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S. Notarrigo and P. Cuzzocrea: SHELL EFFECTS IN (n, p) AND (n, α) CROSS SECTIONS AT $\approx$ 14 MeV. -

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In the last few years, certain systematic regularities have been observed in the (n, p) and (n, α) reactions when the cross sections at $\approx$ 14 MeV where analyzed as a function of the mass number or the proton number or the neutron number of the target nucleus(1-8).

These regularities have been interpreted in the light of the statistical model of nuclear reactions(1-8), but many discrepancies were observed that would not fit this picture and call for a direct interaction mechanism(7, 8).

Principally the observed regularities were of two different kinds: 1) the (n, p) cross sections, when analyzed as function of A, on a semilog paper, fell on parallel straight lines about equally spaced with Z as parameter(3, 4); and 2) the (n, α) cross sections showed maxima when the target nucleus had a closed shell of neutrons and minima with closed proton shells(5, 6).

We will show in the present note that both kinds of regularities are present in both types of reactions and that they may be attributed to two different mechanisms.

Let us start by observing that the regularities in 1) might, presumably, be observed also assuming as parameter N-Z and this would allow one to compare the lightest nuclei where the comparison is not possible with Z as parameter because of the scarce number of stable isotopes for each element.

This, in fact, is the case as shown in Fig. 1a, where the (n, p) cross section values for nuclei with A < 60 are analyzed as a function of A with N-Z as a parameter.

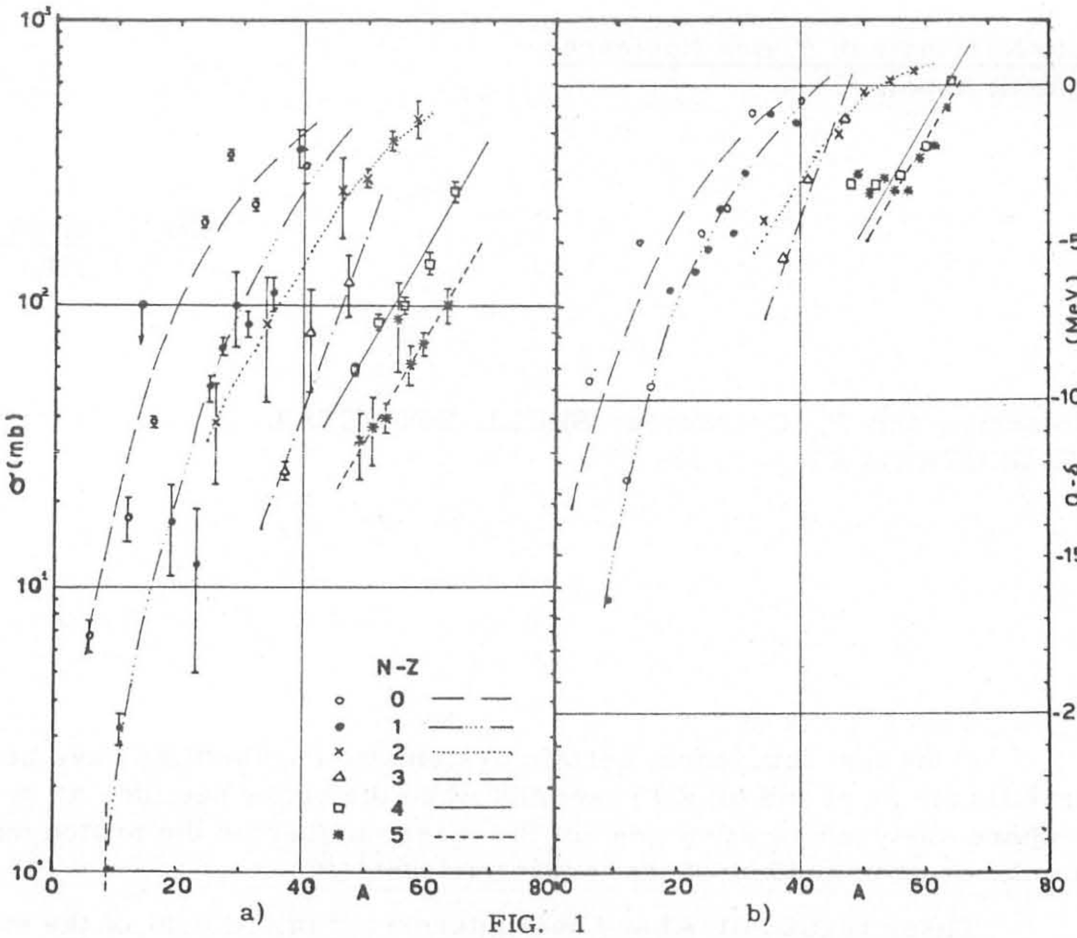

FIG. 1

a) - (n, p) cross sections vs. mass number A for nuclei with A < 60 and N-Z ≤ 5. The points, marked differently for each value of N-Z, represent weighted means of the experimental data reported in ref. (3) (see text).

b) - (Q- δ) vs. A for the same nuclei of a) (see footnote (x)). The dotted lines in a) and b) are intended only as a guide for the eye.

