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NUCLEON BINDING IN NUCLEI AT HIGH ANGULAR MOMENTUM

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Neutron and proton binding energies in nuclei are calculated as functions of angular momentum employing the method of sloping Fermi surface and the deformed Woods–Saxon potential.

One of the principal questions concerning the behaviour of atomic nuclei in the presence of very large angular momenta is the estimate of the nuclear instability in the new region. Cohen, Plasil and Swiatecki [1] analysed the possibility of fission in nuclei which rotate very fast; their considerations were based on the model of a rotating liquid drop. However the influence of the nuclear shell structure on the instability, as well as on the other properties of spinning nuclei may be also important [2–7]. A fast rotating nucleus may get rid of its energy and angular momentum by emitting particles [8, 9]. The instability with respect to particle emission should be relatively more important in light nuclei.

This note aims at performing a preliminary estimate of the dependence of nucleon binding on angular momentum I; the limiting values, I_e, for the emission of a nucleon from rotating nuclei, are also studied. The calculation is entirely based on the ideas and methods of ref. [4] (see also ref. [10]). In order to keep track of the bound and unbound orbits we have employed the deformed Woods–Saxon potential as a basis for the calculation of the single particle configurations (parameters of the Woods–Saxon potential have been described in ref. [11]; for the method of including the deformation in the potential see also ref. [12]) instead of the modified harmonic oscillator potential [4].

We have also limited ourselves to nearly spherical and oblate, axially symmetric nuclear shapes, as in the case of the yrast traps calculations [10, 13, 14]. In this case the method of "sloping Fermi surface" [15] in the plot of the single particle energies e_ν as functions of the corresponding projections m_ν of their angular momentum proves to be very useful [4, 10]. The occupied states are represented in such a plot as the points lying below a tilted straight line, the position and slope of which are defined by the number of particles and angular velocity of rotation, ω.

The states obtained with this method are called "optimal". Other states, lying between the optimal states are reached by creating particle-hole excitations as described in refs. [4, 10]. In all the cases minimization with respect to deformation is performed.

It is rather easy to determine the highest occupied orbit for each angular momentum employing such representation. The energy of the least bound particle for each angular momentum I, obtained in this way, is closely related to the proton or neutron separation energy at angular momentum I. Obviously, this energy treated as a function of I decreases with increasing I, and may become zero at certain critical value $I = I_e$ corresponding to particle instability.

Fig. 1 illustrates our calculation in the case of protons at the deformation $\beta = -0.16$ for the Woods–Saxon potential parameters corresponding to $A = 66$. Owing to the well pronounced gaps in the single particle spectrum at $Z = 34$ and $Z = 38$ (the latter corresponding to filling of the orbits of the $(2p_{3/2})$ and $(1f_{5/2})$ multiplets) extending over the relatively large deformation region, as seen in the bottom part in fig. 1, the zero energy states are reached by the sloping

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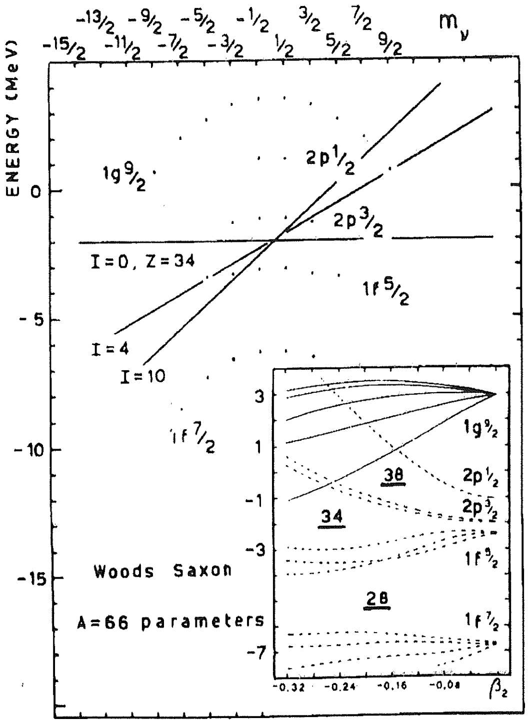

Fig. 1. Proton single particle energies (black dots) versus single particle angular momentum projection m_ν at $\beta_2 = -0.16$ deformation. The sloped Fermi surface for $I = 10$ indicates the energy of the first unbound state of the proton, the $m_\nu = 9/2$ member of $1g_{9/2}$ multiplet. The right-hand side at the bottom of the figure illustrates single particle energies plotted versus deformation ranging from $\beta_2 = -0.32$ to $\beta_2 = 0.0$. The well pronounced gaps corresponding to $Z = 34$ and $Z = 38$ extending over a large deformation region deserve notice.

Fermi surface at a rather low spin of the protons (e.g. $I_{prot,e} = 10$ for $Z = 34$ or $I_{prot,e} = 6$ for $Z = 38$). In order to obtain the total spin value one has to add the corresponding proton and neutron contributions, $I = I_{prot} + I_{neut}$, with I_{neut} obtained in similar way.

