In the past major experimentical information in this field came from isospin-forbidden proton scattering providing proton decay widths and other properties of the isospin-nonconserving decay of the lowest $T = 3/2$ resonances in light $A = 4\,n + 1$, $T_z = -1/2$ nuclei from ^{12}C to ^{40}Ca [1, 2]. Similar investigations of the isospin-forbidden neutron decay are comparatively scarce and were only made for $^{24}Mg + n$ [3] and $^{28}Si + n$ [4]. Therefore, the present work is an important extension of previous studies of $A = 4\,n + 1$, $T_z = +1/2$ nuclei. The high-resolution measurement of total neutron cross

sections of C and O between 3 and 30 MeV provided precise determinations of excitation energies, total widths and partial neutron decay widths for a large number of narrow T = 1/2 and T = 3/2 resonances [5]. Concerning T = 3/2 states in ^{17}O an extensive study has recently been finalized [6]. Experimentally ten known T = 3/2 resonances were observed in the total cross section and analyzed. The study also yielded information on seven additional candidates for T = 3/2 resonances at higher energies. For carbon the extracted information on T = 3/2 states is still comparatively small. At present only the first T = 3/2 state at E_x = 15.11 MeV has been analyzed. While our previous work concentrated primarily on the properties of T = 3/2 resonances in ^{17}O and on the systematics of isospin-forbidden decay widths for the first T = 3/2 resonances in various T_z = +1/2 and T_z = -1/2 nuclei, the present paper describes an approach to experimentally determine isospin mixing matrix elements which is expected to give additional information on the dominating isospin mixing mechanisms.

In section 2 we describe some details of the transmission experiment. The formalism used in resonance analyses of narrow states is outlined in section 3. Section 4 describes the method employed in the determination of average mixing matrix elements. The results are presented in section 5 and compared with previous experimental data and some theoretical predictions.

2. EXPERIMENTS

The experiments were performed at the fast neutron time-of-flight spectrometer of the Karlsruhe Isochronous Cyclotron using the 190 m flight path and employing standard transmission techniques. A detailed description of the recently improved system and the calibration methods involved has been published elsewhere [5]. Thus, only a brief summary is given below. A schematic diagram of the experimental set-up is shown in Fig. 1. Neutrons are produced by bombardment of a thick natural uranium target with ~ 50 MeV deuterons from the internal cyclotron beam. The use of the "KfK deflection-bunching" system allowed the production of neutron bursts of ~ 0.8 ns duration at 50 kHz repetition rate and with a time-averaged intensity of the order of 10^{13} n sr^{-1} s^{-1}. Neutrons were detected in a 1.2 cm long by 5 cm diameter NE 102 A plastic scintillator coupled to a Valvo 56 AVP photomultiplier. The time resolution of the detector was about 300 ps for the dynamic range covered in the experiment. Neutron flight-times were measured by a digital time analyzer (LABEN UC-KB). The start pulse was derived from the cyclotron r.f., while the stop input was provided from a fast constant fraction discriminator. The neutron spectra were accumulated in 28 K channels of 0.25 ns width and stored in the core memory of a modified CDC-3100 on-line computer.

Every effort was made to obtain a high total time resolution. This depends mainly on the neutron burst width and thus on the proper timing of the cyclotron phase. The slight adjustments of the unisochronism and the phase width of the deuteron beam bursts, which were necessary, could easily be performed by using the on-line computer programme CICERO [7]. With this method a total effective spectrometer resolution of $\Delta t/L$ = 5.5 ps m^{-1}, yielding an energy resolution $\Delta E/E = 4.8 \times 10^{-4}$ at E_n = 10 MeV, was achieved.

For oxygen a liquid sample of natural isotopic composition and thickness 1.20 atoms barn^{-1} was used, while the carbon run used a pyrolytic graphite sample of 1.02 atoms barn^{-1}. The liquid oxygen was irradiated in a large Dewar spere of ~ 28 cm diam. In this case the empty Dewar transmission spectrum was also measured for background subtraction. The large target thickness for both elements was chosen to obtain high sensivity for weak resonances which are typical for the many-MeV region.

In order to perform also very precise absolute resonance energy determinations, suitable calibration methods were applied. Absolute energy determinations depend on the flight time of resonance neutrons and on the effective flight path length. Employing an opto-electronic method for the long distance measurement, a total effective flight path length of

L = (18925.27 ± 0.09) cm was obtained. Absolute flight time measurements involved the peak of prompt γ-rays from the neutron target and the cumulative probability method to fix the time zero point with an accuracy of ± 25 ps. On this basis absolute resonance energies were determined with accuracies ranging between 10^{-5} and 10^{-4}, depending on the statistical quality of the resonance anomalies.

A typical result obtained from the transmission experiment is shown in Fig. 2. The total neutron cross section of oxygen in the region from 4.5 - 8.0 MeV is an example of the high quality data obtained for both elements over the whole range from 3 to 30 MeV. It was found that the systems $^{12}C+n$ and $^{16}O+n$ exhibit a simple resonance structure with a large number of narrow, isolated levels. Only at very high neutron energies the narrow resonances are increasingly superimposed on broad "background" resonances.

