PHYSICAL REVIEW C VOLUME 32, NUMBER 6 DECEMBER 1985

Emission of preformed α particles through a collective process in ^{150}Sm(p,α)

R. Bonetti and L. Colli Milazzo
Istituto Fisica Generale Applicata dell'Università di Milano, Milano, Italy

(Received 15 April 1985)

Analysis of the ^{150}Sm(p,α) reaction with the triton pickup and α knockout models fails to give the magnitude of the measured cross section. We show that a calculation based on a collective form factor successfully gives both the angular distribution and the absolute magnitude of the cross section. Some insight into the collective process is provided by the recent extension of the interacting boson model to alpha clustering in deformed nuclei.

I. INTRODUCTION

Until now, in nuclear reactions of the (p,α) type the absolute value of the cross section had always been an unsolved problem. A great many calculations of transitions to resolved low-lying levels of residual nuclei in a wide range of masses induced by (p,α) reactions were done in the frame of the triton pickup model.

These calculations often succeeded in reproducing the angular distribution of emitted particles but were always incapable of giving the correct magnitude. These results were definitely established during the last few years because of the high degree of sophistication recently introduced in the distorted-wave Born approximation (DWBA) microscopic formulation of the (p,α) process.[1–5] It can now be definitely stated that these calculations generally underestimate the experimental cross sections by up to two or three orders of magnitude. On the other hand, the shape of the continuum α spectra due to (p,α) or (n,α) reactions was nicely reproduced by means of the semiclassical calculations based on the preequilibrium exciton model, where it was assumed that the knocked out α particle is preformed in the target nucleus.[6–8] In this light, detailed DWBA calculations of knockout (p,α) reactions were recently also made for transitions to low-lying levels.[9] Although the shape of the angular distributions was reproduced reasonably well, the cross-section magnitude continued to be largely underpredicted. This situation is reminiscent of α decay studies. Accurate analysis of spontaneous α decay has been done by many authors[10–12] in order to obtain a quantum mechanical calculation of the reduced width of the α transitions, but as far as we know these calculations always greatly underestimated the experimental values, even when a large configuration mixing of shell model wave functions is included.[12]

In consideration of all these facts, it seems clear that the well-known nuclear structure models currently in use have serious problems when utilized to describe microscopically the emission of α particles. For these reasons, we were highly impressed by the phenomenological approach to α clustering recently proposed by Iachello and Jackson.[13] Starting from the well-known interacting boson model, they suggest that in heavy nuclei α particles could be present in some kind of vibrational state created by dipole oscillations of the α cluster in relation to the remaining deformed nucleus. The authors find evidence of such states in many levels of natural α radioactive nuclei, characterized by negative parity ($1^-,3^-$) and low α-hindrance factors. In the light of this new model we reconsidered a number of (p,α) experiments done several years ago and already partially published.[6,7] These experiments were done at ~20 MeV on a group of rare earth nuclei: four isotopes of samarium, indium, neodimium, and a few others. The spectra from these nuclei exhibit a striking feature, which remained without explanation until now. Many of them, namely the Sm isotopes and In, show one or two very strongly excited peaks, usually at a low residual excitation energy, as can be seen in Fig. 1. In the case of ^{150}Sm rather accurate angular distributions of the two peaks have also been measured at $E_p=23.1$ and 28.65 MeV at the Milano AVF cyclotron. It is therefore possible to compare them with the theoretical calculations based on the different models.

II. CONVENTIONAL DWBA CALCULATIONS: PICKUP AND KNOCKOUT MODELS

The direct mechanism nature of the transitions being studied is supported by the strong forward peaking of their angular distributions and by explicit calculations showing the negligibility of compound nucleus contributions in the high energy region of the spectrum where such transitions are found.[7] Starting from the generally accepted opinion that the direct (p,α) reaction can be explained by means of the triton pickup mechanism, a DWBA calculation was done with the help of the computer code TWOFNR (Ref. 14). This code incorporates a full finite-range formalism and under the cluster approximation can treat both the pickup and the knockout processes with a variety of shapes for the two-body interaction and the bound-state wave functions. Figure 2 shows the results of these calculations made using the parameters given in Table I. The proton-triton effective interaction was taken to be a Gaussian with range 1.42 fm and strength 70 MeV.[2] The angular distribution of the ground-state transition is not well fitted, and the absolute value is underpredicted by a factor of ~20. Both this failure as well as the results obtained from the continuum part of the spectrum, namely the preformation of α particles in this nucleus,[6,7] suggested that we do another calcu-

