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Alpha-preformation in even-even alpha emitters: An alpha-decay without tunnelling approach

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Abstract. An 'alpha-decay without tunnelling' approach shows that alpha-preformation probability in trans-lead even-even alpha-emitters lies in the range of 0·17–0·08, indicating a clear shell-closure effect at $N = 126$ and exhibits appreciably enhanced values in open-shell nuclei and executes a zig-zag nature with increasing neutron number in an isotopic series. All these findings are in fair qualitative agreement with experimental observations. Experimental results are found to overestimate this parameter for these heavy deformed nuclei.

Keywords. α-preformation probability; shell-closure effect; open-shell nuclei; zig-zag nature.

1. Introduction

Knowledge of α-preformation is basic to the understanding of the problems of natural α-decay as well as α-pick-up and α-transfer reactions; hence the great interest in α-preformation. Study of α-preformation probability is almost as old as α-decay itself. Until recently there existed only a very confusing idea about its magnitude and order of magnitude in different nuclei. A clear picture started evolving only with the experimental α-preformation probability determinations $P_{\alpha\,(\mathrm{expt})}$ during the last four years (Braga *et al* 1973; Colli and Marcazzan 1972, 1973; Colli *et al* 1974, 1975; Chevarier *et al* 1975). But as pointed out by the present author (Basu 1976) in a recent study along the 'α-decay without tunnelling' (ADWT) line, there is much room for improving the accuracy of $P_{\alpha\,(\mathrm{expt})}$ values. The ADWT approach to α-preformation in which an empirical expression was introduced for the absolute α-preformation probability was found to provide a reliable and accurate method for its evaluations in even-even nuclei and to predict all possible shell and sub-shell closure effect on α-preformation probability. Shell-closure effect on P_α at $N = 126$ has, in fact, been recently confirmed by Colli *et al* (1975) in a fresh set of $P_{\alpha\,(\mathrm{expt})}$ values which, moreover, exhibit comparatively enhanced values of P_α in open-shell nuclei far from a shell-closure. P_α evaluations for even-even α-emitters by Bonetti and Colli (1974) on the basis of Weisskopf's statistical model of α-decay $P_{\alpha\,(\mathrm{stat})}$ also conform qualitatively to Colli *et al*'s observations. It is, indeed, these latest findings by Colli *et al* together with the work by Bonetti and Colli which provide a fresh background for reinvestigation of α-preformation probability in the region of naturally α-active nuclei along the ADWT line. Confined to only trans-lead even-even α-emitters, the present investigation will be devoted mainly to a critical survey of $P_{\alpha\ (\mathrm{expt})}$ and $P_{\alpha\ (\mathrm{stat})}$ values relative to preformation probability $P_{\alpha\ (\mathrm{emp})}$ calculated from the ADWT approach.

2. Theory

The empirical expression for α-preformation probability of even-even nuclei in the 'α-decay without tunnelling' picture (Basu 1974) is given by

$$P_{\alpha\ (\mathrm{emp})} = E^{\alpha}_{\mathrm{Cl}}/B(\alpha) \tag{1}$$

where E^{α}_{Cl} = effective clustering energy of the last $2n$-$2p$ system inside the parent nucleus; and $B(\alpha)$ = binding energy of a free α-particle.

The last two neutrons and the last two protons in the highest orbits of the nucleus have been found to be the definite constituents of the emitted α-particle (Basu 1974; Basu and Sen 1975). This lends validity to expression (1) and also lends credence to Wilkinson's (1961) hypothesis that the low-density nuclear surface abounds in α-clusters. The surface nucleons which are feebly subject to the Pauli exclusion principle because of the low density, are very much prone to α-clustering.

P_{α} in eq. (1) admits of a very easy evaluation in that E^{α}_{Cl} in it can be easily computed from the mass-relation due to Basu (1972) with the help of the latest mass-data (Wapstra and Gove 1971). The accuracy o f $P_{\mathrm{mp)}}$ in turn entirely depends on the accuracy of the mass-data. In respect of accuracy, the present ADWT method has a definite superiority over the other two methods, *viz*., Weisskopf's statistical model of α-decay and the pre-equilibrium analysis of reaction cross-sections. The accuracy of P_{α} determined from the latter two methods suffers in two ways: (1) inaccuracy of the experimental input-data (life-time data in the statistical model and reaction cross-section data in the pre-equilibrium model), and (2) vagaries and inherent limitations of the theoretical models (*viz*. choice of the value of the single-particle level-density and transmission coefficient calculation in the statistical model; choice of the two-body matrix-element in the pre-equilibrium model). A close scrutiny of the present expression reveals that though it is obtained in the 'α-decay without tunnelling' picture, yet in the last analysis, it is clearly model-independent. This is a very desirable feature as α-preformation is a typical configuration of the last $2n$-$2p$ system of the ground-state parent nucleus prior to α-emission and as such its probability should be independent of the mode and hence model of α-emission. Satisfaction of this essential criterion of model-independence by expression (1) makes it naturally more reliable and accurate than the other two methods. $P_{\alpha\ (\mathrm{expt})}$ and $P_{\alpha\ (\mathrm{stat})}$ are obviously not at all free from the inaccuracies mentioned already.

