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M. COPPOLA and H.-H. KNITTER

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Joint Nuclear Research Center
Geel Establishment - Belgium

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SUMMARY

Angular distributions of neutrons produced in the $^{14}C(d,n)^{15}N$ and $^{15}N(d,n)^{16}O$ reactions were measured at incoming deuteron energies of 1.3, 1.8 2.8 MeV and 1.0, 1.8, 3.0 MeV respectively, using a fast neutron time-of-flight spectrometer. Neutrons leading to the ground states and to some of the excited states of ^{15}N and ^{16}O were detected showing, in some cases, typical stripping patterns.

$^{14}C(d,n)^{15}N$ and $^{15}N(d,n)^{16}O$ Reactions (+)

Introduction

The possible use of the $^{14}C(d,n)^{15}N$ and $^{15}N(d,n)^{16}O$ reactions as neutron sources for future work was studied in the present experiment. A "good" neutron source should fulfill several requirements. First it should be easy to be made and easy to be handled. Second, it should be monocromatic. Third, it should yield a large amount of neutrons over a relative broad range of energies. Typical neutron sources, like the $T(p,n)^3He$ (Q =-0.764 MeV), the $D(d,n)^3He$ (Q =+3.268 MeV) and the $T(d,n)^4He$ (Q =+17.588 MeV) reactions meet all these requirements and are widely used in neutron experiments.

In the case of the present study, the more advanced technology makes now easily available highly enriched ^{14}C and ^{15}N targets which are also easy to be handled because they are solid. In the second place, the $^{14}C(d,n)^{15}N$ reaction has a Q-value of +7.987 MeV and the $^{15}N(d,n)^{16}O$ reaction a Q-value of +9.886 MeV. Furthermore the ^{15}N nucleus has the first excited level at 5.28 MeV and the ^{16}O the first excited level at 6.04 MeV. This brings that the ground state neutrons are produced in an energy region well suited to fill the gap between the D(d,n) and the T(d,n) neutron sources and that these ground state neutrons are well separated from the ones leading to excited states. Concerning the intensities of the neutron groups corresponding to the ground states, one finds that for both reactions the cross sections are relatively small and remain so over a wide range of deuteron energies (1, 2, 3).

In the case of the $^{14}C(d,n)$ reaction, the excitation curve at 0° for the ground state neutrons stays between 3.5 and 10 mb/sr about from 1.31 to 3.08 MeV deuteron energy, while for the $^{15}N(d,n)$ reaction it stays between 0 and 6 mb/sr from 0.5 to 5.3 MeV deuteron energy. For comparison purpose one can look at the available results (4) of the $D(d,n)^3He$ reaction for production of neutrons with energies higher than about 8 MeV. Here the zero degree excitation curve is monotonically increasing and goes roughly from 70 mb/sr at 5 MeV to 95 mb/sr at 9 MeV deuteron energy. With a deuteron target, then the neutron production at 0° is more than an order of magnitude

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larger than with ^{14}C and ^{15}N targets in the above neutron energy range, but unfortunately the deuteron energies required cannot be usually reached with a single stage Van de Graaff accelerator and not at all with the 3 MeV machine of CBNM. In sum it turns out that the ^{14}C and ^{15}N targets are to be considered a useful tool for investigating neutron interaction processes at neutron energies larger than 8 MeV, when discrimination between the ground state group and the other neutron groups can be obtained. Of course, for intensity reasons, the use of relative thick targets has to be envisaged.

The usefulness of these neutron producing targets is demonstrated by H.Liskien and A.Paulsen (5) who have recently measured in this laboratory the cross sections of the $^{60}Ni(n,p)^{60}Co$ and $^{63}Cu(n,\alpha)^{60}Co$ reactions, using activation techniques, at neutron energies between 8.46 and 11.48 MeV.

Experimental Equipment and Procedure

The measurements were made at the 3 MeV pulsed Van de Graaff accelerator of CBNM, using fast neutron time-of-flight techniques. A pulsed deuteron beam with 1 nsec burst width and 1 MHz repetition rate was focussed on enriched targets of ^{14}C and ^{15}N respectively. For the $^{14}C(d,n)^{15}N$ experiment, the graphite target, mounted on an aluminium backing, was 2.03 mg/cm^2 thick and contained 97% ^{14}C. For the measurements of the neutron angular distributions of the reaction $^{15}N(d,n)^{16}O$ a target was used which consisted of a 1.75 mg/cm^2 thick Si_3N_4 layer mounted on a copper backing. The nitrogen of this chemical compound was 95% ^{15}N. The neutron time-of-flight detector was inserted in a shielding which also collimated the neutrons produced in the target. The shielding, including the detector, could be rotated in the horizontal plane around the beam spot on the target. The detector and the associated electronics was already described in detail (6). The target-to-detector distance was 227 cm for the measurements performed in the angle range between 0° and 137°. For geometry limitations the distance had to be decreased to 148.5 cm when measurements were made between 137° and 148°.

As a neutron monitor a second time-of-flight detector system in connection with a single channel analyzer and a preset scaler was used. This time-of-flight monitoring system allows to select certain events coming from the target against most of the machine background, which is not negligible if deuterons are accelerated.

In order to get from the experimental time spectra the final neutron angular distributions it was necessary to introduce a correction for the relative detector efficiency. Up to a neutron energy of 2.03 MeV the relative detector efficiency was obtained by comparing the measured yield of neutrons scattered from the hydrogen nuclei of a polyethylene sample, at several angles between 20° and 67.5°, with the known n-p differential scattering cross section (7). The primary neutrons were produced by the $T(p,n)^3He$ reaction at $E_p = 3.1$ MeV. These data on hydrogen were corrected for the attenuation of the outgoing scattered neutrons (8). As a scatterer a hollow polyethylene cylinder, 1.00 cm outside diameter, 0.60 cm inside diameter and 4.00 cm height, was used. The weight was 1.840 g and the hydrogen content $(14.31 \pm 0.06)\%$. In the energy range between 1.84 MeV and 6.27 MeV the relative efficiency was obtained by measuring directly the neutron yield of the $D(d,n)^3He$ reaction at several angles between 0° and 145° and comparing this result with the known differential cross section of this reaction (4). Angular distributions were measured at $E_d = 2.0$ MeV and 3.0 MeV. In the same way the relative detector efficiency was determined in the energy range between 12.76 MeV and 16.75 MeV, using the $T(d,n)^4He$ reaction. The differential cross section needed for comparison was taken from ref. (4). The composed efficiency curve is shown in fig. 1.