3. RESONANCE ANALYSES

The narrow resonances observed in the total neutron cross sections of carbon and oxygen were analyzed employing a single-level S-matrix formalism. The assumption of single isolated resonances is reasonable even in the case of interference with broad nearby states. Such an interference mainly alters the phase relations, i. e. the interference pattern of the narrow resonances. It leaves, however, the important parameters such as the resonance energy and the total and partial widths practically unchanged. Thus, any broad resonance amplitude can be treated as part of a smoothly energy dependent background amplitude.

In this paper only a brief summary of the main formulae characterizing the special formalism will be given. For the resonance channel with orbital and total angular momentum L and J, respectively, the complex scattering matrix element S_{LJ} can be expressed by [8]

$$S_{LJ} = S_{LJ}^{nr} - i \frac{\Gamma_{no}}{E-E_R+i\Gamma/2} \exp\left[2i(\mathrm{Re}\delta_{LJ}^{nr} + \phi_{LJ}^{r})\right] \qquad (1)$$

where S_{LJ}^{nr} is the weakly energy dependent background amplitude, Γ_{no} the groundstate neutron decay width, E the cm energy of the neutron-target system, E_R the resonance energy, Γ the total widths, $\mathrm{Re}\,\delta_{LJ}^{nr}$ the real part of the background phase shift and ϕ_{LJ}^{r} a possible resonance phase. Using the usual relation for the total cross section

$$\sigma_t = \frac{2\pi}{k^2} \sum_{lj} (j+1/2)\mathrm{Re}(1-S_{lj}), \qquad (2)$$

where k is the c.m. neutron wave number, it is possible to separate the expression for the total cross section into a non-resonant background term σ_t^{nr} and a purely resonant term (or a sum of resonant terms, if more than one level is involved):

$$\sigma_t = \sigma_t^{nr} + (J+1/2)\frac{\pi}{k^2}\frac{\Gamma_{no}}{(E-E_R)^2+(\Gamma/2)^2}\left[2(E-E_R)\cos 2\psi + \Gamma \sin 2\psi\right] \qquad (3)$$

with

$$\psi = \mathrm{Re}\,\delta_{LJ}^{nr} + \phi_{LJ}^{r} + \pi/4 \qquad (4)$$

For numerical calculations the weakly energy dependent term σ_t^{nr} was parametrized by the usual quadratic expression:

$$\sigma_t^{nr} = a + b(E-E_R) + c(E-E_R)^2. \qquad (5)$$

This parametrization allows the determination of the essential resonance parameters E_R, Γ and Γ_{no} (or $(J+1/2)\,\Gamma_{no}$, if J is not known) without any detailed specification of the background amplitudes. Employing ψ as a single

fit parameter the seven parameters a, b, c, ψ, E_R, Γ and Γ_{no} were adjusted to the experimental data by a non-linear least-squares fitting routine [9]. Since the correlation between the fit parameters is weak, the resonance parameters E_R, Γ and Γ_{no} could be determined with high precision. The excitation functions calculated from equ.(3)were folded by the total effective resolution function before comparison with the experimental data. The effective resolution function was obtained by folding the measured time spectrum of the prompt γ-peak, the Gaussian Doppler broadening and the rectangular time spread introduced by the neutron transit times through the 1.2 cm thick scintillator of the neutron detector. The time spread caused by the neutron source length was negligible small in the present experiments.

Employing the described formalism resonance parameters for a large number of narrow T = 1/2 and T = 3/2 states were determined from our total neutron cross section measurements. At present we have analyzed eighteen T = 1/2 and seventeen T = 3/2 resonances (or candidates for T = 3/2 states) in ^{17}O, whereas the respective results for ^{13}C cover six T = 1/2 resonances and one T = 3/2 state. Measured transmission data in the region of the first seven O^{17}(T = 3/2) resonances and of the first ^{13}C (T = 3/2) state are shown in Figs. 3 and 4. The solid lines through the data points are best fit curves from our resonance analysis.

4. DETERMINATION OF ISOSPIN MIXING MATRIX ELEMENTS

Isospin impurities and isospin mixing matrix elements were calculated using the method proposed by Weigmann et al. [3]. In this method the small isospin admixture in the ground state of the target nucleus is neglected. An estimate of the isospin impurity in the T = 3/2 compound state can be derived from the reduced width of the T = 3/2 state and the average reduced width of nearby T = 1/2 resonances having the same spin and parity.

Concerning isospin mixing matrix elements Weigmann et al. used first order perturbation theory and derived two expressions for a zeroth order guess $\langle \overline{T = 3/2|V|i} \rangle_o$ and a lower limit $\langle \overline{T = 3/2|V|i} \rangle_{min}$ of the average isospin mixing matrix element. Their expression to derive the zeroth order guess is:

$$\Gamma_n^L(T = 3/2) = |\overline{\langle T=3/2|V|i\rangle_o}|^2 \sum_i \frac{\Gamma_n^L(i)}{[E_i - E(T=3/2)]^2} \qquad (6)$$

where the sum extends over all T = 1/2 resonances of the respective J^π value.

The lower limit is determined by the equation.

$$\Gamma_n^L(T=3/2) = |\langle \overline{T=3/2|V|i} \rangle_{min}|^2 \left| \sum_i \frac{\Gamma_n^L(i)^{1/2}}{|E_i - E(T=3/2)|} \right|^2 \qquad (7)$$

In the present work the required reduced widths Γ_n^L were calculated according to the definition commonly used in neutron resonance physics:

$$\Gamma_n^L = \frac{\Gamma_n}{P_L} \left(\frac{1eV}{E_{cm}}\right)^{1/2}; \qquad (8)$$

$$P_o = 1,\ P_1 = \frac{\rho^2}{1+\rho^2},\ P_2 = \frac{\rho^4}{9+3\rho^2+\rho^4},\ P_3 = \frac{\rho^6}{225+45\rho^2+6\rho^4+\rho^6}$$

with $\rho = kR$ and $R = (1.25\ A^{1/3}+0.8)f$.