Fig. 2 illustrates the energy of the least bound proton as a function of angular momentum I for several nucleides. One can see that the binding energies decrease with angular momentum as expected. However, the decrease is not smooth, and jumps in the curves reflect the single particle nature of the effect. One can see that the proton emission channel does not open below $I = 40$ in heavy nuclides (cf. ^{150}Gd), or medium heavy ones (cf. ^{122}Xe). For lighter nuclei the limit is much lower as it can be seen from the plot for ^{66}Ge, or ^{40}Ca. It should be noted however, that in light nuclei some other particle decay channels, such as

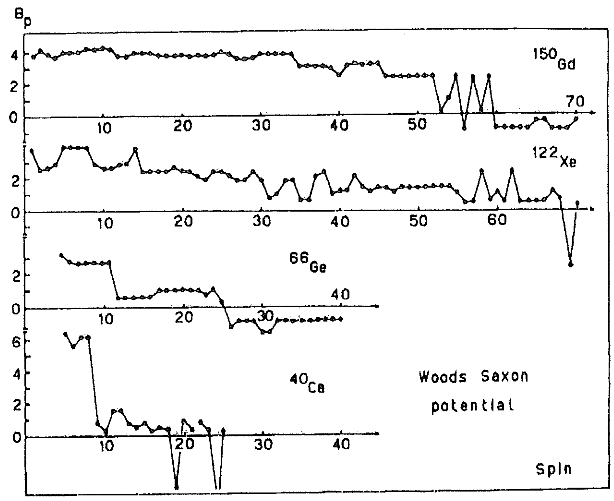

Fig. 2. Binding energies of the last proton are plotted as functions of the total angular momentum for the nuclei ^{150}Gd, ^{122}Xe, ^{66}Ge and ^{40}Ca. The irregular dependence of I_e on the mass number A, reflecting the single particle nature of the effect, can easily be inferred by comparing the curves for ^{150}Gd and ^{122}Xe with those in the bottom of the figure.

alpha decay, may become predominant.

Fig. 3 illustrates the same plot for neutrons, but the energies are considerably higher in this case. This follows from the fact that mostly neutron deficient nuclei are considered here and, actually, only ^{40}Ca shows the possibility of a neutron emission below $I = 40$.

The results for the limiting angular moment I_e for the particle emission are collected in table 1. For comparison also the critical angular momenta for the fission channel are given. One can see that I_e for the proton emission is lower than the corresponding fission limit I_f. The difference is especially well pronounced in light nuclei.

A comment should also be made on the uncertainties in our estimates resulting from the uncertainties in the single particle potential parameters. It has been checked by a straightforward calculation that variation of the Woods–Saxon potential parameters (e.g. replacing those of Rost by the parameters of Blomqvist and Wahlborn) results in variation of I_e within few spin units for lighter nuclei; the difference may, however, be greater for heavier nuclei and thus the improved parameters of ref. [11] were used for ^{122}Xe and ^{152}Dy nuclei.

We want to emphasize that only the binding energies of protons and neutrons in high spin nuclei were calcu-

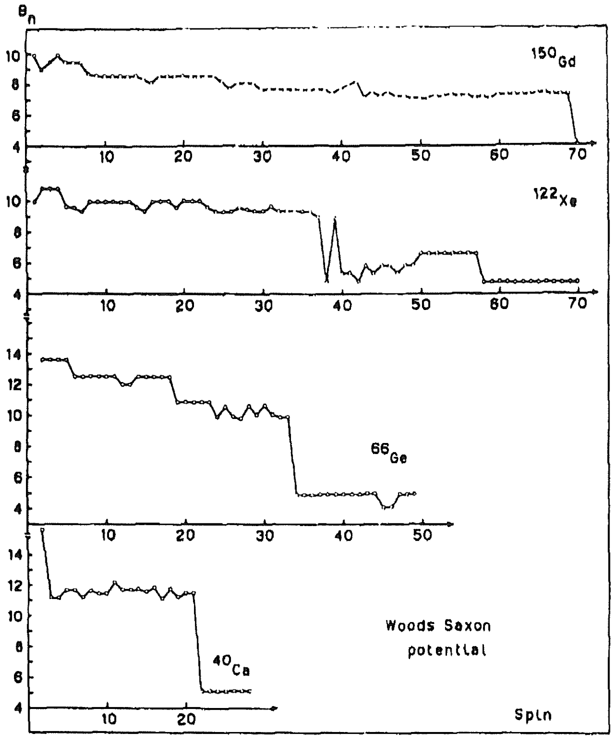

Fig. 3. The same as in fig. 2 but for neutrons.

lated in this paper. It does not mean, of course, that at zero binding the particle would be emitted freely. In fact, the existence of the centrifugal and Coulomb barriers will delay the emission. These effects have not been considered in this note.

We can conclude that the binding energies of neutrons and protons are decreasing functions of angular momentum. The decrease is not smooth and looks rather as a step function. Protons have much lower binding than neutrons in the considered neutron deficient nuclei and the fission limit seems to come between the binding limits for protons and neutrons.

The authors are deeply indebted to Professor B. Mottelson for suggesting this problem and to him, as well as to Professor A. Bohr for many illuminating discussions.

Table 1

Spins $I_{e,prot}$ and $I_{e,neut}$, corresponding to the first unbound single particle state (along the yrast line) are compared with the fission limit predicted on the base of the classical-liquid-drop model estimates of ref. [1].

Nucleus	$I_{e,prot}$	$I_{e,neut}$	I_f
^{40}Ca	19	> 30	39
^{66}Ge	26	> 50	61
^{122}Xe	69	> 70	89
^{150}Gd	56	> 70	88

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