Results

$^{14}C(d,n)^{15}N$ reaction

Fig. 2 shows a typical time-of-flight spectrum at a deuteron energy of 1.35 MeV and an angle of 137° in the laboratory system.

Here one can recognize the peak n_γ due to gamma-rays from the target and several other peaks due to neutron groups leading to different levels in the ^{15}N nucleus: n_o to the ground state, n_{12} to the 5.28 and 5.31 MeV levels which are not resolved, n_3 to the 6.33 MeV level, n_{456} to the 7.16, 7.31 and 7.57 MeV levels which are also not resolved in the present experiment. In the time spectrum, it is also recognized a small peak, denominated n_{Al}, which is presumly due to neutrons from the $^{27}Al(d,n)^{28}Si$ reaction in the thick aluminium backing of the target. A test made with the aluminium backing alone, shows that these neutrons give rise to a smeared spectrum which is more pronounced in the region of the n_{Al} peak. From the shape of such a diffused distribution of neutron pulses the right correction to the n_o-neutrons was always applied, while for the other neutron groups the relative small contribution from the reactions in the backing material was always neglected and only time uncorrelated background was subtracted.

From the resolved peaks in the time spectrum at 1.35 MeV, the angular distributions of the n_o, n_{12}, n_3, n_{456} neutrons groups were derived. As mentioned, a constant background was estimated from the count rate in the region between the gamma and the n_o peaks, and was subtracted from the angular distribution points. The same applies to the measurements at E_d=2.00 MeV where angular distributions of the n_o, n_{12}, n_3, and n_{456} neutron groups were measured, while at E_d=2.80 MeV only the n_o-angular distribution was obtained, because of insufficient time resolution.
The results are presented in figs. 3, 4 and 5.

$^{15}N(d,n)^{16}O$ reaction

Fig. 6 shows a typical time-of-flight spectrum taken at a deuteron energy of 1.00 MeV and ϑ_{lab} = 60°. As in the case of the previous reaction, several peaks are here resolved too. Using the same notation as before we see the peak n_γ due to gamma rays, n_o due to the ground state neutrons of ^{16}O, n_{12} to the 6.06 and 6.14 MeV levels, n_{34} to the

6.92 and 7.12 MeV levels, n_5 to the level at 8.88 MeV and n_{67} to the 9.58 and 9.84 MeV levels. The prominent peak n_{NC} at low energy is due to ^{14}N and ^{12}C content in the target material. A contribution to the low energy tail of the n_5 peak comes from the $^{28}Si(d,n)^{29}P$ ground state neutrons, because of the chemical composition Si_3N_4 of the target. Such an effect becomes evident at higher energies, but at 1.00 MeV, it is still small and was not subtracted from the n_5 results. Backing material effects are in this case negligible because of the high Coulomb barrier of the copper material used as a target backing. The time uncorrelated background was always subtracted using the above described procedure.

Because of the resolution limitations only at E_d = 1.00 MeV angular distributions of the n_0, n_{12}, n_{34} and n_5 were evaluated, while at E_d = 1.80 and E_d = 3.0 MeV the n_0 angular distributions alone were extracted.
The results are presented in figs. 7, 8 and 9.

Discussion

A. $^{14}C(d,n)^{15}N$ reaction

The excitation curves of the ground state neutrons at different angles show a resonance-like structure, although the peaks are not very prominent. Comparison of the data of Ren Chiba (1) and W.L.Imhof (2) indicates that for deuteron energies smaller than 1 MeV the excitation falls to zero, while for somewhat higher energies, at least three resonances or resonance-groups are present at 1.3, 2.0 and 2.8 MeV respectively. Ren Chiba gives also an attempt of unfolding the excitation curves by postulating a certain number, seven, of resonances between 1.0 and 3.3 MeV deuteron energies. The presence of such a resonance structure suggests that the $^{14}C(d,n)^{15}N$ reaction must proceed, at least partially, through compound nucleus formation.
The attempt of explaining the asymmetric shape of some angular distributions only as a result of interference between

neighbouring resonances may be considered too, but it is unlikely that such an effect can justify the strong asymmetries observed in some cases of the present experiment.

In other hand strong asymmetric angular distributions may be explained assuming the (d,n) reaction proceeding through a direct process, like deuteron or heavy ion stripping. In this situation we can say that in the energy region of the present experiment both compound nucleus formation and direct interaction processes are present and contribute to the neutron yield. Since the relative importance of these two modes of interacting is not known it appears surely difficult to fit reasonably the experimental data with a simple and consistent theory. Such an effort would be, moreover, outside the goal of the present paper.

E_d = 1.35 MeV

The only distribution which shows clearly a deuteron stripping pattern is the one corresponding to the doublet at 5.28 and 5.31 MeV. The direct reaction proceeds with an angular momentum transfer of $l = 0$. Evidence for heavy particle stripping may be found, instead, in the case of the ground state neutrons where the angular distribution is strongly backward peaked.

E_d = 2.0 MeV

The results at this energy confirm the previous considerations and assignments. Moreover, in the case of the neutrons to the 6.33 MeV level the compound neutron contribution appears to be predominant.

E_d = 2.8 MeV

Here the absence of a well defined pattern does not allow to make any definite statement about the reaction mechanism.

B. $^{15}N(d,n)^{16}O$ reaction

The same general remarks apply here as in the case of the $^{14}C(d,n)^{15}N$ reaction. J.L.Weil and K.W.Jones calculated differential cross sections for the ground state neutron group from 1.148 to 5.026 MeV deuteron energies, using the exchange stripping theory of Owen and Madansky (9). As they point out the large variability left to the parameters introduced in the formalism is only justified on a phenomenological base. With this in mind, one can say that their fits with the experimental results are rather good but at the lower energies, which are the ones of the present experiment, where the excitation curve at zero degree shows that the resonance structure is more pronounced.