©1985 The American Physical Society

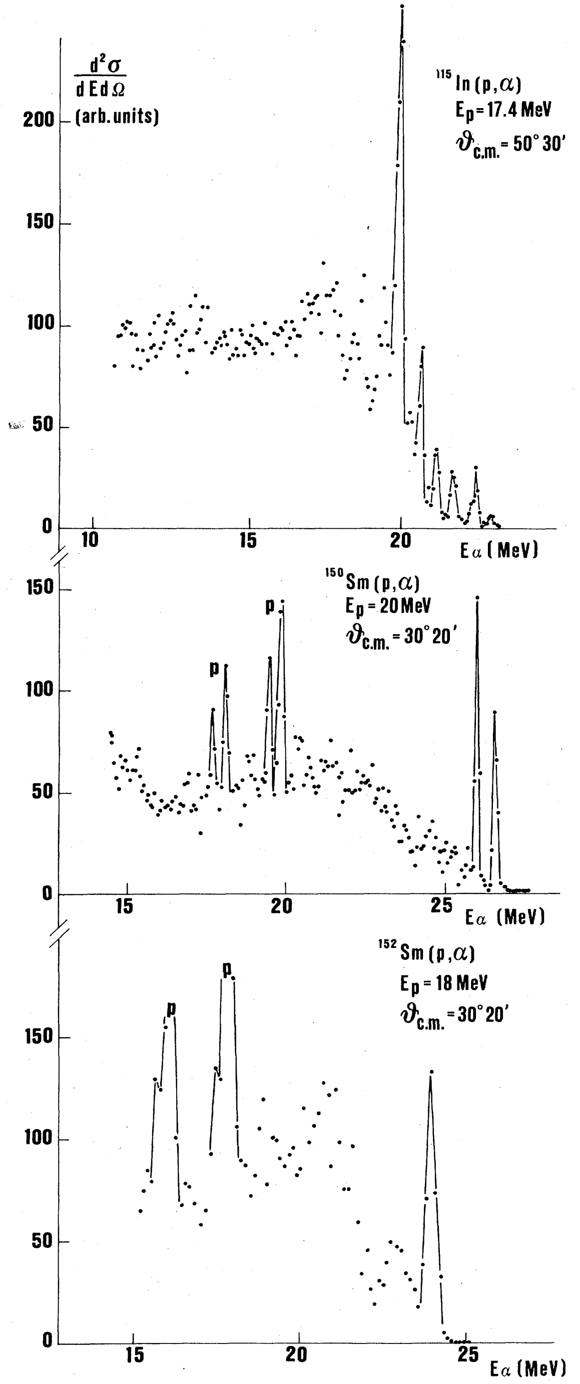

FIG. 1. A few α spectra at forward angle. The peaks marked "p" are due to scattering of protons in Si detectors (for details, see Ref. 6).

lation in the frame of the α knockout mechanism, where the incoming proton is considered as being captured in a shell model orbit exciting an α particle up to the continuum. The incoming and outgoing distorted waves are the same as in the previous calculation, but the form factor is obviously different. In particular, for the bound α particle we used two different descriptions:

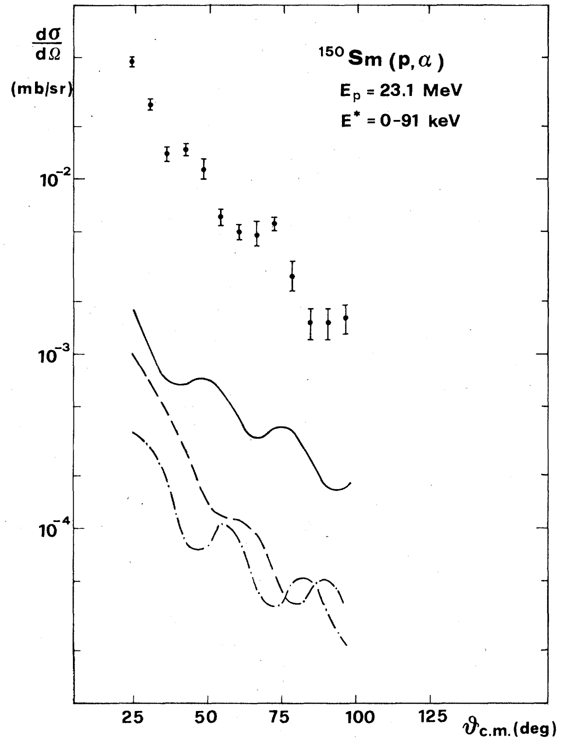

FIG. 2. Comparison of experimental data at $E_p = 23.1$ MeV with DWBA calculations based on different models. Full line: triton pickup; dashed line: α knockout, Woods-Saxon α bound state wave function; dot-dashed line: knockout, Gaussian α bound state wave function. All the calculations were done with a spectroscopic factor equal to one and are therefore upper limits.

(1) The wave function was generated in a Woods-Saxon potential with the parameters shown in Table I and with the number of radial nodes (9) given by the usual harmonic oscillator energy-conserving condition.

(2) Using as a starting point the well-known concentration of α clusters at the nuclear radius, the α particle wave function was assumed to be a Gaussian centered at the nuclear radius (7.1 fm). The range parameter $\eta = 4.3$ fm was derived from the measured value of the rms radius of the α particle using the relationship $\langle r^2 \rangle = 9/64\eta^2$.[15]

In both cases the proton-α effective interaction was taken to be a Gaussian with range 1.7 fm and strength 60 MeV.[16] The results are shown in Fig. 2. The fit of the angular distribution shape is not better than in previous triton pick-up calculations, and the magnitude is largely underpredicted.

All possible efforts to increase the cross section [use of different families of α optical model (OM) potential and bound state parameters] were frustrated. In conclusion, all these calculations were unsuccessful, which confirmed and extended to the α knockout mechanism the findings of many other authors.[1-5] It must be emphasized that

TABLE I. Parameters of the Woods-Saxon OM potentials used in the DWBA calculations. Depths are in MeV, radii and diffusenesses in fermis.

	V_R	r_R	a_R	W_v	W_{sf}	r_i	a_i	v_{so}	r_{so}	a_{so}	Ref.
$p+{}^{150}Sm$ 23.1 MeV	55.43	1.17	0.75	2.382	8.1	1.32	0.631	6.2	1.01	0.75	19
$p+{}^{150}Sm$ 28.65 MeV	53.66	1.17	0.75	3.603	6.72	1.32	0.631	6.2	1.01	0.75	
$\alpha+{}^{147}Pm$	249.5	1.236	0.592	27.5		1.236	0.592				20
triton bound state (a)	c	1.2	0.5								5
α bound state (b)	c	1.35	0.6								
proton bound state (b)	c	1.25	0.6								

[a] Data for triton pickup calculation.

[b] Data for knockout calculation.

[c] Selected to give the particle separation energy.

the above calculations are *upper limits,* since they have always been done assuming the α-spectroscopic factor to be equal to one.

III. DWBA CALCULATIONS WITH A COLLECTIVE FORM FACTOR

At this point we felt that it was necessary to consider another model besides the more standard triton pickup or the less used α knockout to explain the highly excited α peaks of the $^{150}Sm(p,\alpha)$ reaction. As a starting point we considered the essentially collective model of Iachello and Jackson[13] applied by the authors to the case of spontaneous α decay. Due to the collective nature of the vibrating state in which an α particle can be found in a distorted nucleus, this new model is indeed able to reproduce α decay probabilities and other characteristics[17] of states of light actinides with small α hindrance factors.

When applying the idea behind the Iachello and Jackson model to our reaction, the interaction of the incoming proton was no longer considered microscopically as a two-body interaction with a preformed α particle, as it had been in the knockout calculation described above. Instead, it was assumed to be an excitation of collective degrees of freedom consisting of the preformed α particle which oscillates relatively to the rest of the nucleus and is emitted. In the DWBA calculation that describes such a process the problem is naturally that of the form factor. As a first approximation we used the same form factor adopted in the analysis of highly excited collective transitions induced by inelastic scattering, namely the first derivative of the proton OM potential.

The incoming and outgoing distorted waves were of course the same as in the calculations described above. Such a simple calculation, although certainly not completely satisfactory from a formal standpoint, can still provide a quick estimate of the physical validity of the picture outlined above. The results are shown in Fig. 3. As far as the shape of the differential cross section is concerned, the fits are not perfect though they do give the principal characteristics of the data; in any case they are definitely no worse than some given by the more standard triton pickup calculations.