In this definition Γ_n means the measured c.m. neutron decay width, E_{cm} the c.m. resonance energy, P_L the penetration factor in the channel with orbital angular monumentum L and A the mass number of the target nucleus.

T = 3/2 states in ^{13}C above the ^{12}B (T = 1)+p threshold $E_{th}(^{13}C)$ = 17.53 MeV and in ^{17}O avove the $^{16}N(T=1)$+p threshold $E_{th}(^{17}O)$ = 13.78 MeV are unbound with respect to isospin-allowed decay. Therefore, isospin impurities

and meaningful isospin mixing matrix elements can only be determined for the first T = 3/2 resonance in ^{13}C and the first five T = 3/2 states in ^{17}O. The necessary information on T = 1/2 resonances was taken primarily from our resonance analysis of narrow T = 1/2 states. This information was complemented by experimental results collected in ref. 1 by Ajzenberg-Selove. Adopting the method of Weigmann et al. we encountered some difficulty arising from resonances with unassigned or uncertain l and J values which occur increasingly at high excitation energy. In addition neutron decay widths for many of the high energy resonances are not known. In order to circumvent this difficulty the following procedure was adopted: In the calculation of the zeroth order value from equ. (6) only resonances with defined spin and parity and known neutron decay width were included in the summation over i, whereas the estimate of the lower limit by equ. (7) also included resonances with tentative spin assignments (i. e. resonances with either one correct value among a few possible J^{π} assignments or with correct J value, but undetermined parity). We excluded, however, those resonances which applied to the above spin state selection, but which were only observed in particle decays other than neutron decay.

In Table 1 a the resonance parameters of the first five T = 3/2 resonances in ^{17}O as determined from our analysis are summarized. Table 1 b gives the respective preliminary values for the first T = 3/2 state in ^{13}C. The T = 1/2 states used in the derivation of isospin mixing are listed in Tables 2 - 7. Only the resonances without parentheses have been used in conjunction with equ. (6), while the whole set given in each table was used to derive the lower limits via equ. (7).

5. RESULTS AND DISCUSSION

The fractional isospin impurities $\Gamma_n(3/2)/\bar{\Gamma}_n(1/2)$ and the two estimates for the average isospin mixing matrix elements determined from the present study are given in Table 8. Of particular interest is that the fractional isospin impurities vary over the large range of ~ 0.1 to 4 %. In contrast to this result the zeroth order values of the mixing matrix elements do not vary significantly from resonance to resonance and between the two different nuclei. With one exception their values lie all in the narrow range between $\sim$ 100 and 250 keV. Only the matrix element for the fourth ^{17}O (T = 3/2) resonance with 340 keV appears to be comparatively high. In this case, however, the spread in resonance widths is unreasonably small, which might indicate that the high zeroth order value is due to the neglection of important T=1/2 resonances at higher excitation energies.

The present results may be compared to other sources of information on isospin mixing. First of all, we can compare the present results with experimentally determined mixing matrix elements for some low lying T = 3/2 resonances in ^{25}Mg [3] and in ^{29}Si [4]. Isospin impurities and isospin mixing matrix elements for these nuclei determined by the same method are included in Table 8. It can be seen that the zeroth order values are in general agreement with the observations from our work. The relatively small value for the second T = 3/2, J = $3/2^+$ resonance in ^{25}Mg has already been discussed by the authors [3]. They mentioned in their publication, that the value may not represent the true average mixing matrix element, but rather approximate the individual mixing matrix element between the 555,4 and the 844,2 keV resonances in ^{25}Mg. Concerning fractional isospin impurities the previous determinations in ^{24}Mg + n and ^{28}Si + n gave values of $\sim$ 18 % for both T = 3/2 s-wave resonances. These seemed to be rather high in comparison to the $\sim$ 2 % admixture obtained for the two d-wave resonances in ^{25}Mg. Therefore, it was argued that this might be related to differences in "external" or "boundary condition" mixing for different partial waves. This supposition is, however, considerably weakened by the present work, which gives a very small admixture of 0.16 % for the third T = 3/2, J = $1/2^+$ resonance in ^{17}O.

It is further interesting to note that the resulting charge-dependent matrix elements of the present work compare well with those deduced for (T=1) analog - (T=0) antianalog mixing in the neighbouring A=4 n nuclei ^{12}C [10, 11] and ^{16}O [12].