E_d = 1.0 MeV

Anything about evidence of **direct** interactions can hardly be said at this energy. It seems, instead, that in all the distributions the compound nucleus interaction mechanism is the very predominant one.

E_d = 1.8 MeV

Here the reaction to the ground state seems to proceed through deuteron stripping with $l = 0$.

E_d = 3.0 MeV

At this larger energy the possibility of interpreting the reaction to the ground state mainly in terms of exchange stripping theory shows to be adequate and the present experimental results are in reasonable agreement with the calculations of Weil and Jones. As pointed out, this agreement is consistent with the fact that at this energy the deuteron energy is larger than the Coulombbarrier of the ^{15}N nucleus. Indeed, in this conditions, the probability of absorption of both deuteron nucleons by the ^{15}N nucleus followed by direct emission of a neutron is increased.

The authors gratefully acknowledge the cooperation given by Messrs. A. Crametz, R. Duchez and J. Leonard during the experiment.

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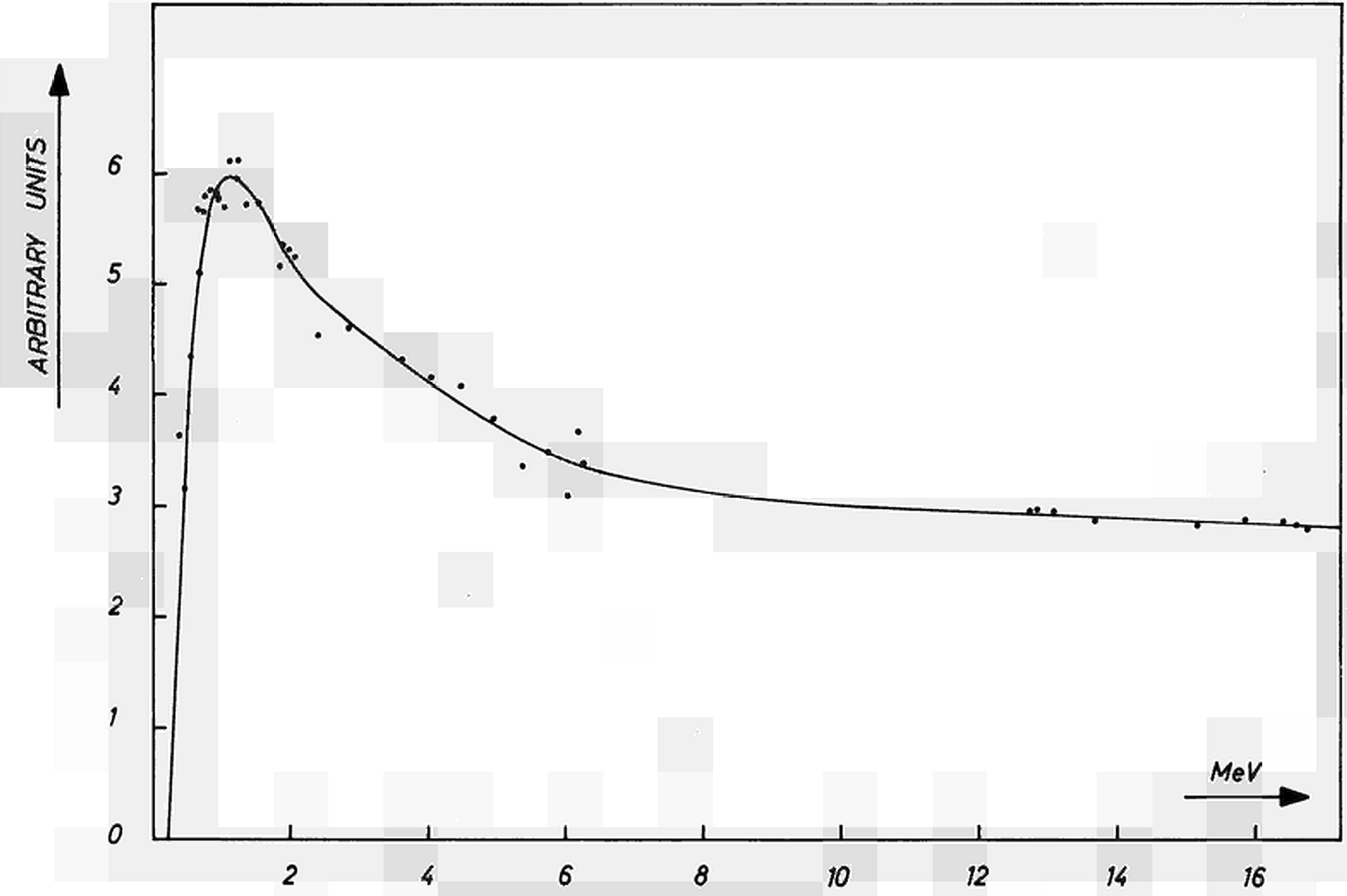

Fig. 1 Detector efficiency curve.

