Vol. B18 (1987) ACTA PHYSICA POLONICA No 11

AN INTERPRETATION OF PROTON SPECTRA FROM THE ^{58}Ni(n, p)^{58}Co REACTION AT NEUTRON ENERGY CLOSE TO 20 MeV

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(Received October 31, 1986)

The differential cross-sections of the ^{58}Ni(n, p)^{58}Co reaction have been measured at 17.3 MeV neutron energy. The comparison of the results with data obtained earlier at 18.5 MeV suggests that multistep proton emission with excitation of the GDR as a doorway state takes place at these neutron energies.

PACS numbers: 25.40.Fq

1. *Introduction*

The ^{58}Ni(n, p)^{58}Co reaction has been investigated at different neutron energies. Transitions to parent analog states of GDR have been observed in some experiments. The identification of the transitions is mainly based on finding agreement between the angular distributions obtained experimentally and the DWBA calculated with $L = 1$ transfer. Some of the angular distributions of protons from the ^{58}Ni(n, p)^{58}Co reaction measured at 14.8 MeV [1] and at 22 MeV [2] neutron energies show a certain forward peaking. These angular distributions have been fitted as a sum of two components, one predicted by a collective theory for the direct excitation of analog states of the GDR and the other being the isotropic compound component [3]. Transitions to these states have been also reported at about 60 MeV [4].

We have investigated the ^{58}Ni(n, p)^{58}Co reaction at 18.5 MeV [5]. The continuum contribution was subtracted to isolate possible transitions to parent analog states of the GDR. Although the compound contribution has been subtracted, an additional isotropic contribution had to be included to obtain agreement between the experimental angular distribution and the DWBA calculations in the proton energy range of interest. This has suggested that the structure seen in the proton spectrum is not only due to direct excitation but also to other mechanisms.

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2. *Considerations of the reaction mechanism*

The multistep reaction mechanism has attracted some attention in the recent years. Angular distributions have been calculated for two statistical multistep processes: one involving particle bound states of composite systems (SMCE), and the other involving unbound states [6]. A sum of these contributions has been successfully fitted to experimental data of the (p, n) reaction at 26.7 MeV [7]. The contribution of SMCE is relatively large for low projectile energies and is almost isotropic.

We have considered the multistep reaction mechanism assuming the GDR excitation in the first step of the reaction. The giant resonances as doorway states have been investigated in inelastic proton scattering to low lying discrete states [8]. The proposed mechanism, which is a certain form of the SMCE, is illustrated in Fig. 1. The excitation energy of nucleus is higher after the capture of the 18.5 MeV neutron than that of the GDR, so the energy is shared by the GDR and other states. For the nuclear masses of interest the states excited beside the GDR are in the energy range of high level density.

In the case considered the GDR can deexcite by proton emission. This can take place both in the second step of the reaction and in one of the later ones (see Fig. 1). In this kind of reaction mechanism a number of protons have an energy equal to the excitation energy of the GDR minus the binding energy of the proton. The energy of this proton is independent of the incident neutron energy. If the yield of such a transition is high enough, the structure of the GDR should be imprinted in the proton spectrum. The proton groups seen in the proton spectrum at 18.5 MeV (marked by arrows in Fig. 2) can be due to this mechanism. The best way to prove this hypothesis would be to compare the proton spectrum measured at a slightly different neutron energy with that measured at 18.5 MeV. The positions of the proton groups in the spectrum should be independent of the neutron energy.

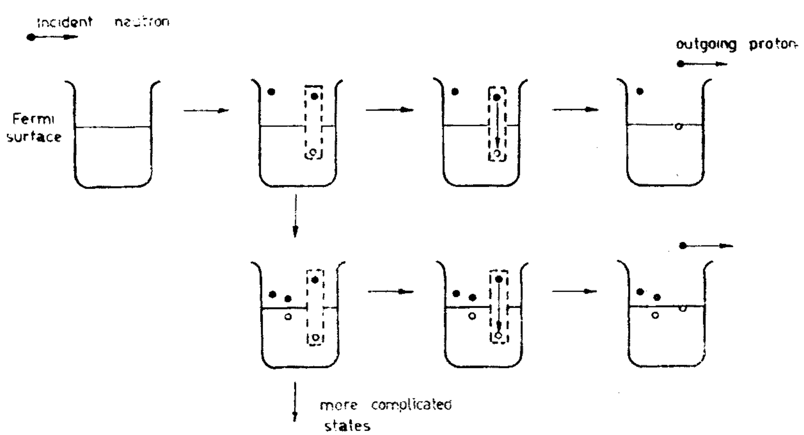

Fig. 1. Simple presentation of the multistep reaction mechanism with the GDR excitation. The GDR is shown as a particle-hole excitation (dashed rectangle). The upper part of the figure presents the immediate GDR deexcitation and the lower one — that after the spreading of energy over more states