Even though a complete discussion of our results in terms of particular mixing mechanisms is beyond the scope of this paper, we would also like to compare our experimental results with some model predictions: In a simple schematic model Mc Donald and Adelberger [13] calculated the effective charge-dependent matrix elements for antianalog mixing which have been shown to be an important source of isospin mixing in light nuclei [14]. These authors demonstrated that antianalog mixing is mainly due to effects of isospin-nonconserving two-body matrix elements. These matrix elements were found to be more or less independent of A and of the order of $\sim$150 - 200 keV for T_z = +1/2 nuclei, in accordance with findings of the present work. This observation may suggest, that the isospin-nonconserving neutron decay is mainly caused by antianalog mixing. This suggestion is further supported by the fact, that the model of Mc Donald and Adelberger is presently the only one which can explain the large charge asymmetry observed in the isospin-forbidden particle decay of the first T=3/2 states in several T_z=+1/2 and T_z=-1/2 nuclei. Unfortunately, however, this model cannot explain the strong mass dependance for the reduced neutron widths, which was found to vary more like A^4 than like $A^{2.7}$ [6] as required by a combination of the models of Mc Donald and Adelberger and of Trainor et al. [15]. Moreover, Auerbach and Lev [16] have calculated isospin mixing matrix elements for several light nuclei using the projection operator formalism [17]. In contrast to Mc Donald and Adelberger they conclude that the most important contribution to the isospin mixing comes from the one-body Coulomb matrix element between analog and antianalog configuration states. Their values for several T_z=-1/2 nuclei range between $\sim$200 and 350 keV. These results also compare well with our present results, but are in conflict with the extremely small proton decay widths observed for light T_z=-1/2 nuclei [1, 2].

Two-body Coulomb matrix mixing elements between the first T=3/2 states in ^{17}O and ^{17}F and a number of T=1/2 shell model states were calculated by Walker and Schlobohm [18]. Their calculations show that the most important contribution is due to the mixing of the T=3/2 states with their antianalog states. These authors obtained a value of 196 keV for the antianalog mixing of the lowest T=3/2, $J = 1/2^-$ state in oxygen assuming that the antianalog state is located around 3.1 MeV excitation. Comparing this to the matrix element for the T=3/2, $J = 1/2^-$ state of ^{17}O in Table 8, it would indicate that the T=1/2 resonances in the included energy range contain on the average an almost 100 % component of the antianalog configuration state which does not seem to be reasonable. Furthermore, with respect to the latter two models it should be mentioned that neither of them can explain the large charge asymmetry effects for the reduced decay widths observed for the first T=3/2 states in various T_z=+1/2 and T_z=-1/2 nuclei and for several low lying analog resonances of A = 4n+1 mirror nuclei [6, 13].

In summary, it appears that the size of experimentally determined mixing matrix elements is, in general, consistent with models for mixing mechanisms proceeding through admixtures of nearby T=1/2 levels. However, in order to decide which particular T=1/2 states are primarily responsible for the isospin mixing, it is necessary to inspect in more detail the contributions from single or groups of single T=1/2 resonances. Such investigations are a promising task for the future. Studies of this type could certainly further gain from additional resonance parameter assignments, especially at high excitation energies. For carbon and oxygen improved T=1/2 resonance sets can, in principle, be obtained from additional analyses of some broader resonances observed, but not yet analysed in our high-resolution cross section measurements.

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Table 1 a

Resonance parameters of the first T = 3/2 states in ^{17}O

E_r (keV) c.m. system	Γ (keV)	Γ_{n_o} (keV)	Γ_n^L (eV)	J^π [a]
6934.38 ± 0.17	2.4 ± 0.3	1.88 ± 0.12	0.87 ± 0.06	$1/2^-$
8321.7 ± 0.6	6.9 ± 1.1	1.27 ± 0.14	0.52 ± 0.06	$3/2^-$
8795.7 ± 6	6 ± 2	0.21 ± 0.14	0.071 ± 0.05	$1/2^+$
8854.0 ± 0.6	2.5 ± 1.0	0.40 ± 0.06	0.59 ± 0.09	$5/2^-$
9419.0 ± 2.3	9 ± 5	0.24 ± 0.09	0.13 ± 0.05	$(5/2^+)$

[a] Ref. 1 [b] constrained to value of ref. 19

Table 1 b

Resonance parameters of the first T = 3/2 state in ^{13}C (preliminary)

E_r (keV) c.m. system	Γ (keV)	Γ_{n_o} (keV)	Γ_n^L (eV)	J^π [a]
10160.0 ± 2.0	5.49 ± 0.25 [b]	0.43 ± 0.09	0.16 ± 0.03	$3/2^-$

[a] Ref. 1 [b] constrained to value of ref. 20

Table 2

Resonance parameter of $J^{\pi} = 3/2^{-}$; T = 1/2 resonances in $^{12}C + n$

E_r (keV) c.m. system	Γ (keV)	Γ_{n_o} (keV)	Γ_n^L (eV)	J^{π} [a]	Ref.
4948.19 ± 0.17	23.7 ± 0.4	20.6 ± 0.5	12.7 ± 0.3	$3/2^{-}$	this work
6904.6 ± 5	68 ± 4	68. ± 4	32.7 ± 1.9	$(3/2^{-})$	ref. 1
7125.6 ± 2.0	81.5 ± 3.3	69.0 ± 3.0	32.4 ± 1.4	(3.2^{-})[b]	this work
8334	340	(340)	(143)	$(3/2^{-})$	ref. 1