We noticed that we could get better fits by using a slightly smaller value for the diffuseness parameter in the imaginary part of the form factor (0.48 instead of 0.631), which could be a sign of the well-known surface localization of α clusters. More importantly, our calculation gives the correct magnitude of the two $L_{tr}=4$ transitions with a reasonable value for the hexadecapole deformation parameter, $\beta_4=0.02$. Although such a comparison should not be taken too seriously because of the dissimilar nature of the two kinds of reactions, this number is fairly close to

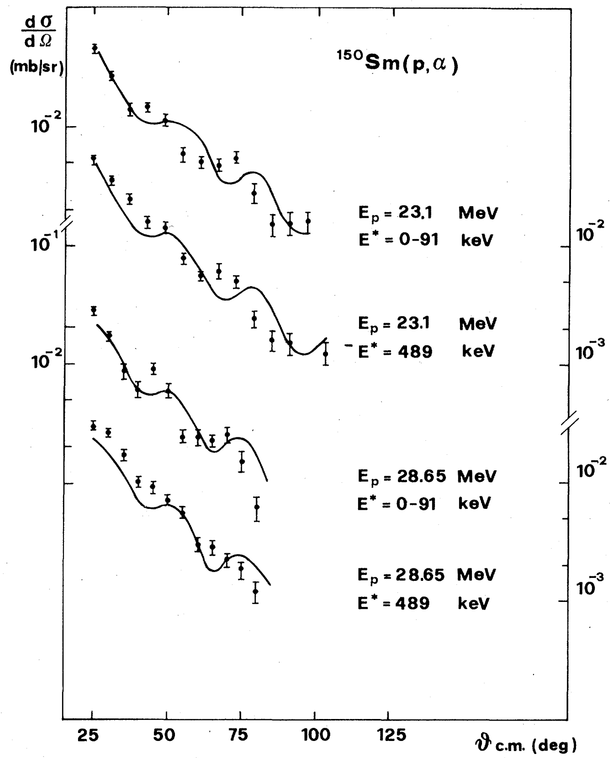

FIG. 3. Comparison of angular distribution of the two α peaks at 23.1 and 28.65 MeV with DWBA calculations based on a collective form factor. A deformation parameter of $\beta_4=0.02$ was used. The first peak is due to transitions to both g.s. $\frac{7}{2}^+$ and 91 keV $\frac{5}{2}^+$ while the second one most probably to the 489 keV $\frac{7}{2}^+$ state. Both angular distributions were calculated with $J^\pi=\frac{7}{2}^+$.

the values 0.04—0.05 extracted from α inelastic scattering analysis on Sm isotopes.[18] Moreover, the calculation implicity assumes an α spectroscopic factor (which in this case has the meaning of α preformation probability) equal to one.

The extracted number given above is therefore a lower limit, subject to increase with α spectroscopic factors smaller than one. For the transitions analyzed here, the reasonableness of the extracted β_4 value implies that the α preformation probability is not too much smaller than one, a result which is consistent with the large average α preformation probability φ (0.2—0.45) extracted for the Sm isotopes from a preequilibrium analysis of the continuum spectrum.[6,7]

Our calculation also seems quite promising in giving the correct energy dependence, which was not true of the triton pickup calculations.[21] Although the two series of data are taken at incident energies, 23.1 and 28.65 MeV, that are not too far apart, it is nevertheless gratifying to find that the β_4 values are the same for both energies.

IV. DISCUSSION AND CONCLUSIONS

The substantial success of the analysis of the highly excited (p,α) transitions on ^{150}Sm using a collective form factor in the DWBA calculations and in particular the correct prediction of the magnitude of the cross section, which to the best of our knowledge has never happened before with a (p,α) reaction, demonstrate that preformed α particles in open shell nuclei are emitted by collective excitation. Formal justification must now therefore be found for such a form factor in reactions other than inelastic scattering.

Although at the present stage no quantitative link has yet been established between our reaction calculation and Iachello and Jackson's nuclear structure model, our calculation is consistent with this model on the basis of their common collective, vibrational nature. As shown in Ref. 17, indeed, satisfactory reproduction of levels of actinides is achieved only by assuming that the clustering is described by vibrations of the α particle-core nucleus system (the "vibron model").

