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EMISSION OF ALPHA PARTICLES IN REACTIONS INDUCED BY MEDIUM ENERGY NUCLEONS

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The mechanism of the emission of alpha particles resulting from the bombardment of nuclei with medium energy nucleons was considered in view of some recent results on (n, α) and (p, α) reactions. It was found that in the region of heavy nuclei ($A > 100$) strong evidence exists for the preponderance of knock- out processes involving the transfer of an alpha particle and the simultaneous capture of a nucleon in a single particle state. The situation is less clear in the medium mass region ($20 < A < 100$). In particular, for nuclei in the neighbourhood of the $f_{7/2}$ shell, (p, α) reactions show features similar to one nucleon transfer reactions. This implies a pick-up type process, where a single proton and a pair of neutrons are captured by the incident proton to form an alpha particle. No definite conclusions are possible at the moment for very light nuclei ($A < 20$). Arguments suggesting the knock-out process can, however, be found.

1. *Introduction*

The theoretical interest in the study of (n, α) and (p, α) reactions on heavy nuclei is connected to the mechanism of direct processes, nuclear surface investigation, *etc.* A number of experiments has been performed to identify the mechanism of (n, α) reactions at 14 MeV. The experimental data indicate that the reaction mechanism is correlated to the mass number of the target nucleus.

Fast neutron induced (n, α) reactions on light elements ($A < 30$) show salient features of a direct process. The forward peaked angular distributions have been fitted equally well either by pick-up or by knock-out mechanisms, but there is evidence in favour of knock-out processes [1]. Nevertheless, the observed variations in the excitation function of these reactions can be hardly accounted for by a direct process [2].

In the region of medium weight nuclei ($30 < A < 90$), most of the experimental results might be interpreted in terms of the compound nucleus model [1].

The analysis of the experimental data on (n, α) reactions in the mass region $A > 100$ shows that alpha particles are emitted mainly through a direct mechanism. The shape of

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the spectra and angular distributions in this mass region give clear evidence for direct surface processes [1]. The available data on (p, α) reactions support these statements [3].

The direct (n, α) and (p, α) reaction mechanism can in general be pictured as either a pick-up of a three nucleon cluster or a knock-out of an alpha particle cluster. It would intuitively appear more probable that alpha particle clusters, due to their higher stability, more frequently occur on the surface of heavy nuclei than ^{3}He or ^{3}H clusters. This argument would tend to favour the knock-out rather than the pick-up process. Extremely simple pictures based on the surface knock-out process assumption have yielded reasonable results concerning the cluster structure of heavy nuclei [4], [5]. It is, however, obvious that further evidence is needed for a clear distinction of these two direct surface processes.

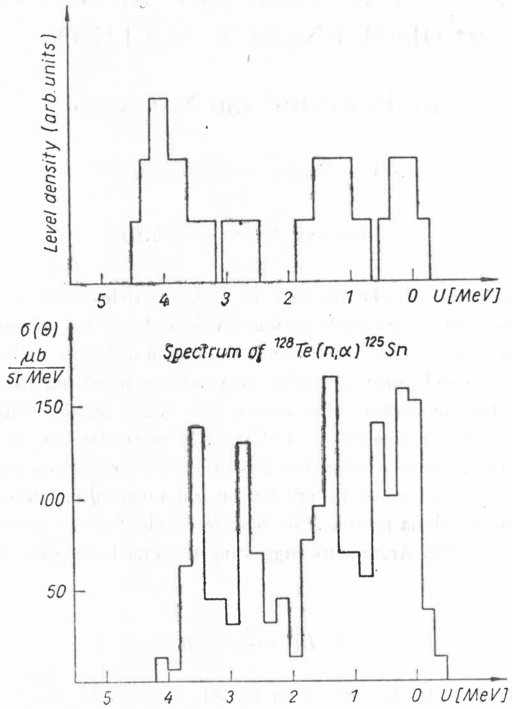

Fig. 1. The energy spectrum of alpha particles from 14 MeV neutrons incident on ^{128}Te, (upper diagram), compared with the single neutron level density of the residual ^{125}Sn nucleus (lower diagram) (Ref. [9])