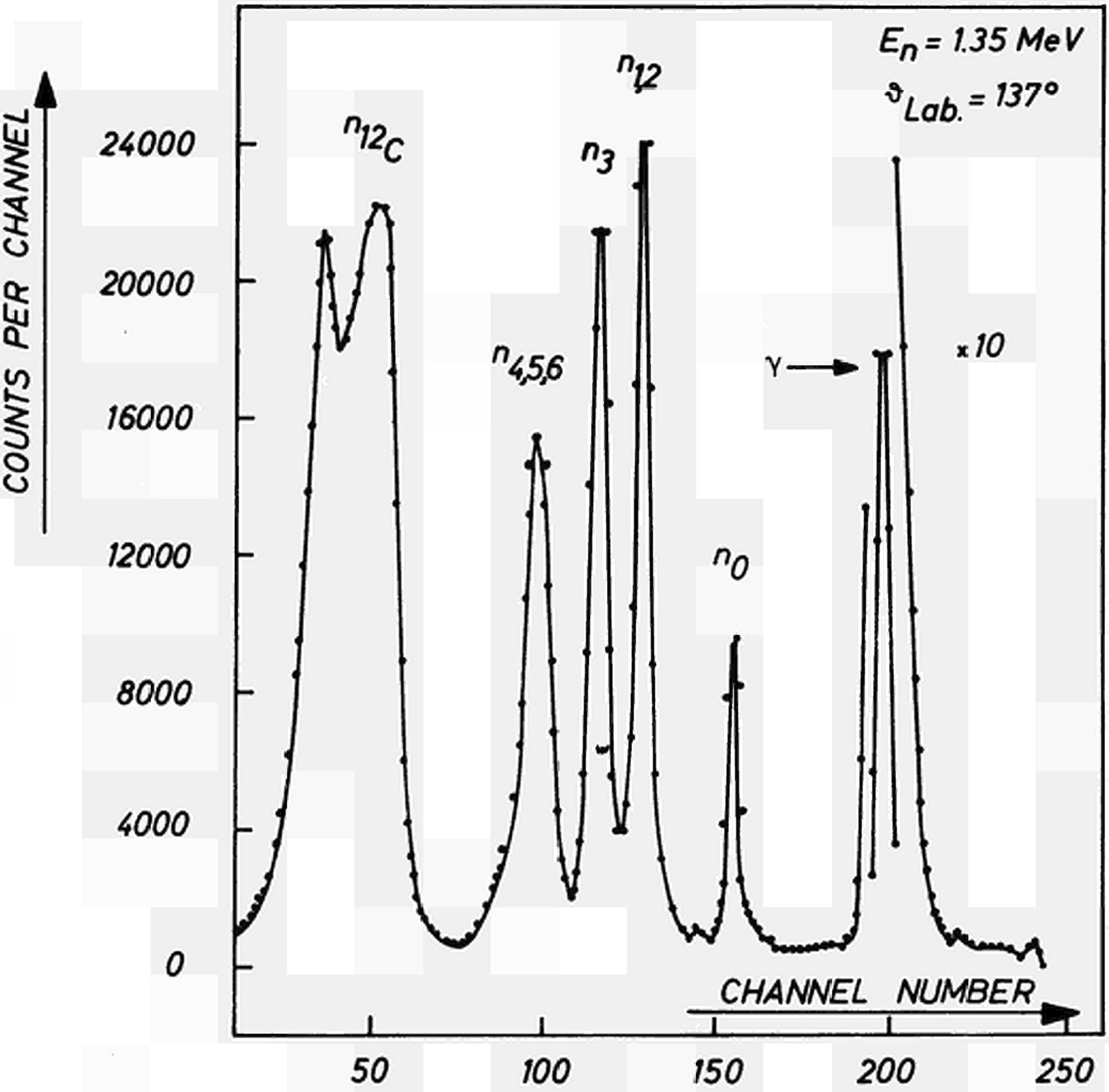

Fig. 2 $^{14}C(d,n)^{15}N$ reaction. Typical time-of-flight spectrum.

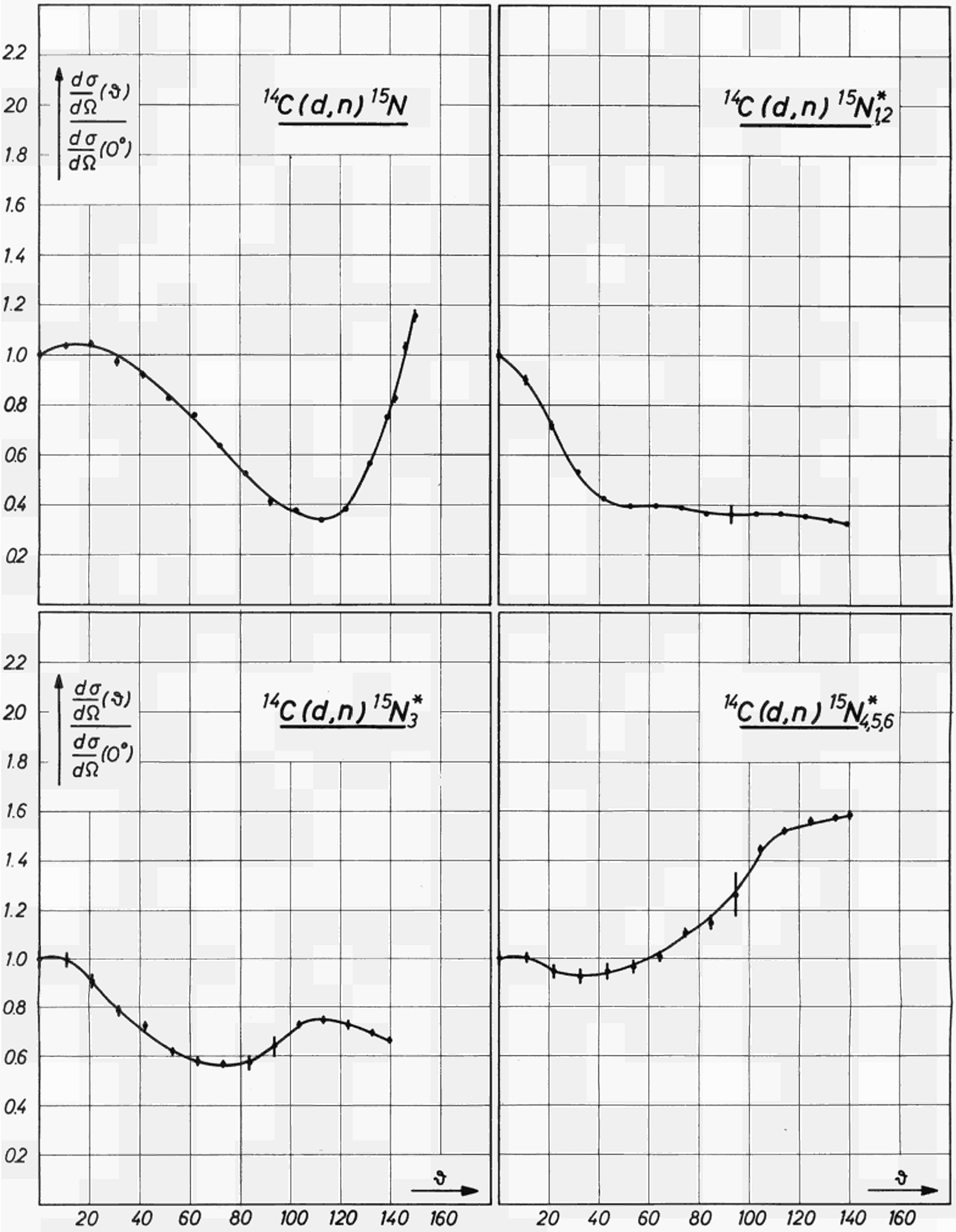

Fig. 3 Neutron angular distributions in the CM-system.
Deuteron laboratory energy 1.35 MeV.