The points, with different marks for each values of N-Z, represent the weighted mean that we performed with all the data at ≈ 14 MeV, for each given isotope, reported by Gardner[3], assuming as weights the square of the reciprocal of the errors quoted for each single measurement.

The errors, displayed in Fig. 1a, are the standard errors of the weighted mean either the external or the internal whichever is the larger[9]. The Birge's consistency criterion was adopted[9].

This criterion led us to discard several of the cross sections measured by Allan[2] and a few more data that, from this statistical analysis, showed the presence of a systematical error. In fact the Allan data were taken in a particular experimental condition in order to measure only the statistical contribution and discard the direct contribution[2].

In Fig. 1a one notes that these averaged cross sections for the different values of N-Z follow regular lines. The same trend is observed in Fig. 1b for the $(Q-\delta)$ values of the corresponding reactions[x]. This suggests a strong correlation with the excitation energy of the residual nucleus.

In fact, when the same data of Fig. 1a are plotted against the excitation energy of the residual nucleus (Fig. 2), it can be seen that, with few exceptions (marked with an arrow in the figure), all points scatter, within a factor of two, around a straight line corresponding to the equation

$$\sigma\ (n,p) = e^{0.43\ E^{x}} \tag{1}$$

with

$$E^{x} = E_n + Q - \delta \tag{2}$$

Let us anticipate: a) that the exceptions are due to shell effects similar to those observed in (n,α) reactions[5,7]; b) that, aside from these exceptions, the cross sections throughout the entire range of mass number of atomic nuclei fall around the same straight line when one takes