2. *A survey of experimental evidence and discussion*

A. Heavy nuclei

A number of (n, α) reactions in the $A > 100$ region has been studied at 14 MeV [1], [5–9]. A common feature of these data is that all angular distributions show a strong forward peaking and, furthermore, it is not possible to fit the energy spectra with the evaporation theory. Jaskola *et al.* [6] noticed a similarity in the structure between the ^{159}Tb (n, α) ^{156}Eu spectrum and the single neutron level density of ^{156}Eu. To explain this, it was assumed that the knock-out mechanism proceeding by the transfer of an alpha cluster from the surface necessarily implies the capture of a neutron by the remaining core which is usually unperturbed. Accordingly, the alpha energy spectrum should predominantly show the excitation of the single neutron states in the final nucleus. Of course, it is reasonable to expect the same mechanism for (p, α) as for (n, α) reactions in the corresponding energy and mass regions.

Structure in the energy spectra of the emitted alpha particles has indeed been observed in a number of (p, α) and (n, α) measurements carried out by several groups. These investigations indicate that (n, α) or (p, α) reactions show features similar to the one-nucleon transfer. The one particle transfer aspects of these reactions may be understood qualitatively in terms of *a*) an alpha particle transfer from the nuclear surface and the capture of the incoming nucleons by the core, and *b*) a pick-up of two paired nucleons connecting the 0^+ ground states, while the odd nucleon determines the cross-section.

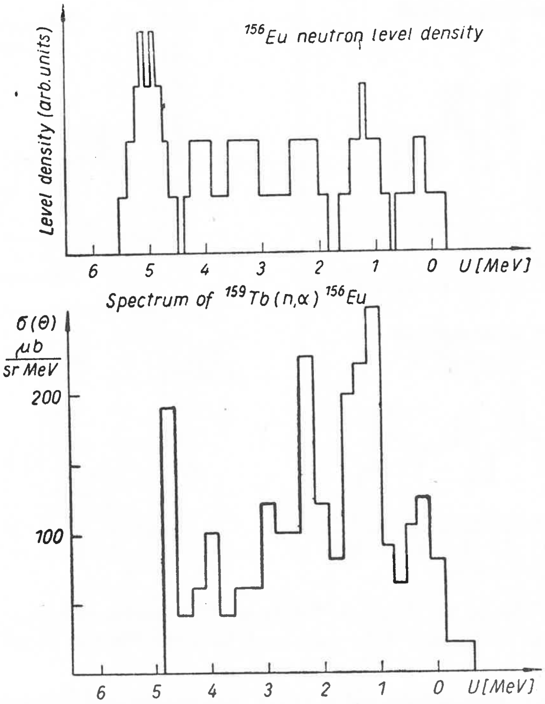

Fig. 2. Comparison of the ^{159}Tb (n, α) ^{156}Eu spectrum to the ^{156}Eu neutron level density calculated from the Nilsson model

In the former case the single particle states, and in the latter the single hole states, are expected to be excited with high yield; other levels may also be formed, but a smaller yield is expected. Thus, the energy spectra will show a predominantly single particle structure in the case of a knock-out mechanism, and a single hole structure in the case of a pick-up mechanism.

Experimental single particle and single hole level densities can be obtained from the appropriate stripping and pick-up reactions, or calculated from nuclear models (*e.g.* the Nilsson model).

The comparison of the single neutron level density of the residual Sn nucleus with the corresponding measured ^{128}Te$(n, \alpha)^{125}$Sn spectrum is shown in Fig. 1; the single neutron level density was calculated under the assumption that the states strongly excited in (d, p) reactions [10], [11] are single neutron states, and that all the states are excited with equal probability. The level density was then smeared out to correspond to the energy resolution of the (n, α) experiment. The agreement is fairly reasonable and it is more or less reproduced for (n, α) reactions and several other Te isotopes ($^{124, 125, 126}$Te) [9].