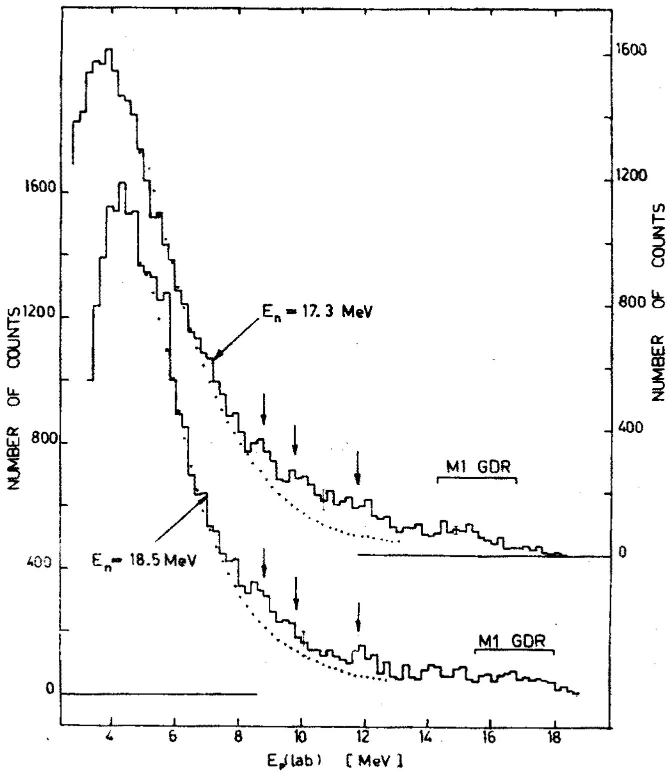

Fig. 2. The proton spectra from the ^{58}Ni(n, p)^{58}Co reaction at 17.3 MeV and 18.5 MeV neutron energies. The spectra are summed over four measured angles from 10° to 40° to improve the statistics. Ordinates are in arbitrary units. The dotted lines represent the calculated continuum. The proton groups indicated by arrows in the 8–14 MeV energy range are at the 8.6, 9.6 and 11.8 MeV proton energies

3. *Experimental procedure*

The experimental equipment and procedure used are the same as those described in our previous paper [5]. The eight-telescope chamber makes it possible to measure simultaneously eight proton energy spectra at eight different angles. Operation of the telescopes and the two-dimensional analysis employed to identify the charged particles are described elsewhere [9]. The present investigations involved only two major differences: (*i*) Some changes in the construction of the neutron source were made. Owing to them it was possible to measure the proton spectra from near 0° to 170° in 10° steps. The measurements at 80° and 90° angles were excluded since only 16 angles can be measured in two positions of the chamber. (*ii*) Different semiconductor detectors were used. Each detector consists of two surface barrier Si detectors placed face to face as close as possible so they operate as one thick "tandem detector" [10]. The detector bias was continuously checked during the measurement to ensure the proper depletion layer of the detectors, especially of those acting as transmission ones.

Neutrons of an average energy of 17.3 MeV were produced in the $^{3}T(d, n)^{4}He$ reaction, the deuterons having been accelerated to 1.5 MeV in the Van de Graaff accelerator. The neutron energy spread was about ± 150 keV. The neutron flux was monitored. The absolute normalization was performed with respect to the n-p differential cross-section for recoiled protons [11]. The energy scale was determined by measuring the particles from a ThC′ source incident on the back of the transmission detector before and after the measurements. The deuteron spectra, which were also measured during the experiment, were used additionally to check the energy scale at forward angles to make the comparison of proton spectra obtained at neutron energies of 17.3 and 18.5 MeV most reliable. The other control and normalization measurements were described in our previous paper. Each run took an average of about 10 hours, and for one telescope setting 10 runs were carried out.