3. Results and discussion

α-preformation probability computed from expression (1) for almost all the trans-lead even-even α-emitters *vs* neutron-number N are plotted in figure 1. The values lie in the range of 0·17–0·08 and are as low as 0·08 at the shell-closure and as high as 0·17 in the open-shell. A comparative study between the present set of values and $P_{\alpha\,(\mathrm{expt})}$ values is unfortunately not possible because of the lack of values of the latter in this region of nuclei. $P_{\alpha\,(\mathrm{expt})}$ values due to Colli *et al* (1975) are, however, below 0·1 at the shell-closure region and are in good agreement with the corresponding $P_{\alpha\,(\mathrm{emp})}$ values but are as high as 0·35 (^{228}Th) in open-shell nuclei almost twice the corresponding $P_{\alpha\,(\mathrm{emp})}$ values. This discrepancy, as emphasized in this paper and elsewhere (Basu 1976), is due to the error in $P_{\alpha\,(\mathrm{expt})}$ values which are obtained by treating the α-preformation probability as a freely adjustable parameter in the α-preformed pre-equilibrium model of reactions and as a consequence, absorb the inaccuracy of the input data and the vagaries of the theoretical model. $P_{\alpha\,(\mathrm{emp})}$ values are, on the contrary, free from such errors as pointed out earlier.

An extensive set of α-preformation values for these nuclei are due to Bonetti and Colli (1974) on the basis of Weisskopf's statistical model of α-decay. These values lie in the range of $\approx$ 1·0–0·01. At shell-closure $P_{\alpha\,(\mathrm{stat})}$ is fairly in agreement with the corresponding values of $P_{\alpha\,(\mathrm{emp})}$ and $P_{\alpha\,(\mathrm{expt})}$; but in the open-shell nuclei it is many times off $P_{\alpha\,(\mathrm{emp})}$ and $P_{\alpha\,(\mathrm{expt})}$, and is, therefore, a gross over-estimation of this parameter. Such high P_α values in the neighbourhood of unity are not only contrary to the decreasing trend of P_α values with increasing mass as observed previously (Basu 1976; Colli *et al* 1973, 1974), but also not plausible from the following theoretical considerations. The last two neutrons and the last two protons, constituents of the emitted α-particle, belong to two different shell-model orbits in these heavy nuclei and mostly situated, at two different major shells or sub-shells; as a result they have a poor overlap of their wave functions and hence small E^{α}_{CI} and P_α. Even α-nuclei in which the last two neutrons and the last two protons belong to the same shell-model orbit with consequent large

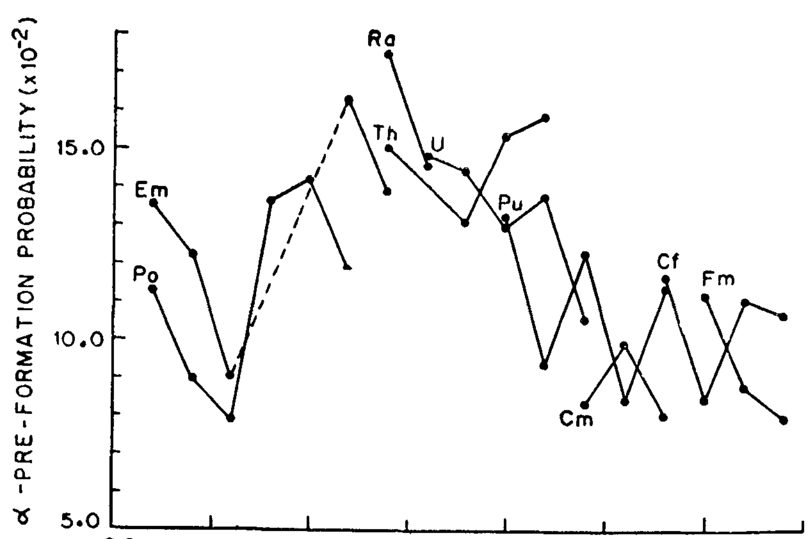

Figure 1. Alpha-preformation probability *versus* neutron number of trans-lead even-even alpha-emitters.

overlap of their wave functions do not have α-preformation as high as unity (Basu 1972). The errors in $P_{\alpha\,(stat)}$ values may be due to any or both of factors mentioned earlier. These values not corroborated by $P_{\alpha\,(emp)}$ and $P_{\alpha\,(expt)}$ are to be treated with reservation.