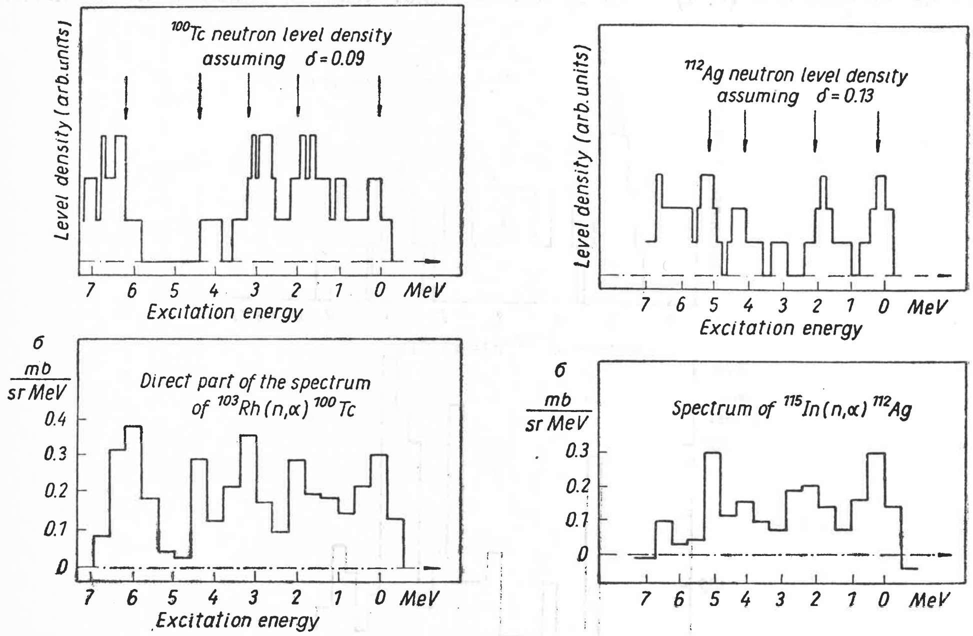

Fig. 3. Comparison of the ^{115}In (n, α) ^{112}Ag and ^{103}Rh(n, α) ^{100}Tc spectra with the corresponding neutron level densities od ^{112}Ag and ^{100}Tc, calculated from the Nilsson model (Ref. [7])

Figure 2 shows a comparison of the ^{159}Tb$(n, \alpha)^{156}$Eu spectrum with the smeared out neutron level density calculated from the Nilsson model [12], using a deformation parameter $\delta = 0.29$. This comparison was carried out for other nuclei, too.

Figure 3 shows the comparison between the ^{115}In$(n, \alpha)^{112}$Ag and ^{103}Rh(n, α) ^{100}Tc reactions and the corresponding calculated level densities of ^{112}Ag and ^{100}Tc [7]. While in the first example some gross agreement between the peaks of the two diagrams can be found, no such correspondence is visible in the latter case. Now, an explanation of this absence of correspondence could be found by taking into account the compound nucleus smearing present in the $A \approx 100$ mass region.

An example that deserves particular attention is the comparison of the ^{93}Nb(n, α) ^{90}Y zero degree spectrum with the levels in ^{90}Y excited by (d, p) on ^{89}Y (Fig. 4). There, the

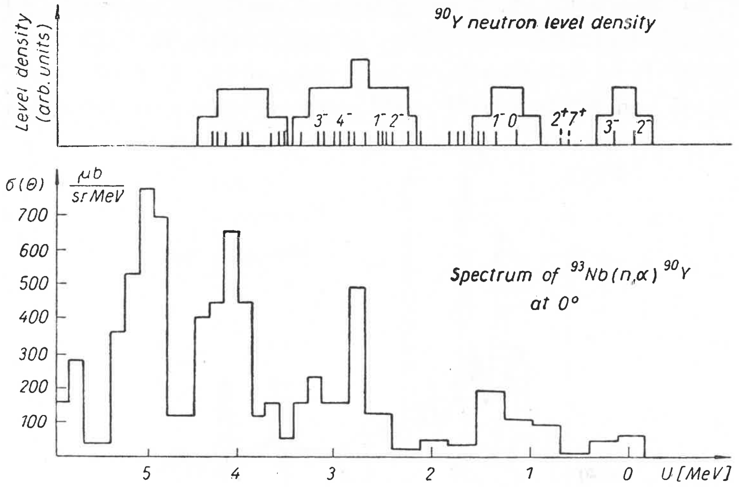

Fig. 4. The ^{93}Nb(n, α) ^{90}Y 0° — spectrum with the levels in ^{90}Y excited by the (d, p) reaction on ^{89}Y