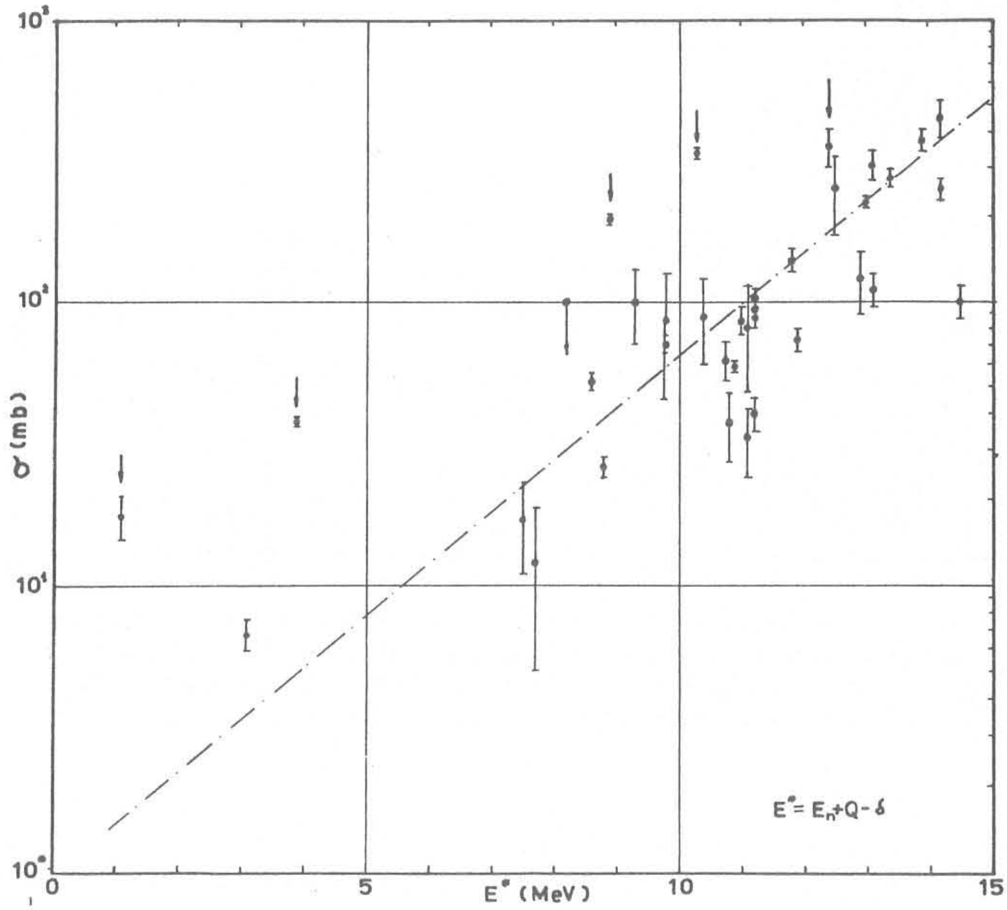

FIG. 2 - (n, p) cross sections vs, energy excitation E^{x} of the residual nucleus. Data are the same as fig. 1 a). The straight line was arbitrarily plotted as a mean trend. The points marked with arrows are connected with shell and sub-shell closures (see text).

into account the Coulomb barrier for the outgoing charged particles, by u sing, instead of E^* as given by equation (2), E^+ given by [13, 14]

$$E^+ = E_n + Q - \delta - kV \tag{3}$$

where k is a penetrability factor and V is given by

$$V = \frac{z Z e^2}{r_o A^{1/3}} \tag{4}$$

with r_o = 1. 5 fermi[o].

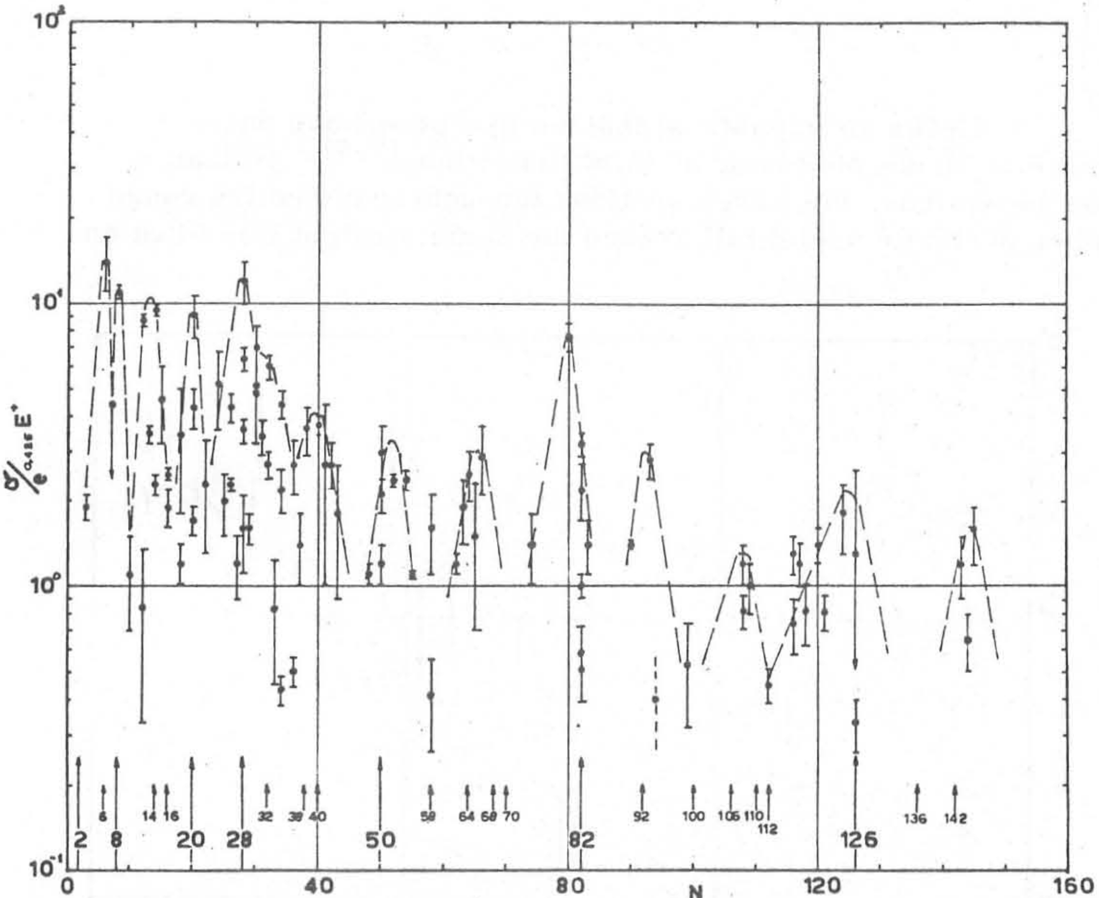

FIG. 3 - R = $\sigma(n, p)/e^{0.43E^+}$ (with $E^+ = E_n + Q - \delta - kV$) vs. neutron number N. The dotted curves are intended only as a guide for the eye. The arrows at the bottom indicate shell and sub-shell closures (Note that points at the same N refer to nuclides with different Z).