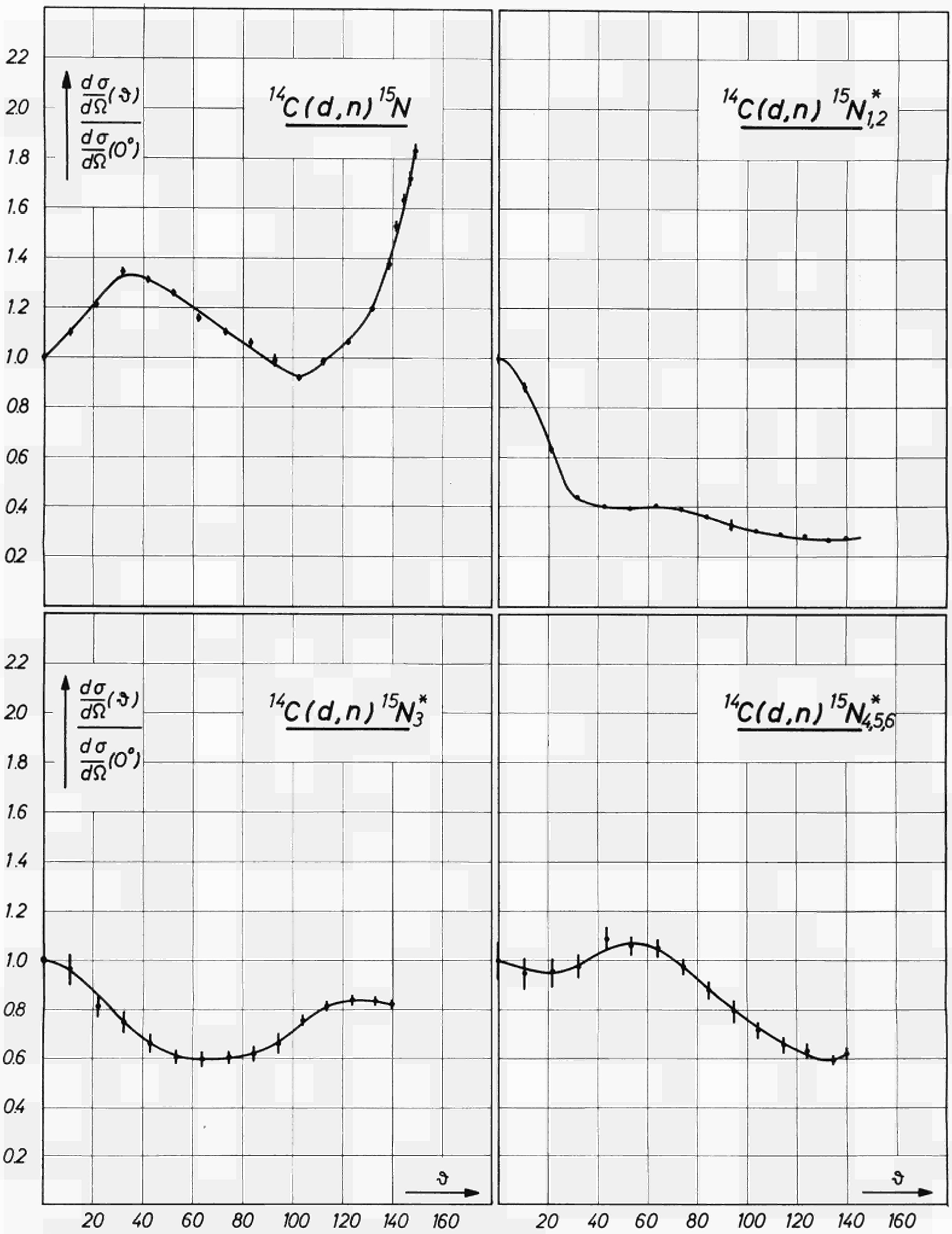

Fig.4 Neutron angular distributions in the CM-system.
Deuteron laboratory energy 2.00 MeV.