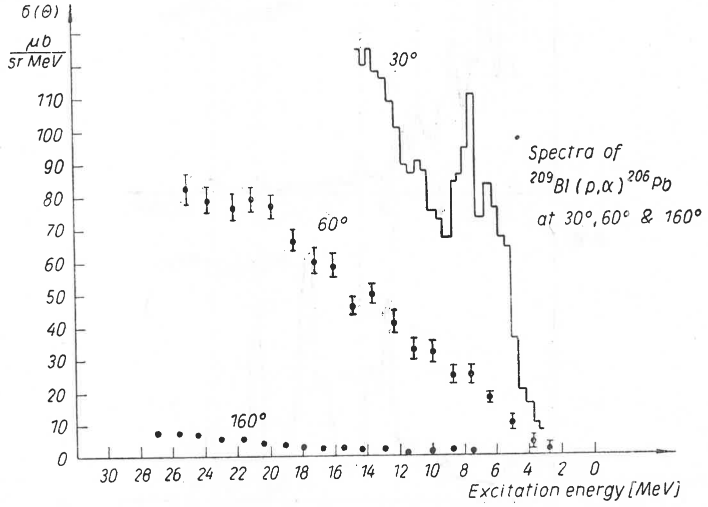

Fig. 5. The ^{209}Bi (p, α) ^{206}Pb spectra at 30°, 60° and 160° (Courtesy of W. Falk *et al.*, The University of Manitoba, Winnipeg, Canada)

correspondence is again striking. In fact, if we keep in mind our simple knock-out picture, this should be expected. ^{90}Y is a particularly simple nucleus, with one proton and one neutron outside a semiclosed core (^{88}Sr). Hence, the clarity of the single particle aspects was not blurred out.

An important point to stress is that in the comparison of (n, α) spectra with *calculated* level densities the best agreement was found for those values of δ which were known from other experiments or expected from the systematics of neighbouring nuclei.

There are too few (p, α) measurements on heavy nuclei to draw definite conclusions. Figure 5 shows the energy spectra of alpha particles from 40 MeV proton bombardment of ^{209}Bi at 30°, 60° and 160° [13]. A strong forward peaking is observed. If the spectrum at 160° is assumed to be mainly due to the evaporation process, then the compound nucleus contribution appears to be rather small. Figure 6 compares (p, α) results on ^{209}Bi with the ^{205}Tl(α, t) ^{206}Pb[14] and ^{208}Pb$(p, t)^{206}$Pb [15] reactions leading to the same final nucleus.