This is shown in Fig. 3 where the ratio R = $\sigma(n, p)/e^{0.43E^+}$ is plotted against the neutron number of the target nucleus. (Note that the Coulomb effect yields corrections greater than two orders of magnitude in the heaviest nuclei).

Apart from the very marked deviations, as high as a factor of ten for the lightest nuclei and systematically connected with shell or sub- -shell closure of the neutrons of the target nucleus, the points scatter around the straight line $\sigma(n,p)/e^{0.43\,E^{+}} = 1$, within a factor of two. Note that the points around the closed shells with same N, staying under the dotted curve, have different proton numbers.

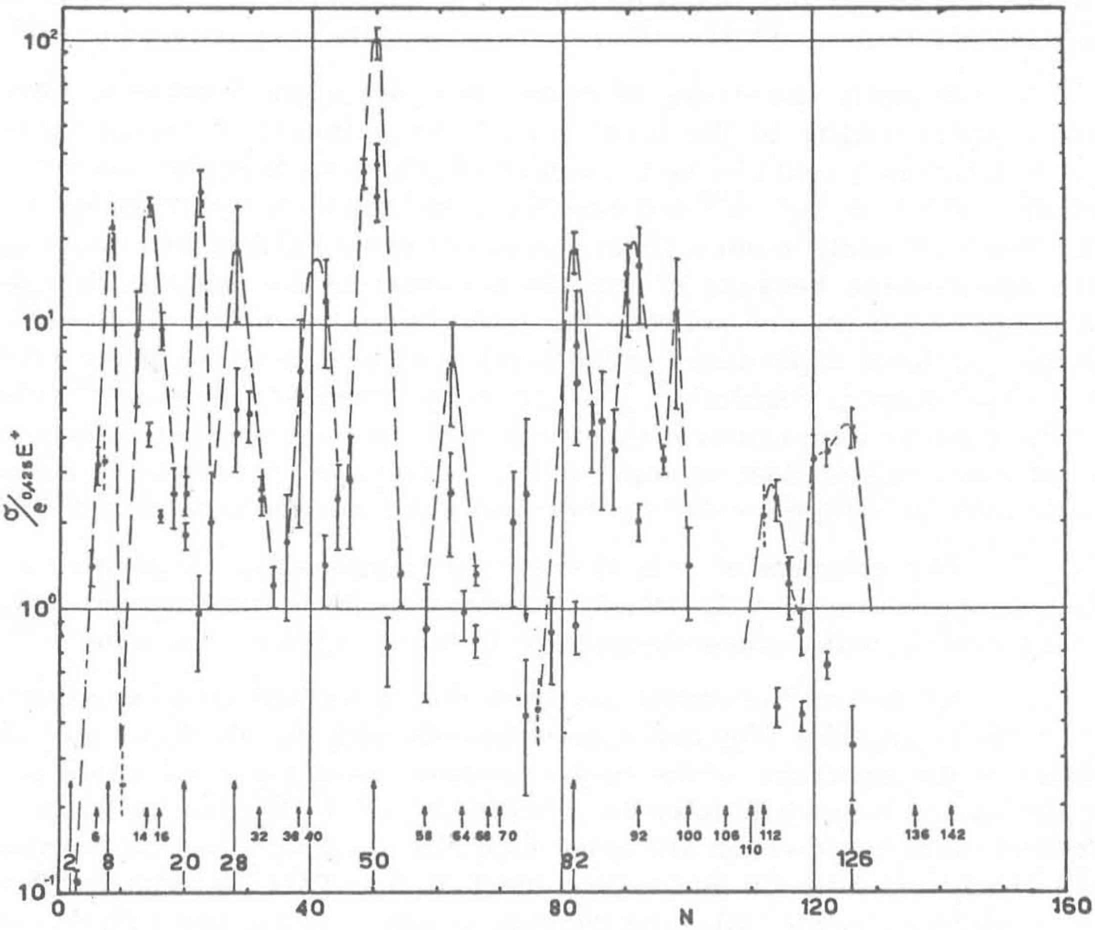

FIG. 4 - Same as fig. 3 for (n, α) reactions.