4. *Results and discussion*

The differential cross-sections of the $^{58}Ni(n, p)$ reaction were measured at 17.3 MeV neutron energy. Analyses of the experimental data have been performed independently in two proton energy ranges.

a. The 8–13 MeV proton energy range

The 8–13 MeV proton energy range contains the expected multistep transitions with the GDR as a doorway state. The proton spectrum measured at 17.3 MeV is compared with that measured at 18.5 MeV in Fig. 2. Proton groups at about 8.6, 9.6, and 11.8 MeV are seen in both spectra. The continuum contributions were subtracted from the proton spectra to enable a more precise comparison. The procedure applied in continuum subtraction is described in our previous paper [5]. It was based on the normalization of the (n, p) and (n, np) compound spectra described by approximate formulae [12, 13] to the experimental data. Small, energy independent precompound contributions were also included. The continuum-subtracted proton spectra in the 8–13 MeV energy range are presented in Fig. 3. Although the proton groups occur at the same energies the spectra are not quite similar, especially in the 10–12 MeV energy range. It seems that the observed differences between those spectra can be due to excitation of other states after the neutron capture beside the GDR. Let us pay some attention to the density of the single particle states in the proper excitation energy range. According to the Ngo-Trong et al. calculations [14] the $1g_{9/2}$ and $2d_{5/2}$ single particle states should be centered in ^{58}Ni at excitation energies of about 5 and 7.2 MeV, respectively. These energies are calculated relative to the $2p_{3/2}$ state which is dominant in the ground state configuration of ^{58}Ni [15]. The relation between the energy of the considered states (E^*) and those of the protons emitted during the GDR deexcitation (E_p) is given by the simple equation:

$$E_p = E_{GDR} - E_w^p = E_n + Q - E^*, \qquad (1)$$

where the GDR energy $E_{GDR} = E_n + E_w^n - E^*$; E_n is incident neutron energy, E_w^p and E_w^n are the binding energies of proton and neutron, respectively, and $Q = E_w^n - E_w^p$.

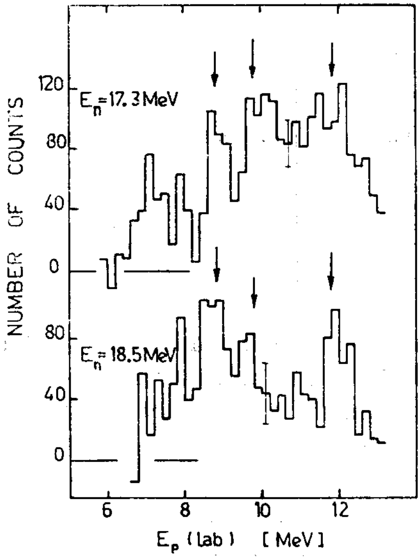

Fig. 3

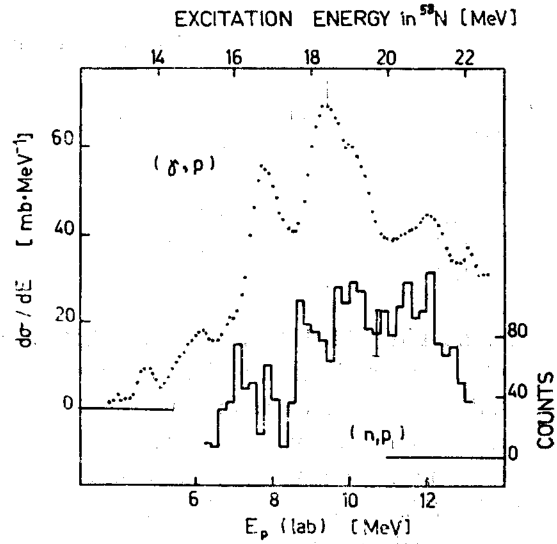

Fig. 4

Fig. 3. Continuum-subtracted proton spectra at 17.3 and 18.5 MeV in the 8–14 MeV energy range obtained from those in Fig. 2