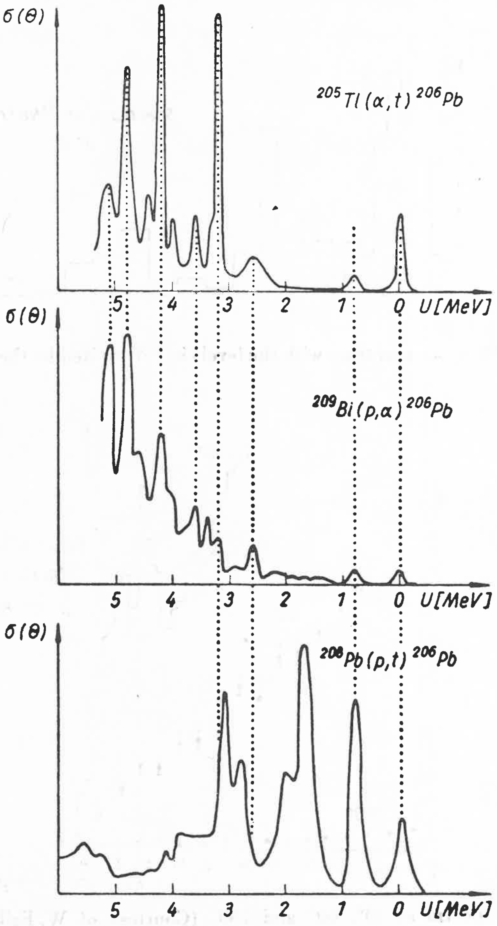

Fig. 6. The energy spectrum of alpha particles from 40 MeV protons incident on ^{209}Bi, compared with the ^{205}Tl (α, t) ^{206}Pb (Ref. [14]) and ^{208}Pb (p, t) ^{206}Pb (Ref. [15]) spectra

The similarity of the (p, α) and (α, t) spectra, namely, the strong excitation of single proton states, favours the knock-out hypothesis for (p, α) reactions. Moreover, there is little similarity between the (p, t) and the (p, α) spectra except for the first two peaks which correspond to the excitation of the ground state and the 2^+ collective state of the final (lead) nucleus.

The relatively large experimental (p, α) cross-sections and also the larger (p, α) cross-section to the low-lying states for even proton nuclei lend further support to the interpretation of these reactions as a knock-out process.

B. Medium weight nuclei

As mentioned before, in the mass region $20 < A < 100$ the compound nucleus is the prevailing mechanism for (n, α) reactions at 14 MeV. Hence, we shall consider here only (p, α) reactions at higher energies (17.5 and 40 MeV).

The investigations of medium weight nuclei by Nolen [16] and by the Manitoba group [17] indicate that (p, α) reactions show aspects similar to one nucleon transfer.

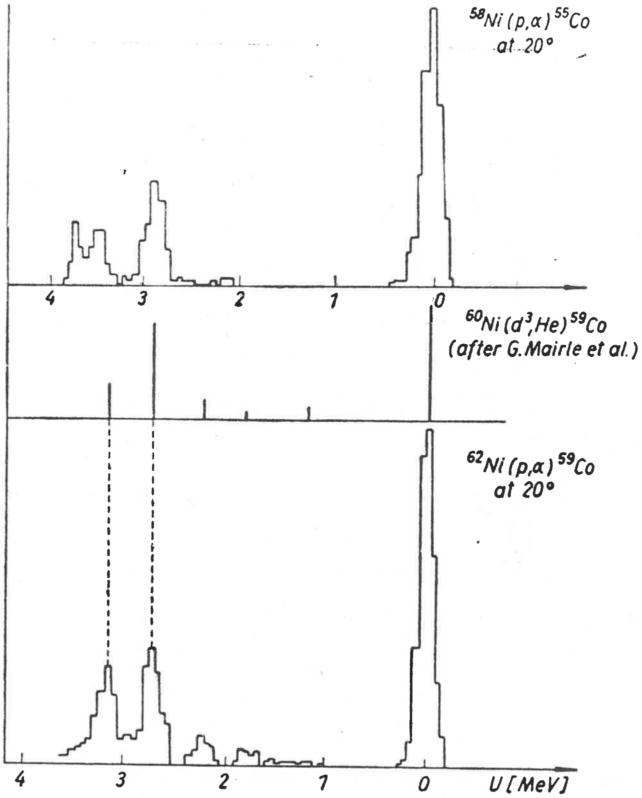

Fig. 7. Alpha particle spectra from 40 MeV protons incident on ^{56}Ni and ^{62}Ni (Ref. [17]), compared with the ^{62}Ni $(d, {}^3$He$)$ ^{59}Co results (Ref. [18])