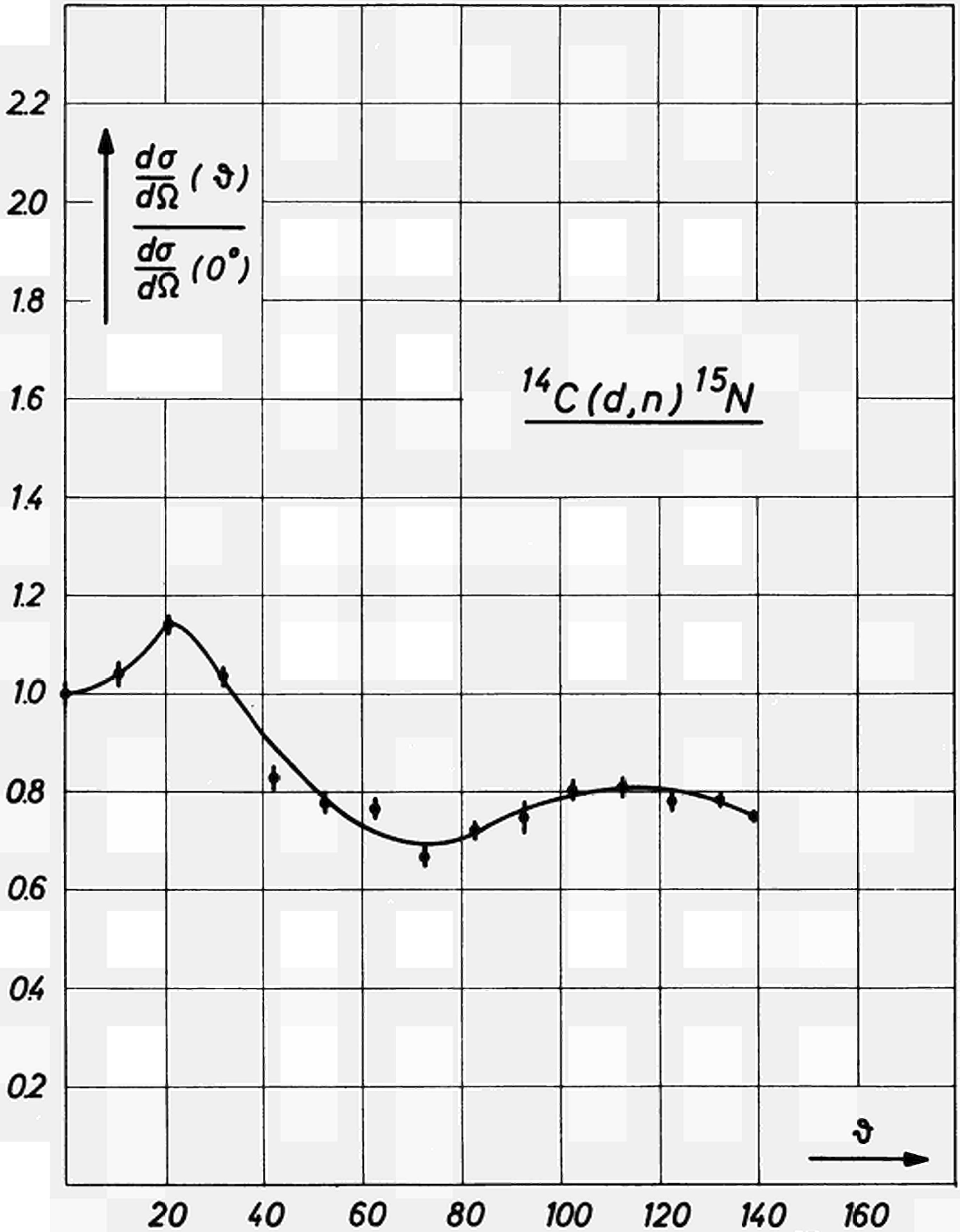

Fig.5 Angular distribution in the CM-system for the ^{15}N ground state neutrons. Deuteron laboratory energy 2.80 MeV.

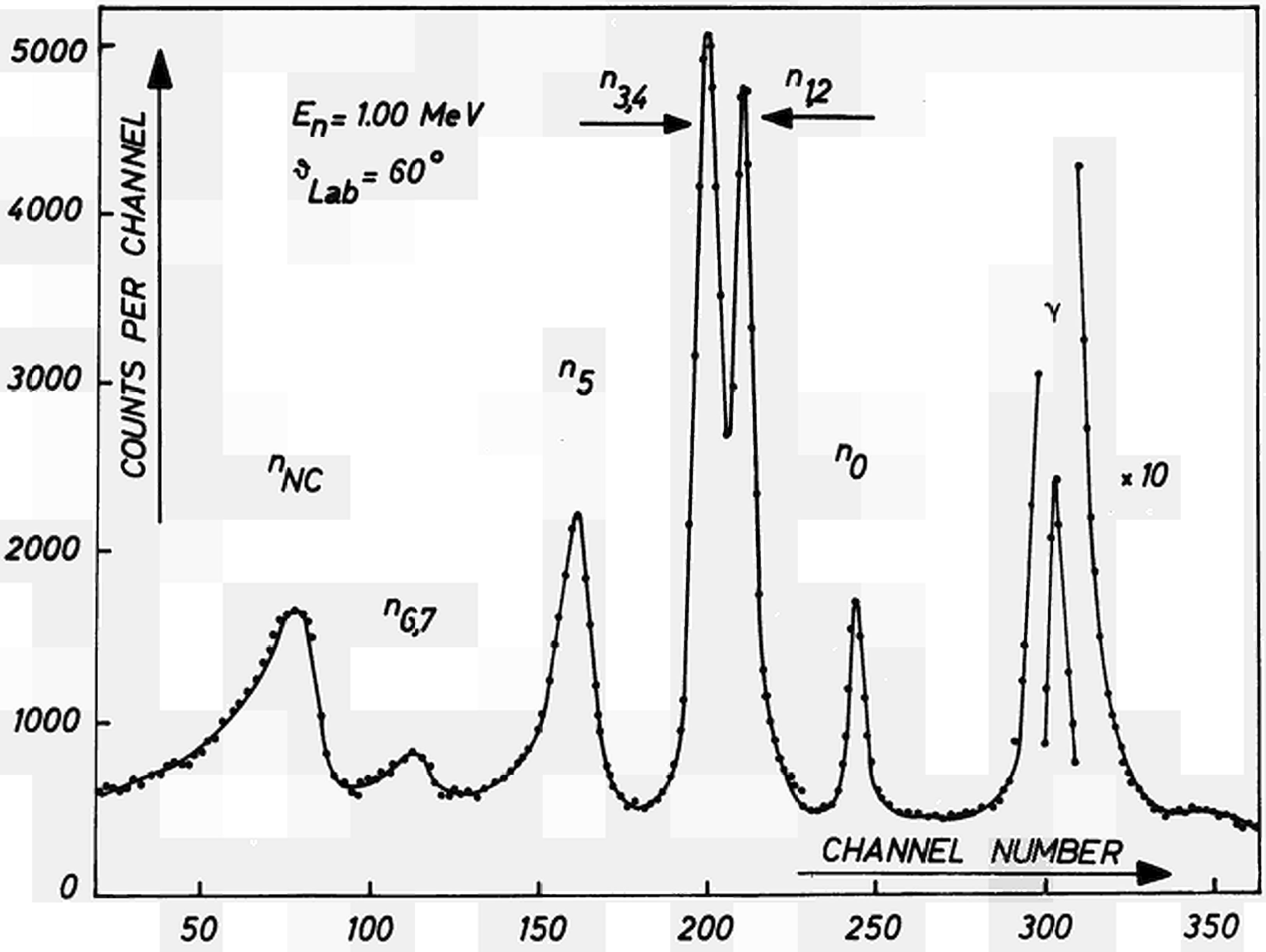

Fig.6 $^{15}N(d,n)^{16}O$ reaction. Typical time-of-flight spectrum.