[a] Ref. 1 unless otherwise noted [b] tentative assignment of this work

Table 3

Resonance parameter of $J^{\pi} = 1/2^{+}$; T = 1/2 resonances in $^{16}O + n$

E_r (keV) c.m. system	Γ (keV)	Γ_{n_o} (keV)	Γ_n^L (eV)	J^{π} [a]	Ref.
2213 ± 8	124 ± 12	124 ± 12	83.4 ± 8.1	$1/2^{+}$	ref. 1
3812 ± 6	90 ± 9	87 ± 8.7[b]	44.6 ± 4.5	$1/2^{+}$	ref. 1
4198.08 ± 0.24	11.4 ± 0.5	8.1 ± 0.3	4.0 ± 0.1	$1/2^{+}$	this work
(6629 ± 10)	80 ± 20	(80 ± 20)	(31 ± 8)	$1/2^{+}, 7/2^{-}$	ref. 1

[a] Ref. 1 unless otherwise noted [b] calculated from Γ_{α} / Γ values of ref. 1

Table 4

Resonance parameters of $J^{\pi} = 1/2^{-}$; T = 1/2 resonances in $^{16}O + n$

E_r (keV) c.m. system	Γ (keV)	Γ_{n_o} (keV)	Γ_n^L (eV)	J^{π} [a]	Ref.
1795.7 ± 8	32 ± 3	32 ± 3	44 ± 4	$1/2^-$	ref. 1
2718.7 ± 2	< 1	< 1 ±	< 0.9	$(1/2^-)$	ref. 1
3810 ± 50	270 ±30	73 ± 8 [b]	52 ± 6	$1/2^-$	ref. 1
4036 ± 20	69 ± 7	61.6± 6 [b]	42.2± 4.1	$1/2^-$	ref. 1
5003	4 ± 3	2.2± 1.7 [b]	1.3± 1.0	$1/2^-$	ref. 1
5732.3 ± 0.9	16.7± 1.7	10.9± 1.2	5.7± 0.6	$(1/2^-)$ [c]	this work

[a] Ref. 1 unless otherwise noted [b] calculated from Γ_α / Γ values of ref. 1
[c] tentative assignment of this work

Table 5

Resonance parameters of $J^{\pi} = 3/2^{-}$; T = 1/2 resonances in $^{16}O + n$

E_r (keV) c.m. system	Γ (keV)	Γ_{n_o} (keV)	Γ_n^L (eV)	J^{π} [a]	Ref.
408.7 ± 2	40 ± 5	40 ± 5	293 ± 37	$3/2^-$	ref. 1
1235.7 ± 2	28 ± 7	28 ± 7	56 ± 14	$3/2^-$	ref. 1
3416 ±20	500 ±50	(500 ±50)	(390 ± 39)	$3/2^-$	ref. 1
4056 ± 7	60	53.4 [b]	36.3	$3/2^-$	ref. 1
4542.7 ± 0.4	55.3 ± 0.6	48.9 ± 1.1	30.5± 0.7	$3/2^-$	this work
5277.7	120	120	67.1	$3/2^-$	ref. 1

[a] Ref. 1 [b] calculated from Γ_α / Γ values of ref. 1

Table 6

Resonance parameters of $J^{\pi} = 5/2^{-}$; T = 1/2 resonances in $^{16}O + n$

E_r (keV) c.m. system	Γ (keV)	Γ_{n_o} (keV)	Γ^{L}_{n} (eV)	J^{π} [a]	Ref.
3020.89 ± 0.16	1.38 ± 0.05	1.38 ± 0.05	34.0 ± 1.2	$5/2^{-}$	this work
3237.23 ± 0.14	0.96 ± 0.20	0.96 ± 0.20	19.2 ± 4.0	$5/2^{-}$	this work
4356.38 ± 0.11	6.89 ± 0.22	2.86 ± 0.08	24.2 ± 0.7	$5/2^{-}$	this work
5348.7 ± 4	15 ± 1	2.25 ± 0.15 [b]	10.9 ± 0.7	$5/2^{-}$	ref. 1
5714.61 ± 0.14	4.01 ± 0.23	3.37 ± 0.20	13.8 ± 0.8	$(5/2^{-})$ [c]	this work

[a] Ref. 1 unless otherwise noted [b] calculated from Γ_{α} / Γ values of ref. 1
[c] tentative assignment of this work

Table 7

Resonance parameters of $J^{\pi} = 5/2^{+}$; T = 1/2 resonances in $^{16}O + n$

E_r (keV) c.m. system	Γ (keV)	Γ_{n_o} (keV)	Γ^{L}_{n} (eV)	J^{π} [a]	Ref.
3243.08 ± 0.19	0.64 ± 0.23	0.64 ± 0.23	1.54 ± 0.5	$5/2^{+}$	this work
4258.00 ± 0.07	6.17 ± 0.13	4.75 ± 0.11	7.32 ± 0.17	$5/2^{+}$	this work
5049.61 ± 0.08	3.53 ± 0.13	2.37 ± 0.08	2.84 ± 0.10	$5/2^{+}$	this work
5833 ±20	80	17.6 [b]	17.3	$5/2^{+}$	ref. 1
6193 ±15	150	(150)	(136)	$5/2^{+}, 7/2^{-}$	ref. 1
6346	75 ± 30	(75 ± 30)	(66)	$5/2^{+}, 7/2^{-}$	ref. 1
6770.8 ± 1.2	41.7 ± 1.4	26.4 ± 0.9	21.4 ± 0.7	$(5/2^{+})$ [c]	this work
10083	150	(150)	(78)	$5/2^{+}$	ref. 1

[a] Ref. 1 unless otherwise noted [b] calculated from Γ_{α} / Γ value of ref. 1
[c] tentative assignment of present work