It would be now interesting to include in the calculation quantitative information drawn from Iachello and Jackson's model, particularly the spectroscopic factor; this would allow the calculation, too, of the relative strengths of the transitions to different states of the same nucleus, which would indicate a different α particle structure. In the vibron model this is taken into account by varying the mixing of dipole (describing the clustering) and quadrupole (describing the deformation of the core) degrees of freedom.[17] This is equivalent to saying that states with α cluster structure varying between 0% and 100% can be, in principle, accounted for; this, in turn, can explain the high selectivity found experimentally in the (p,α) spectra of Fig. 1 (i.e., states with ~0% α cluster structure would not have any chance to be excited in the present model).

It would also be useful to study nuclei having different average preformation factors φ, as determined by phenomenological analysis of the continuum spectrum of (p,α) reactions and α radioactivity.[7] The effect studied in the present paper, in particular, should be practically absent in nuclei for which a very low φ preformation probability was extracted (e.g., ^{208}Pb). Work on these interesting points is in progress.

ACKNOWLEDGMENTS

We are indebted to Prof. F. Iachello for stimulating discussions and to Prof. A. Arima, Prof. P. Hodgson, and Dr. H. Daley for useful comments. Thanks are also due to Prof. K.-I. Kubo for his assistance with the use of the code TWOFNR and for the kind hospitality offered at the Tokyo Metropolitan University. This work was supported by Istituto Nazionale di Fisica Nucleare, Sezione di Milano and by Ministero della Pubblica Istruzione, Italy.

---

[1] F. Brunner, H. H. Muller, C. Dorninger, and H. Oberhummer, Nucl. Phys. **A398**, 84 (1983).

[2] P. D. Kunz, T. Kammuri, and H. Shimaoka, Nucl. Phys. **A376**, 401 (1982).

[3] T. Kammuri, H. Shimaoka, P. D. Kunz, S. Kato, K. Okada, M. Kondo, K. Hosono, T. Saito, N. Matsuoka, S. Nagamachi, T. Noro, K. Ogino, and Y. Kadota, Phys. Lett. **90B**, 197 (1980).

[4] H. Oberhummer, Nuovo Cimento **55A**, 253 (1980).

[5] W. R. Falk, R. Abegg, and S. K. Datta, Nucl. Phys. **A334**, 445 (1980).

[6] L. Milazzo Colli, G. M. Braga Marcazzan, M. Milazzo, and C. Signorini, Nucl. Phys. **A218**, 274 (1974).

[7] L. Milazzo Colli, G. M. Braga Marcazzan, and M. Milazzo, Nuovo Cimento **30A**, 632 (1975).

[8] L. Milazzo Colli, G. M. Braga Marcazzan, R. Bonetti, M. Milazzo, and J. W. Smits, Nuovo Cimento **39A**, 171 (1977).

[9] E. Gadioli, E. Gadioli Erba, P. Guazzoni, P. H. Hodgson, and L. Zetta, Z. Phys. A **318**, 147 (1984).

[10] K. Harada, Prog. Theor. Phys. **26**, 667 (1961).

[11] H. J. Mang, Annu. Rev. Nucl. Sci. **14**, 1 (1964).

[12] I. Tonozuka and A. Arima, Nucl. Phys. **A323**, 45 (1979).

[13] F. Iachello and A. D. Jackson, Phys. Lett. **108B**, 151 (1982).

[14] M. Igarashi, private communication.

[15] A. Bernstein, Adv. Nucl. Phys. **3**, 325 (1969).

[16] R. Bonetti, L. Colombo, and K.-I. Kubo, Nucl. Phys. **A420**, 109 (1984).

[17] H. Daley and F. Iachello, Phys. Lett. **131B**, 281 (1983).

[18] D. L. Hendrie, N. K. Glendenning, B. G. Harvey, O. N. Jarvis, H. H. Duhm, J. Saudinos, and J. Mahoney, Phys. Lett. **26B**, 127 (1968).

[19] F. D. Becchetti and G. W. Greenlees, Phys. Rev. **182**, 1190 (1969).

[20] L. Mc Fadden and G. R. Satchler, Nucl. Phys. **84**, 177 (1966).

[21] P. Guazzoni, M. Pignanelli, E. Colombo, and F. Crescentini, Phys. Rev. C **13**, 1424 (1976).