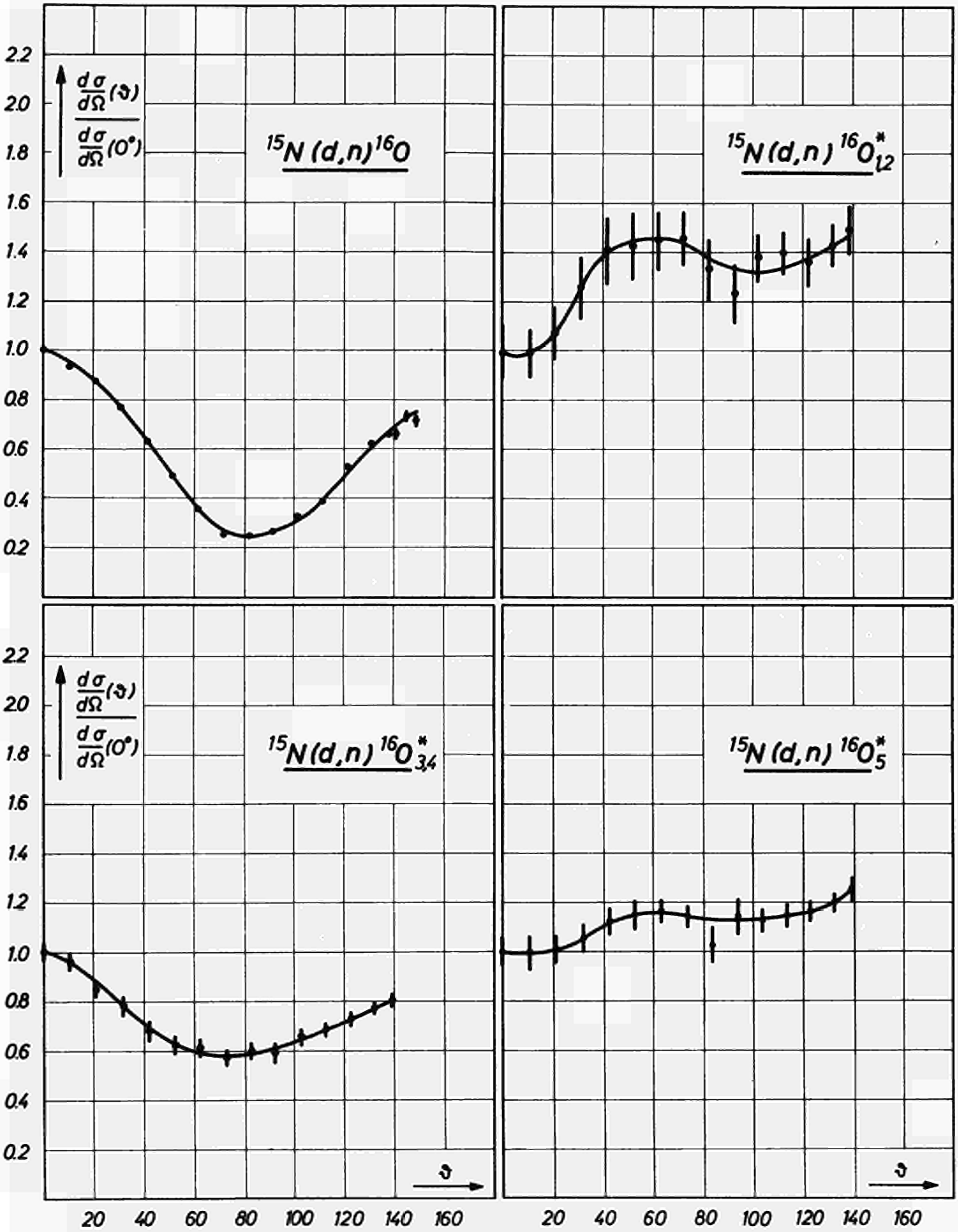

Fig. 7 Neutron angular distributions in the CM-system.
Deuteron laboratory energy 1.00 MeV.