Table 8

Isospin impurities and isospin mixing matrix elements for T = 3/2 resonances

Reson.	J^{π} E_r (keV)	$\Gamma_n(3/2)/\overline{\Gamma}_n(1/2)$ (%)	$\langle\overline{T=3/2\|V\|i}\rangle_o$ (keV)	$\langle\overline{T=3/2\|V\|i}\rangle_{min}$ (keV)	Ref.
^{12}C+n	$J = 3/2^-$ $E_r = 10160.0$	0.62	152	37	this work
^{16}O+n	$J = 1/2^-$ $E_r = 6934.38$	3.6	231	111	this work
^{16}O+n	$J = 3/2^-$ $E_r = 8321.7$	0.54	174	56	this work
^{16}O+n	$J = 1/2^+$ $E_r = 8795.7$	0.16	135	47	this work
^{16}O+n	$J = 5/2^-$ $E_r = 8854.0$	2.9	340	154	this work
^{16}O+n	$J = (5/2^+)$ $E_r = 9419.0$	1.3	166	16	this work
^{24}Mg+n	$J = 5/2^+$ $E_n = 475.4$	2	97	23	ref. 3
^{24}Mg+n	$J = 3/2^+$ $E_n = 555.4$	2	12	7	ref. 3
^{24}Mg+n	$J = 1/2^+$ $E_n = 1567.$	18	150	90	ref. 3
^{28}Si+n	$J = 1/2^+$ $E_n = 1254.$	18	144	97	ref. 4

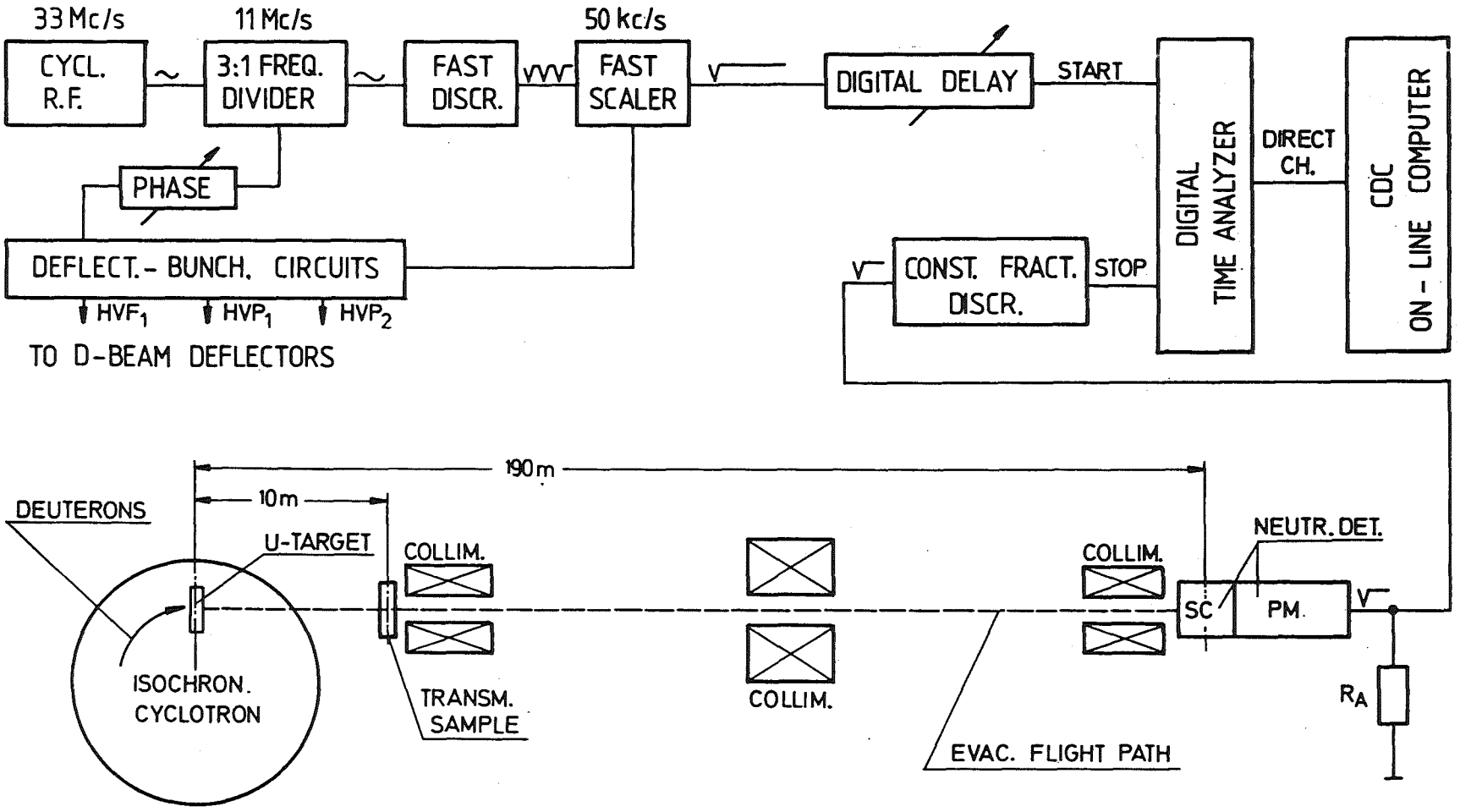

Fig. 1 Schematic diagramm of the time-of-flight set-up. For clarity details of the KfK deflection-bunching system and the complete set of logic circuits are not shown

