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The Peculiar A Stars and the Origin of the Heaviest Chemical Elements

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SUMMARY

The unstable element promethium and such r-process products as uranium, and even transuranium elements have been observed recently in some peculiar A stars. Isotope shifts of the Pt and Hg lines in Ap stars point to an increased abundance of the neutron–rich isotopes of these elements. These observational results may be taken as evidence for an r-process which could be extended perhaps even to yield the superheavy nuclei from the 'additional island of stability' around $Z = 114$. The synthesis of the heaviest chemical elements is considered in the framework of Guthrie's modified version of Van den Heuvel's theory of the origin of Ap stars. Other possibilities of explaining the anomalous abundances are related to the problem of nucleosynthesis of the heaviest chemical elements.

I. THE R-PROCESS AND SUPERHEAVY ELEMENTS IN NATURE

The existence of transbismuth elements in nature is an indication of the peculiar physical processes by which they have been produced. Rapid neutron capture (r-process) has been the most frequently studied one since the pioneer analysis in the B^2FH monograph (Burbidge *et al.* 1957). The r-process in Type I Supernovae was studied by Hoyle & Fowler (1960), while a detailed study of the production of heavy elements has been performed by Seeger *et al.* (1965). For further results up to the end of 1967 the reader is referred to Section 11.8.1 of Volume I of a recent book by Kuchowicz (1968), while the most recent analyses of the production of the heaviest elements up to mass numbers $A \approx 300$ in explosive stellar events have been published by Schramm & Fowler (1971), Ohnishi (1972), and by Schramm & Fiset (1972).

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The possibility that the r-process in stars goes as far as the superheavy elements does not follow in a unique way from present nuclear theory and nuclear data. While according to the above-mentioned papers, and to some others, it is possible to extend the r-process up to nuclei with $A \approx 300$, other authors point to circumstances which render such an extension practically impossible. Thus Viola (1969) claims that both the neutron-induced fission and increased spontaneous fission rate do not allow any production of nuclides with $A > 275$ in an ordinary r-process. Boleu *et al.* (1972) estimated recently fission, alpha and beta half-lives on the basis of a nuclear potential-energy surface calculated from the modified-harmonic oscillator potential; they concluded that it is the neutron-induced fission which decisively blocks the stability island from being reached by the r-process.

In view of some disadvantages of the standard r-process, Amiet & Zeh (1967, 1968) proposed another formation mechanism for the neutron-rich heavy nuclei. This is some kind of slow neutron capture process at a very high density; the region of α-instability is by-passed, and it was estimated that uranium and thorium nuclei may be produced in this way. At the time when these results were reported, there was only the beginning of interest in the island of stability near $Z = 114$, and no necessity was felt to extend the neutron capture tracks up to that region. It was argued later by Kuchowicz (1970a) that such an extension is possible, and that the synthesis of the heavy and superheavy elements may occur in the high-density matter of exploding condensations, perhaps not only in single stars but also in the nuclei of galaxies. This would be some kind of primordial r-process synthesis, in accordance with the concept of Unsöld (1969), and along the lines suggested also by the analyses of Hohenberg (1969) and of Wasserburg, Schramm & Huneke (1969).

It is necessary to mention why we are speaking of heavy nuclei like those with atomic number near 114. Until very recently, it seemed that the heavier a transuranium element is, the shorter its half-life, and the less the hope of finding even its longest-lived isotope in nature. This viewpoint seemed to be justified by what was known about elements 92–105: the half-life of the longest-lived isotopes of these elements decreased in a regular way from $4{\cdot}51 \times 10^9$ yr (for ^{238}U) up to fractions of a second (for the element 105). This agreed with the liquid drop model of the atomic nucleus, but the situation changed when shell corrections were taken into account (Myers & Swiatecki 1966). It turned out that a possible closed proton shell and/or a closed neutron shell may act in the direction of 'stabilizing' nuclei with at least one magic number (of protons or of neutrons). The doubly magic nucleus ^{298}114 was noted first to be especially long-lived, while more detailed calculations (Nilsson *et al.*, 1968, 1969a, b; Muzychka

1969; Tsang & Nilsson 1970) have shown that this situation will occur at a nucleus with a somewhat lower atomic number. Even conservative estimates (Schramm & Fowler 1971) yield at least one nucleus with a half-life not less than 10^8 yr; and altogether eight nuclei with half-lives not below 10^3 yr; while the latest theoretical estimates of the half-lives of nuclei in the interval of atomic numbers 108–116 (Lukasiak, Sobiczewski & Stepien-Rudzka 1971) imply that there are more long-lived nuclei in this interval, and their half-lives may be larger. In this paper, however, we shall restrict ourselves to the half-lives given by Schramm & Fowler, so that our results concerning the abundances of the products of a decay of these superheavy elements may be regarded as lower bounds to what one can expect to occur.