One clearly notices in figure 1 that $P_{\alpha\,(emp)}$ follows closely qualitatively the trend of $P_{\alpha\,(expt)}$ and $P_{\alpha\,(stat)}$. Besides, shell-closure at $N = 126$ reduces the value of α-preformation probability appreciably as compared to its values in the open-shell nuclei. Shell and sub-shell closure effect on α-preformation probability was, in fact, predicted by the author in an earlier communication (Basu 1976) $P_{\alpha\,(stat)}$ due to Bonetti and Colli (1974) and $P_{\alpha\,(expt)}$ due to Colli *et al* (1975) confirm the clear shell-effect at $N = 126$. Becchetti *et al* (1975) also observed reduced values of α-spectroscopic factor at $N = 126$ in their study of the α-pick-up reactions in different even-even nuclei and attributed this to a reduction in P_α due to the shell-closure. Reduction of α-preformation at shell-closure is easy to understand. In the present case, the last two neutrons are the members of the closed core of 126 neutrons and 82 protons and as such, have a poor overlap of their wave functions with those of the last two protons outside the closed core with the consequence of a small α-preformation probability.

Another remarkably interesting feature in figure 1 is the appreciably enhanced values of the α-preformation probability in the open-shell nuclei over those at the shell-closure. This was also clearly noticed by Colli *et al* (1975) in their $P_{\alpha\,(expt)}$ determination and by Bonetti and Colli in their $P_{\alpha(stat)}$ evaluations. Becchetti *et al* (1975) also observed increased values of α-spectroscopic factor in these nuclei in their study of α-pick-up reactions and attributed this to increased values of P_α in these open-shell nuclei as corroborated by the present findings. As these nuclei beyond $N = 126$ are mostly deformed in shape, this observed enhancement of P_α is obviously a deformation effect. The long-range quadruple force, as is well known, deforms the nuclei far off a shell-closure and enhances the α-preformation probability in them *via* the admixture of states. Deformation, in short favours α-preformation to a far greater degree than sphericity in nuclear shape. From the point of view of α-preformation, these open-shell nuclei offer a really interesting field of study.

The above comparative study clearly shows that the qualitative agreement of P_α values obtained from these three approaches is very good. Quantitative agreement at and about a shell-closure is also quite satisfactory.

Quantitatively in open-shell nuclei, however, $P_{\alpha\,(stat)}$ disagrees with $P_{\alpha\,(expt)}$ to a far greater extent than $P_{\alpha\,(emp)}$ disagrees with $P_{\alpha\,(expt)}$. The agreement between $P_{\alpha\,(expt)}$ and $P_{\alpha\,(stat)}$ is not so good as claimed by the authors. For example, in this trans-lead region, maximum $P_{\alpha\,(stat)} \approx 1\cdot0$, maximum $P_{\alpha\,(expt)} = 0\cdot35$ (^{232}Th) (Colli *et al* 1975) and maximum $P_{\alpha\,(emp)} = 0\cdot17$. Obviously $P_{\alpha\,(expt)}$ is much closer to $P_{\alpha\,(emp)}$ than to $P_{\alpha\,(stat)}$. This is to be expected if one takes into account of the fact that the statistical approach is based on the concept of average level-spacing. As pointed out by Hanna (1959), this concept is reasonably useful for a highly excited compound nucleus but is to be regarded to be of the order of magnitude validity for the ground state.

One will not fail to record in the isotope-wise behaviour of P_α (figure 1) of an altogether new property of this important nuclear parameter, hitherto not observed in any other study. It is the zig-zag nature of α-preformation probability which is particularly pronounced in permanently deformed nuclei with $N > 126$. This zig-zagness is evidently the outcome of a change, with increasing neutron number, in the quantum states occupied by the last two protons in the general background of the complex coupling scheme operating among them. It may not be out of place to point out that the fluctuations of α-decay radii about the $A^{1/3}$-law observed in the one-body α-decay model (Hanna 1969) are entirely due to this zig-zag nature observed in α-preformation probability.

4. Conclusion

The present study along the ADWT line entirely devoted to trans-lead even-even α-emitters clearly indicates that there is much room for improvement in the accuracy of the quantitative values of $P_{\alpha\,(\mathrm{expt})}$ and $P_{\alpha\,(\mathrm{stat})}$. Shell-closure effect on $P\alpha$ at $N = 126$ and enhanced values of $P\alpha$ in the open-shell deformed nuclei exhibited by $P_{\alpha\,(\mathrm{expt})}$ and $P_{\alpha\,(\mathrm{stat})}$ evaluations also find added confirmation from the present ADWT approach. It is hoped that all the possible shell and sub-shell effects as predicted in a previous study will be confirmed in due course by $P_{\alpha\,(\mathrm{expt})}$ determination with further improvement in the accuracy of the experimental input data and sophistication of the theoretical models. The zig-zag nature of α-preformation probability in permanently deformed heavy nuclei as revealed in the present study is an interesting characteristic of this parameter hitherto not observed in any other study. A theoretical investigation of this property will definitely provide valuable information about the structure of the parent α-emitter.

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