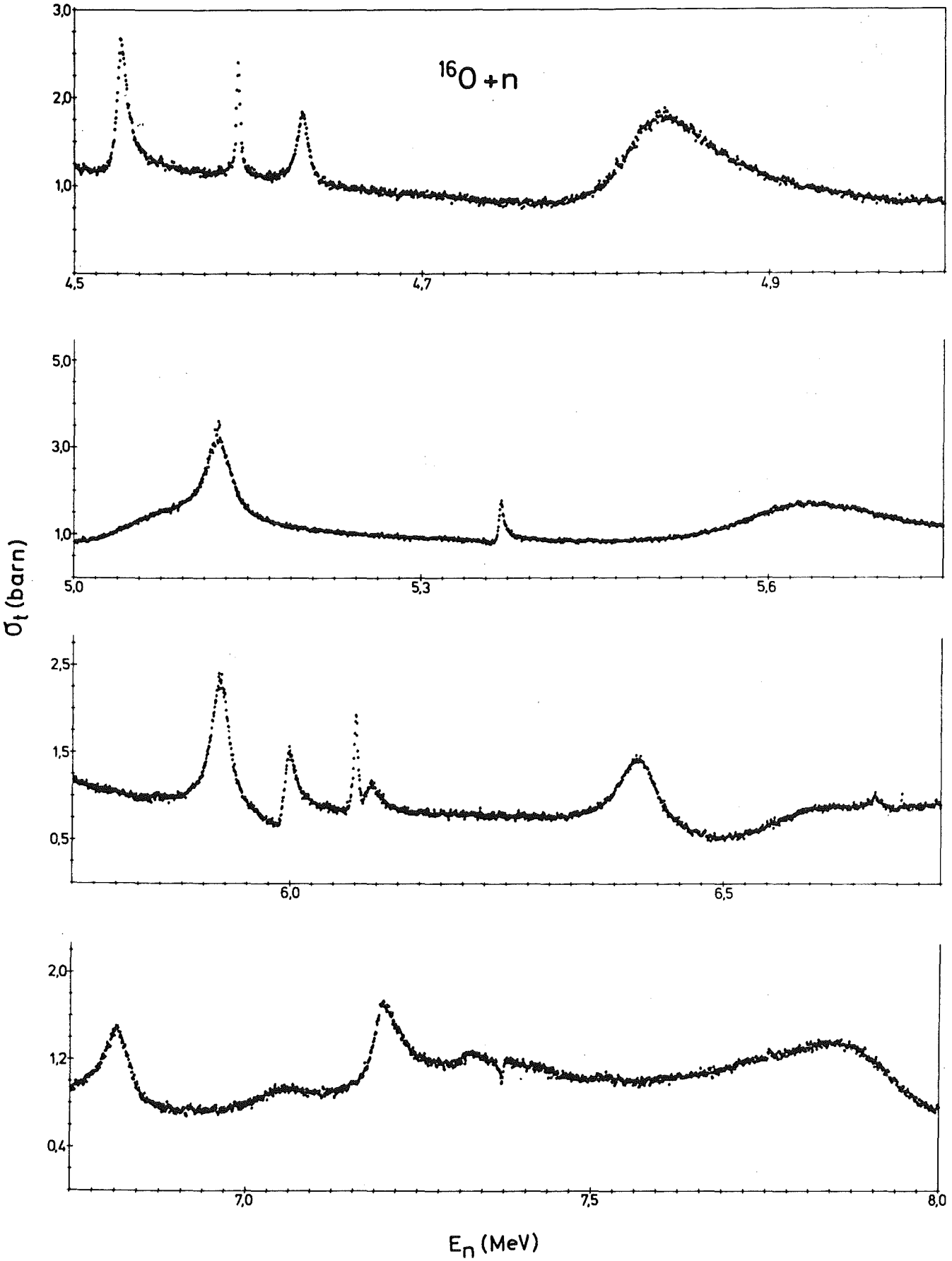

Fig. 2 Total neutron cross section between 4.5 and 8 MeV. These data are an example of the experimental results obtained for C and O between 3 and 30 MeV