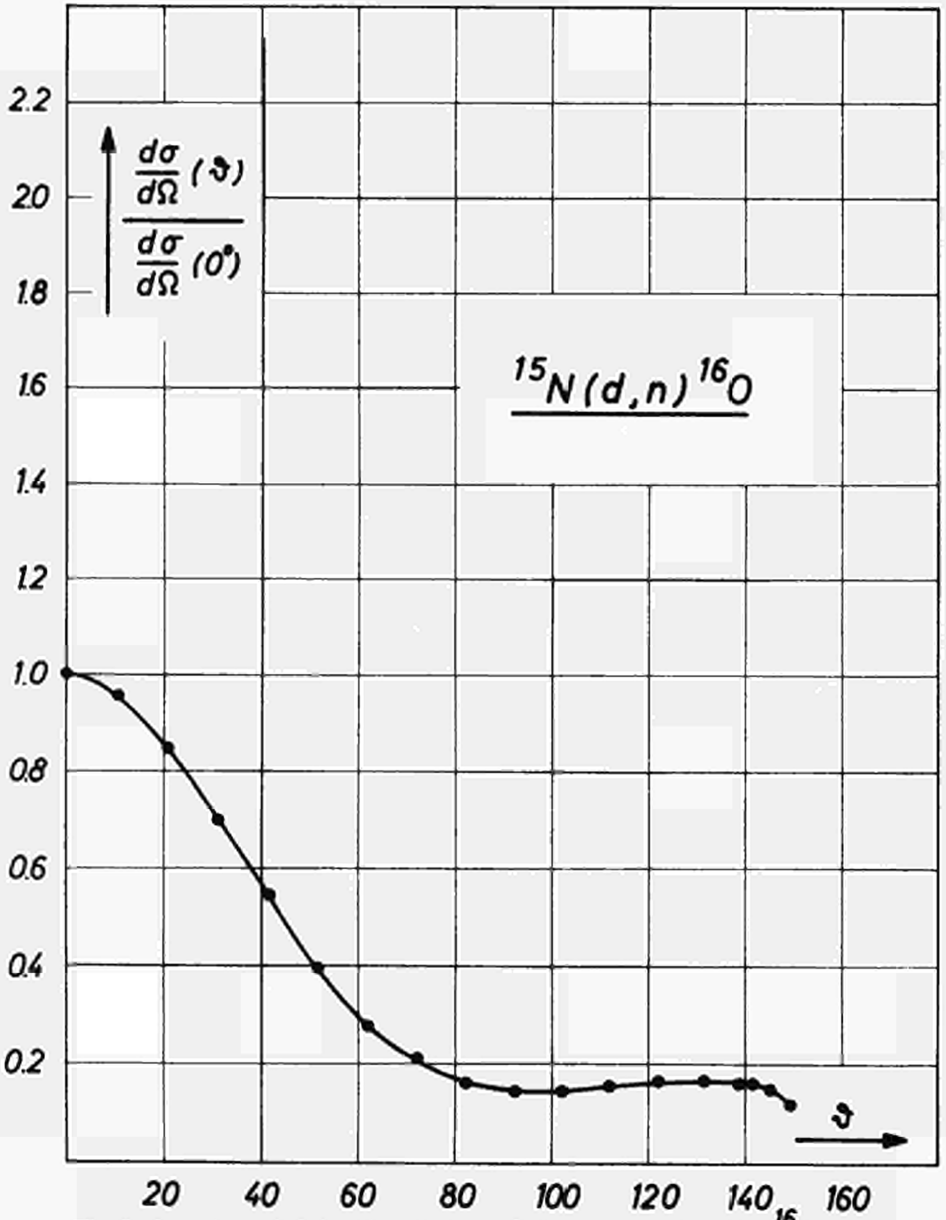

Fig. 8 Angular distribution in the CM-system for the ^{16}O ground state neutrons. Deuteron laboratory energy 1.80 MeV.

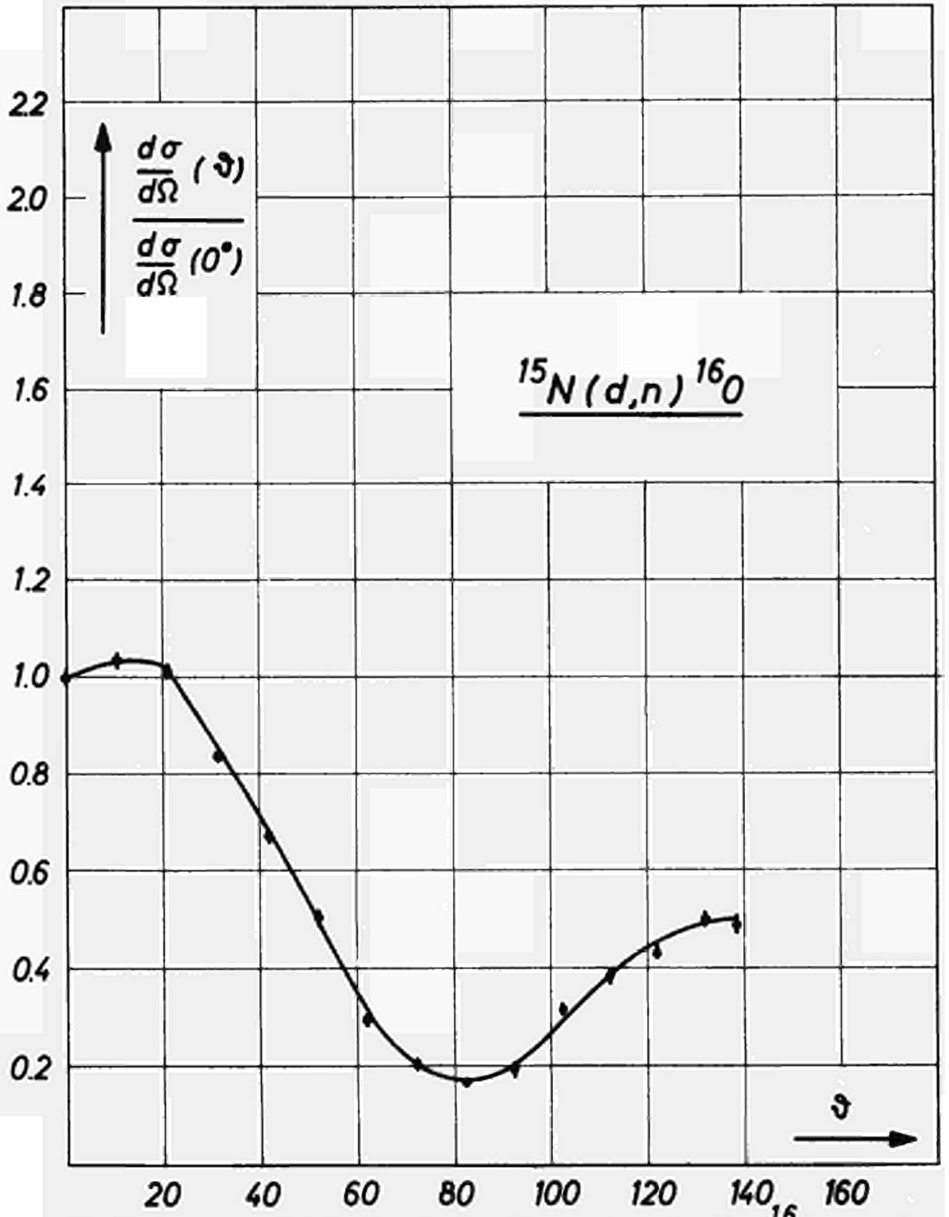

Fig. 9 Angular distribution in the CM-system for the ^{16}O ground state neutrons. Deuteron laboratory energy 3.00 MeV.

To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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