Fig. 4. Continuum-subtracted proton spectrum from the ^{58}Ni(n, p)^{58}Co reaction at 17.3 MeV and the ^{58}Ni(γ, p)^{57}Co excitation function. A shift of energy scales between the spectra is by 0.4 MeV greater than the binding energy of the proton in ^{59}Ni

The enhancement of proton emission at the energy of about 11.3 MeV seen in the proton spectrum at 17.3 can be due to the excitation of the above mentioned single particle states in the first step of the reaction. The corresponding enhancement in the spectrum at 18.5 MeV can be expected to lie at about 12.5 MeV. Thus the direct comparison of the spectra at both neutron energies is difficult because of what was said above. In this situation we have made the following calculation to prove in a convincing way that the proton groups really have the same energies in both spectra. We added the numbers of counts in the continuum subtracted proton spectra at 17.3 MeV in two energy ranges: the first contains two close lying proton groups at 8.6 and 9.6 MeV, and the second contains the third group at 11.8 MeV.

We then calculated an excess of counts in these ranges over the counts in the neighbouring ranges. The calculations were perfoimed according to the following expression

$$EX = (\sum_{i=k}^{k+9} N_i + \sum_{i=k+15}^{k+19} N_i) - (\sum_{i=k-5}^{k-1} N_i + \sum_{i=k+10}^{k+14} N_i + \sum_{i=k+20}^{k+24} N_i), \quad (2)$$

where: N_i is the number of counts in the i-th channel of the spectrum, and k corresponds to the first channel number of the range containing two proton groups.

Subsequently, we calculated the count excess for the proton spectrum at 18.5 MeV for two cases: (i) the energy ranges within the same limits as for the spectrum at 17.3 MeV, (ii) the energy ranges shifted according to the change in the neutron energy. The results

TABLE I

Excess of proton number

Incident neutron energy E_n (MeV)	Proton energy range (MeV)	Channel number k	Excess of proton number
17.3	7.2–13.2	36	505 ± 100
18.5	7.2–13.2	36	443 ± 157
18.5	8.4–14.4	42	-353 ± 142

are presented in Table I. It is easy to see that the count excesses calculated for both spectra without energy shift agree within the error bars. On the other hand they are opposite of sign if the considered proton range at 18.5 MeV has been shifted in energy by 1.2 MeV and the difference between the excesses is equal to 858 ± 174.

Let us now compare the proton spectrum with the GDR structure. It was suggested above that this structure should be imprinted in the proton spectrum. In Fig. 4 the continuum-subtracted proton spectrum and the (γ, p) excitation function are presented [16]. One can see that the proton groups in the (n, p) spectrum correspond to the bumps on the (γ, p) excitation function. A close similarity of the shapes of the spectra should not be expected, since the different nuclei are excited in both reactions and the (n, p) reaction excites also other states beside the GDR.

In the investigated proton energy range the transitions to parent analog states of the GDR are also expected. These transitions were investigated in our previous work at 18.5 MeV [5]. The angular distribution for the 8–14 MeV energy range at 18.5 MeV

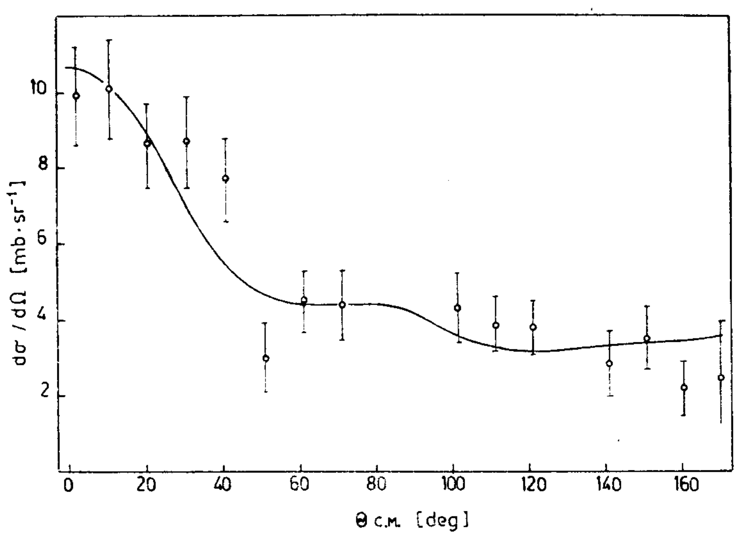

Fig. 5. The measured angular distribution for the 7–13 MeV energy range. The curve is a fitted sum of the DWBA prediction of the direct excitation of the 1^- E1 GDR parent analogs based on the SJ form factor ($L = J = 1$, $S = 0$) and the isotropic contribution