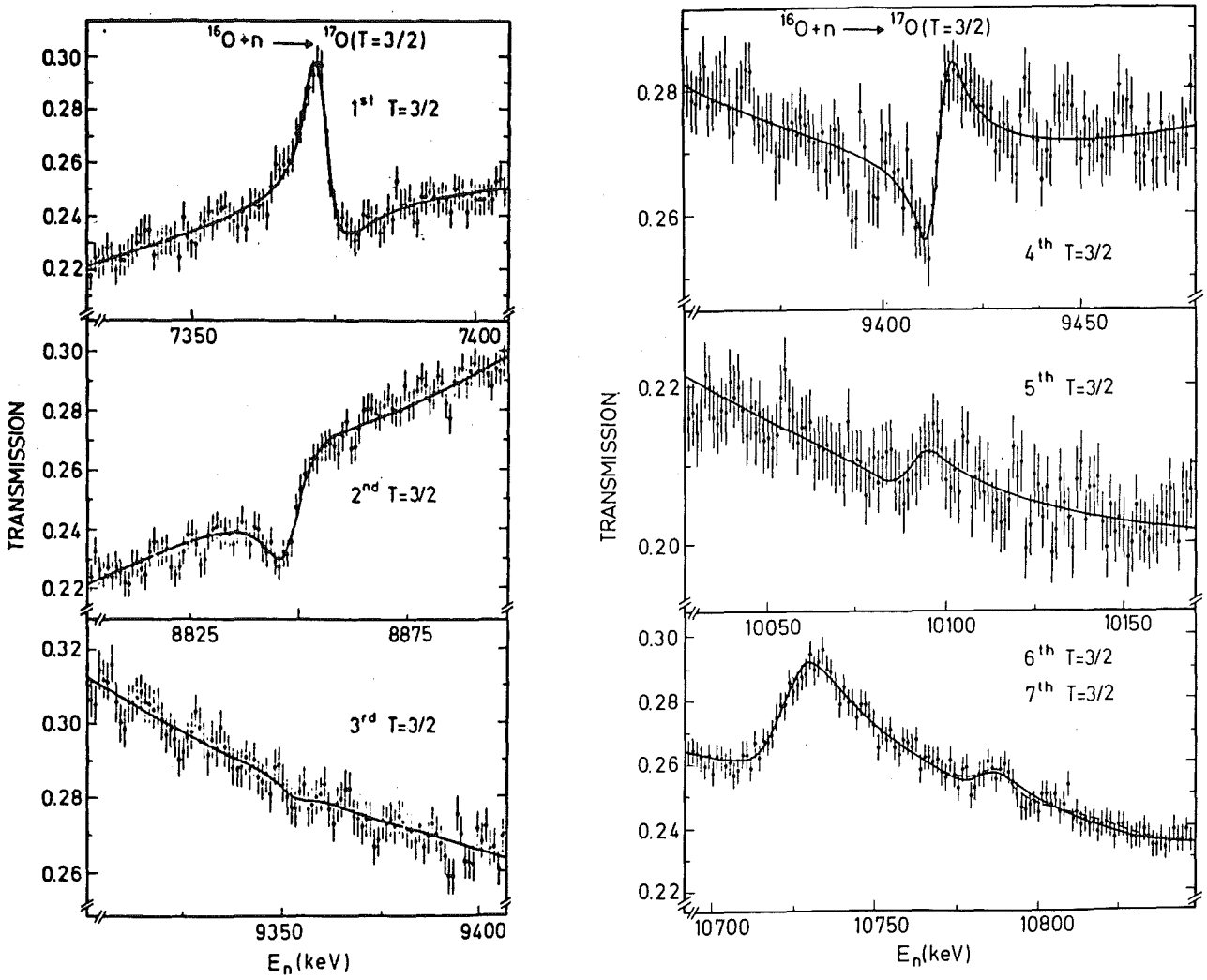

Fig. 3 Measured neutron transmission and best fit curves (solid lines) from our resonance analyses for the first seven ^{17}O (T=3/2) resonances

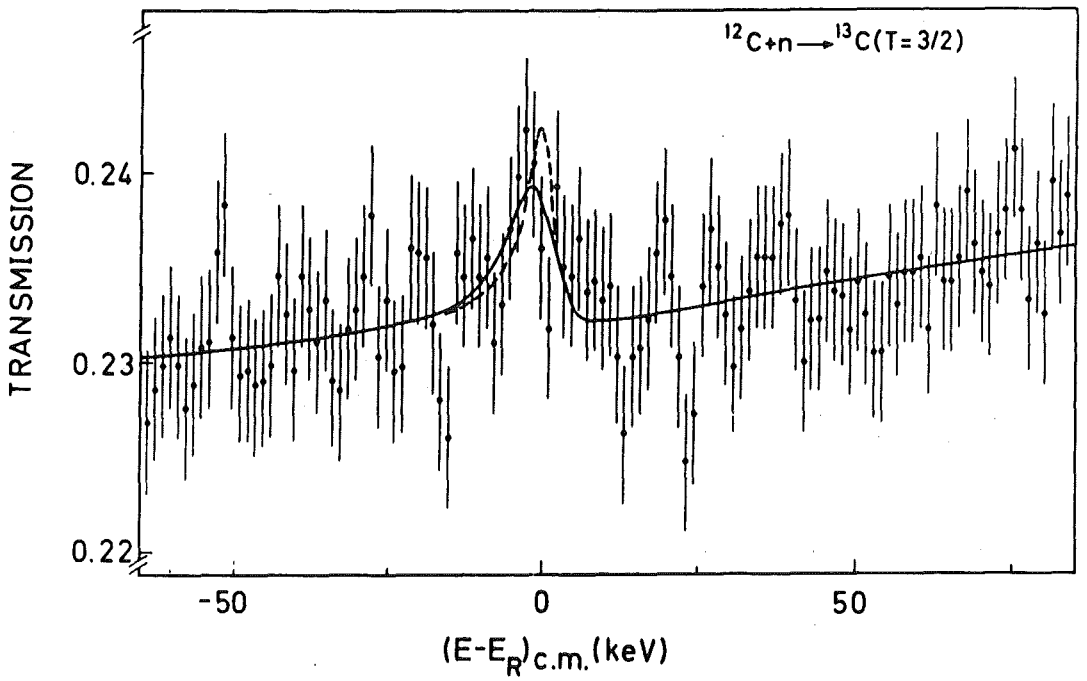

Fig. 4 Measured neutron transmission and best fit curve (solid line) for the first ^{13}C (T=3/2) resonance (preliminary)