The same behaviour is found in (n, α) cross sections (Fig. 4) with stronger deviations (up to two orders of magnitude for the lightest nuclei) due to shell effects.

In this case the experimental cross sections used are taken from refs. (5, 6). The points displayed in the figure are simply the mean absolute deviations(15). The Coulomb correction was as large as four orders of magnitude for the heaviest nuclei(o).

No connection, with this analysis, is observed with proton shells; the minima for closed proton shells observed by Chatterjee (5, 6) are to attribute to Q-value effects, similar to those discussed for the (n, p) cross sections (Fig. 1) and they consequently disappear by performing the ratio $\sigma(n,\alpha)/e^{0.43\,E^{+}}$. The importance of these Q-value effects has been stressed in a recent paper(16).

The fact that (n, p) and (n, α) cross sections, apart from the observed deviations, are about proportional to the exponential of $0.43\,E^{+}$

is in agreement with the statistical assumption, which predicts that the cross section for a given reaction, when Coulomb corrections are taken into account as we did, must be roughly proportional to the level density of the residual nucleus[3,4] which in turn is roughly proportional to $e^{E^+/T}$.

Actually the cross sections may, for a given nucleus, deviate from proportionality to the level density by a factor of two or three in most cases, (as it could be seen by performing some calculations with the formulas given in ref. [13] and assuming that the main contribution to the total reaction width comes from the (n, n') reaction) but this would be of little significance because of the low accuracy of the experimental data, which can be considered reliable just within a factor of two or three[3, 5]. For the functional dependence of the level density it must be observed that many experimental results[17, 18] support the form $\omega(E) \propto e^{E/T}$ where T is the nuclear temperature; this form is not the one theoretically predicted by a model based on an unperturbed Fermi gas but it may be accounted for when pairing correlations between nucleons are considered[18, 19].

The constant of ~ 0.43, we find empirically, would give a nuclear temperature of ~ 2.3 MeV, constant in the entire range of A, in fair agreement with values obtained from other types of reactions[17].

As far as the deviations from the statistical trend are concerned, after noting that they are connected only with the shell and sub-shell closure of the neutrons of the target nucleus (when the shell effect due to the Q- values are eliminated by dividing by $e^{0.43\,E^+}$) one is tempted to attribute them to a mechanism other than the compound nucleus formation and namely to a direct interaction mechanism. This last statement may be supported by the following considerations: 1) the shell effects connected with the statistical model should lead to a depression of the cross section instead of an enhancement as we observe. This is proved by the well known trends observed in neutron capture at 1 MeV[20, 21] and by the minima in (n, α) cross sections at closed proton shells[5, 6]; 2) the few angular distributions measured as yet, of α-particles from (n, α) reactions at about 14 MeV, where these effects are most pronounced, are markedly forward-peaked in the case of

$$Mo_{50}^{92}\,(22);\ Pr_{82}^{141}\,(23);\ La_{82}^{139}\,(24);\ C_{6}^{12}\,(25);\ (n, \alpha) \text{ reactions, all}$$

with closed neutrons shells or sub-shells; conversely they are almost symmetric about 90° in the case of

$$Nb_{52}^{93}\,(23);\ Al_{14}^{27}\,(26);\ Co_{32}^{59}\,(26);\ Mn_{30}^{55}\,(27);\ As_{42}^{75}\,(27);\ \text{in these fi-}$$

ve cases the total (n, α) cross sections stay about on the empirical straight line $\log \sigma = 0.43\,E^+$.

The only striking discrepancy, known to us, seems the case of Ca_{20}^{40} (n, α) where is observed an angular distribution symmetric about

90° but strongly anisotropic[28]. Unfortunately the total (n, α) cross section is not known in this case for a comparison. But at this point it should be reminded that an angular distribution symmetric about 90° might be obtained also for a direct process when one considers the possibility of the heavy-ion pick-up[25,29]. More data are, of course, needed in order to clarify all these questions.

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FOOTNOTES AND REFERENCES

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(x) - Q values are from the compilation of Ashby and Catron[10] or from Tables of Everling et al. [11]. δ pairing corrections are taken from Cameron[12].

(o) - Values of k for protons and α-particles have been taken from ref. (13). In the case of (n, α) reactions the denominator of (4) was (r_0 $A^{1/3}$ + ρ) with values of r_0 and ρ of 1. 5 and 1. 2 fermi respectively[13].

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