was in agreement with this expectation if the isotropic contribution was included. The exhausted fraction of EWSR was about 135%[1]. The angular distribution for the 7–13 MeV energy range at 17.3 MeV is shown in Fig. 5. The continuum-subtracted experimental data were fitted, as in our previous paper, by the sum of two components: one predicted by the DWBA calculation with the $S = 0$ and $L = 1$ transfer, and the other one being isotropic. The DWBA calculations were based on the Steinwedel–Jensen model [17] sets of optical model parameters proposed by Rappaport [18] for neutrons and by Perey [19] for protons having been used. The fit presented in Fig. 5 is quite similar to that obtained at 18.5 MeV. The exhausted fraction of EWSR is 195% which is in reasonable agreement with that at 18.5 MeV. This result confirms the suggestion that the direct transitions to parent analog states of the E1 GDR are present in the considered proton energy range. The isotropic contribution lies within the same error limits as at 18.5 MeV.

b. The 14.4–16.8 MeV proton energy range

The proton spectrum in the 14.4–16.8 energy range, corresponding to the transitions to parent analog states of M1 GDR, is similar to that in the 15.6–18.0 MeV range at 18.5 MeV. The proton peaks A, B, C, D reported at excitation energies of ^{58}Co 1.0, 1.7, 2.2 and 2.8 MeV are seen in the present measurements at the same energies (see Fig. 6).

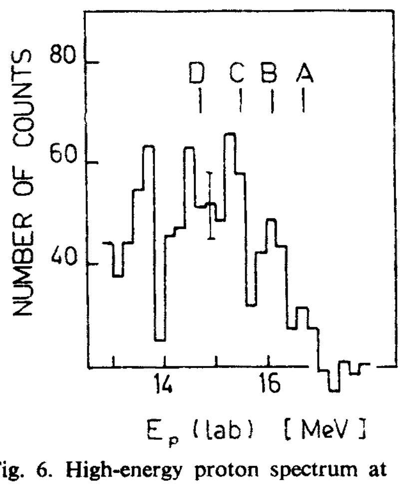

Fig. 6. High-energy proton spectrum at 10°

The peaks A, B, C were related to the analog states in ^{58}Ni at 9.85 (10.55+10.66) and 11.03 MeV, respectively. The peak D at 2.8 MeV was related to the possible 1^+ states at 2.78 and 2.88 MeV reported by Flynn and Garrett [20], however later investigations in the same (^{3}T, ^{3}He) reaction did not confirm the spin assignment for these states [21].

The angular distribution for this energy range is presented in Fig. 7. The experimental data were fitted by DWBA predicted angular distribution with the $L = 0$ and $L = 2$ transfers. The two-parameter least squares fit was described in our previous paper.

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[1] The value of 29% obtained in our paper [5] was corrected because of the wrong expression used for calculation of the $\beta^2(100\%)$ value.