Figure 7 compares a spectrum from the ^{62}Ni$(p, \alpha)^{59}$Co reaction to a ^{60}Ni$(d, {}^3$He$)^{59}$Co spectrum taken from Ref. [18]. Both spectra are dominated by transitions to the ground state and two states at around 3 MeV excitation. The angular distributions indicate that the $2s_{1/2}$ and $d_{3/2}$ hole states at 2.72 and 3.16 MeV, respectively, are strongly excited in both reactions. Likewise, it has been found that also for the ^{56}Fe, ^{58}Ni, ^{60}Ni, ^{63}Cu and ^{65}Cu target nuclei hole states are prominent in the energy spectra. This fact is easily interpreted by assuming that the (p, α) reaction proceeds *via* a pick-up of a neutron pair and a proton from a shell model state, or, in the cluster language, of an ^{3}H structure. The comparison of the ^{58}Ni$(p, \alpha)^{55}$Co and ^{62}Ni$(p, \alpha)^{59}$Co spectra strikingly illustrates this point. The similarity of the two spectra resulting from the proton bombardment of target nuclei differing by as much as four neutrons (and, of course, their similarity with the ^{60}Ni(d, ^{3}He)^{59}Co spectrum) is an impressing confirmation of the single proton transfer character of this process. Moreover, it should be noted that the energies of the $2s_{1/2}$ and $d_{3/2}$ hole states have in fact been determined for the ^{55}Co and ^{56}Fe nuclei by means of the [p, α) reaction [17]. Since these nuclei are not accessible by the usual proton pick-up reactions, the (p, α) reactions thus offer a unique method for investigating proton hole states in these nuclei.

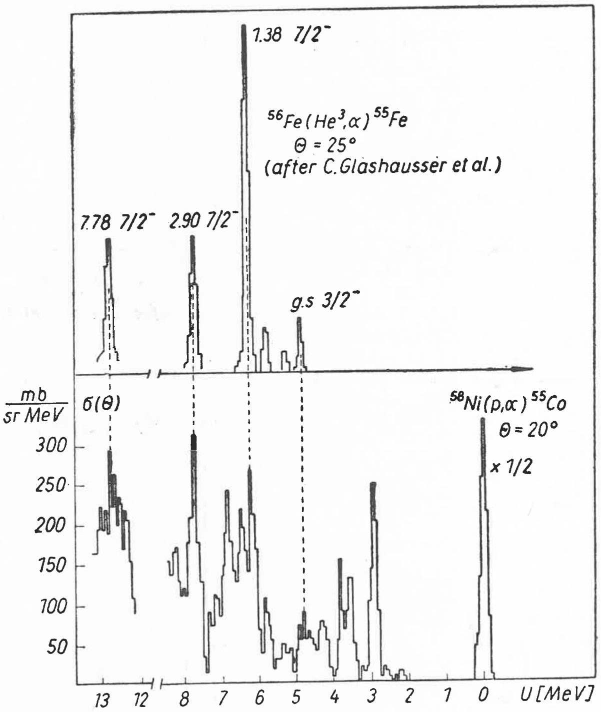

Fig. 8. Comparison of the ^{58}Ni (p, α) ^{55}Co spectrum with neutron pick-up reactions. $E_p = 40$ MeV (Ref. [17])

A further argument supporting the pick-up mechanism is that the $T_>$ part of (p, α) spectra was found to be very similar to the analogue neutron pick-up spectra. Figure 8 shows that in the ^{58}Ni(p, α)^{55}Co reaction the states analogous to neutron holes in the analogue residual ^{55}Fe nucleus are indeed strongly excited.

This fact needs careful considering. A schematic picture of the ^{55}Fe ground state configuration and its analogue in ^{55}Co is shown in Fig. 9. A neutron pick-up experiment on, say, ^{56}Fe ($N = 30$, $Z = 26$) would excite neutron states in ^{55}Fe starting with the $p_{3/2}$ ground state (left hand side of Fig. 9). The analogue of this state in ^{55}Co is a $p_{3/2}$ state (right hand side of Fig. 9) which is known to be at 4.8 MeV excitation energy.

Proton pick-up experiments on, say, ^{56}Ni would in principle excite a series of *proton* hole states in ^{55}Co analogues to *neutron* hole states in ^{55}Fe. The fact that the ^{58}Ni(p, α)^{55}Co reaction excites states in ^{55}Co analogues to single hole states in ^{55}Fe supports the idea that this reaction proceeds *via* a single proton plus two paired neutron pick-up (compare the lower and upper parts of Fig. 8).

Figure 8 shows equally that other levels strongly excited in the ^{58}Ni$(p, \alpha)^{55}$Co reaction are also hole levels: the $f_{7/2}^{-1}$ ground state and the 2.9 and 3.55 MeV levels known as $s_{1/2}^{-1}$ and $d_{3/2}^{-1}$ configurations, respectively.

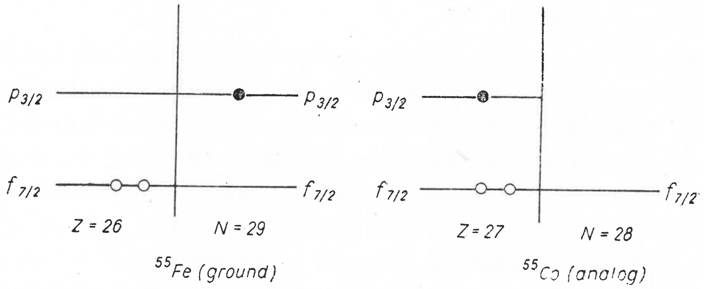

Fig. 9. Shell-model schematic picture of the ^{55}Fe ground state configuration and its analogue in ^{55}Co

The results on Mo(p, α)Nb and Nb(p, α) Zr reactions further support the pick-up assumption. The very weak excitation of single particle states in these reactions would not be expected in the knock-out process [19].

C. Light nuclei

Although in this mass region ($A < 20$) the general belief is that the knock-out process dominates, we feel that this is generally true only of alpha particle nuclei such as ^{12}C or ^{16}O. The overall understanding of these phenomena is far from being satisfactory, especially in view of recent results [2], and will be the object of a separate study.

3. *Conclusion*

The mechanism of alpha emission from medium energy nucleon bombardment of *heavy* nuclei now seems to be fairly well established. The assumption of a direct knock-out process based on an alpha-cluster transfer and the placing of a nucleon into single particle orbits seems to account at least qualitatively for all the cases studied. It is clear that this picture is too crude to account for all details. Furthermore, numerical calculations are still lacking. An attempt to calculate the alpha clustering probability from (n, α) and (p, α) reactions was made by Chatterjee and Jurčević [20]. This attempt is essentially based on the DWBA version of Bassel *et al.* [21], and it gives a possibility of determining the spectroscopic factor of the (core plus alpha) configuration of the target as compared with that of the (core plus nucleon) configuration. The latter is easily determined from stripping reactions.

No calculations, however, have been performed so far with this model. It would be interesting to compare the spectroscopic factor for the (core plus alpha) configurations with those obtained from high energy data.

Now let us turn to the medium mass region $A < 100$; there the situation appears to be less clear. First of all, the 14 MeV (n, α) data are useless due to the predominance of the compound nucleus. Thus, we are left with (p, α) reactions only. The similarity of (p, α) reactions with proton pick-up processes and, in particular, the striking regularity of the $T_>$ states observed in the ^{58}Ni$(p, \alpha)^{55}$Co reaction, strongly supports the pick-up mechanism. At least in the $f_{7/2}$ shell nuclei it appears that the alpha particle is created by the pick-up of a proton coupled to two paired spectator neutrons. Why this sudden change in the mechanism? And, is it so sudden?

The present data do not allow a unique answer to these questions. Extensive and reliable data exist only for nuclei in the vicinity of the $f_{7/2}$ shell. Of the considered target nuclei, ^{50}Fe, ^{60}Ni, ^{63}Cu would have filled neutron orbitals in a simple shell model picture. A more realistic pairing calculation would probably yield large values for the occupation numbers of a neutron pair *out* of a closed shell (or subshell). This is even more likely in ^{65}Cu. Thus, in these nuclei a (p, α) reaction may very easily proceed *via* a pick-up of a neutron pair. However, it is not clear whether the apparent preponderance of the pick-up mechanism for nuclei in the $A < 100$ mass region is a local structure effect related to the peculiarity of the $f_{7/2}$ neighbourhood, or to a more general phenomenon.

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