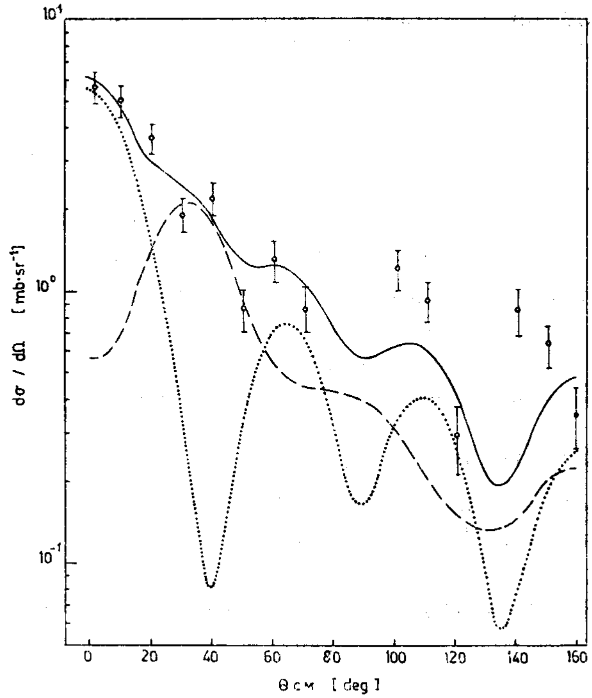

Fig. 7. The measured angular distribution for the proton energy range of 14.4–16.8 MeV corresponding to the transitions to the M1 GDR parent analogs. The solid curve has been obtained as the fitted sum of the DWBA prediction at $L = 0$ (dotted curve) and $L = 2$ (dashed curve)

The strength S_L for $L = 0$ and $L = 2$ transfers is 0.00395 and 0.03845, respectively. These S_L values are close to those obtained at 18.5 MeV for the 15.6–18.0 MeV proton energy range, and the presented angular distributions are similar for both neutron energies.

c. The proton emission cross-section

The proton emission cross-section contains compound, precompound and direct contributions. The precompound contribution in the 8–13 MeV proton energy range is most interesting from our point of view. This contribution has been calculated by using the EMPIRE code [22]. According to these calculations the precompound proton spectrum is almost energy independent in the energy range of interest. The calculated precompound cross-section takes on average a value of about 12.4 mb · MeV^{-1} which is significantly greater than the 3.2 mb · MeV^{-1} obtained as the energy-independent contribution to the continuum proton spectrum, what was said in point (a). Taking into account the considerations of the multistep reaction mechanism one can include the structure of the proton spectrum to the precompound contribution. The cross section of this part of the structure which corresponds to the isotropic contribution in the angular distribution in Fig. 5 amounts to about 32 mb for the 7–13 MeV energy range. Adding this value to the energy-independent contribution we obtain the value of about 54 mb for the considered energy range. This value is still lower than the calculated cross-section of about 75 mb, but it seems that the agreement is quite reasonable in this case.

The (n, p) cross-section for protons emitted as a first particle has been also determined. The obtained value of 724 mb is within the 15% error limits close to that of 604 mb obtained previously at 18.5 MeV. The σ(n, np) has not been determined because the number of protons from this reaction is in the measured energy range very small at 17.3 MeV.

5. *Summary*

The proton spectra of the ^{58}Ni(n, p) reaction, the angular distributions in the 7–13 MeV and 14.4–16.6 MeV proton energy ranges, and the proton emission cross-sections were obtained at 17.3 MeV neutron energy. The shape of the proton spectrum was compared with that measured previously at 18.5 MeV to make clear what is the mechanism responsible for the structure of the proton spectrum in the 8–13 MeV energy range. The proposed multistep reaction mechanism presented schematically in Fig. 8 is a certain form of the

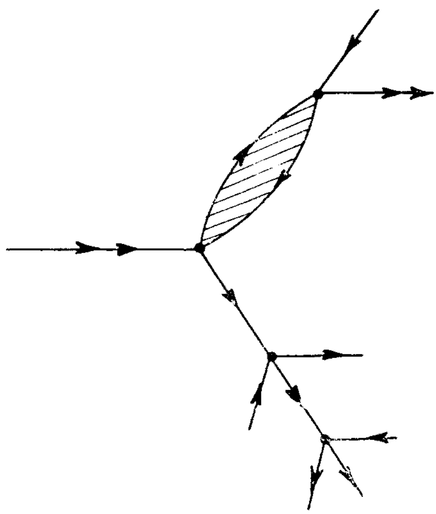

Fig. 8. Schematic representation of the proposed reaction mechanism. The notation of Bohr and Mottelson has been supplemented by the use of double arrows to denote particles in the continuum. Dashed area denote the GDR excitation

SMCE. According to this mechanism the shape of the proton spectrum should be dependent on the GDR structure. The proton groups in the measured (n, p) spectra correspond to the bumps in the (γ, p) excitation function and their positions are independent of the incident neutron energy. This is exactly what the mechanism predicts. The angular distributions at 17.3 MeV are similar to those obtained at 18.5 MeV in the corresponding proton energy ranges. All cross-sections measured at 17.3 MeV are close to those measured at 18.5 MeV.

We would like to thank dr P. Żuprański for useful discussions.

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