Theoretical predictions concerning the superheavy 'island of stability' have stimulated nuclear physicists to try to synthesize such nuclei, also to search for their occurrence in nature. Though the results have been dubious (see e.g. the survey by Flerov & Karamyan 1970) this problem is worth studying since it is related not only to nuclear physics but also to our recent concepts concerning stellar evolution. Superheavy elements may be produced in three kinds of celestial objects:

(1) In supernovae, both by the standard r-process (Berlovich & Novikov 1969; Schramm & Fowler 1971; Schramm & Fiset 1972), and by heavy-ion reactions in a strong neutron flux (Kowalski & Kuchowicz 1969).

(2) In pulsars, when eruption of matter occurs while accompanying sudden period changes (Dyson 1969).

(3) In exploding galactic nuclei which may consist of Ambartsumyan's prestellar matter (Kuchowicz 1970a).

For details concerning the synthesis of superheavy nuclei the reader may be referred to lectures given at two recent conferences: the Transuranium Conference in Houston (Cowan 1969), and the Heavy Ion Physics Conference in Dubna (Kuchowicz 1971a). The aim of this paper is to present certain indirect evidence for the presence of superheavy nuclei in the peculiar A stars, together with a discussion of the mechanisms which make these stars especially suited for a search after the r-process products. In order to make such a discussion possible it is necessary to summarize first some results concerning abundances in these stars.

II. MAIN RESULTS CONCERNING VERY HEAVY ELEMENTS IN AP STARS

Information on the abundances of very heavy elements with atomic numbers $Z > 74$ has accumulated during the last four years. The meagre harvest of the preceding years consisted only of some rather uncertain indications of a possible presence of lead and mercury in a few stars. The major results obtained during the earlier period of investigations of the spectra of the Ap stars were abundance determinations of all the lighter elements including rare earths, showing the exceptionally high overabundances of the latter. Subsequent summaries of these results may be found in several papers (Sargent 1964; Sargent & Searle 1967, also other papers in the same conference proceedings; Renson 1967; Hack 1968; Guthrie 1969a). Let us concentrate here mainly on the new results obtained since the last of these papers was written. Some of them have been briefly summarized in the meantime by Sargent & Burbidge (1970), yet it seems that the recent findings—especially of Pm, Am and Cm—and new theoretical proposals, make a new discussion of the problem advisable.

A summary of information on the elements from $Z = 74$ upwards, which have been observed in the spectra of peculiar A stars, is given in Table I. A note of interrogation after a reference indicates that the result was regarded by the authors as dubious and further confirmation was considered to be necessary. Comments on some of these results seem to be necessary.

TABLE I

Heavy elements observed in peculiar A stars

Element		Star and reference
Z	lines	
74	W I	HD 25354 (Jaschek & Brandi 1972)
		73 Dra (Guthrie 1972)
75	Re I	HD 425354 (Jaschek & Brandi 1972)
		73 Dra (Guthrie 1972)
76	Os I	73 Dra (Guthrie 1969b, 1972; Jaschek & Malaroda 1970)
	Os II	HD 25354 (Jaschek & Brandi 1972)
		HD 5797 (Adelman 1972, private communication)
		5 Ap stars (Brandi & Jaschek 1972)
77	Ir I	73 Dra (Guthrie 1972)
78	Pt II	HR 4072 (Dworetsky 1969); ϕ Phe, 46 Dra, HD 173650 (private communications quoted by Dworetsky 1969)
	Pt I	HD 5797 (Adelman 1972, private communication)
		HR 465 (private communication of Bidelman, quoted by Aller 1972)
		73 Dra (Jaschek & Malaroda 1970; Guthrie 1972)
		HD 25354 (Jaschek & Brandi 1972)
		5 Ap stars (Brandi & Jaschek 1970)
79	Au	HD 25354, HD 71866 (Brandi & Jaschek 1970?)
		73 Dra (Jaschek & Malaroda 1970?)
		HR 4072, χ Lup (Dworetsky *et al.* 1970)
80	Hg I	α And, χ Lup (Bidelman 1962)
	Hg II	HR 4072, χ Lup (Dworetsky *et al.* 1970; Guthrie 1972)
		ϕ Phe, 46 Dra, HD 173650 (private communications quoted by Dworetsky 1969)
		ι Cr B (Preston 1971a); 73 Dra (Guthrie 1972)
		HR 465 (private communication of Bidelman, quoted by Aller 1972)
		10 Ap stars (Table III given by Guthrie 1971a)

Element		Star and reference
Z	lines	
82	Pb I	73 Dra (Guthrie 1972) HR 4072 (Guthrie 1972) α^2 CVn (Burbidge & Burbidge 1955)
83	Bi I	73 Dra (Guthrie 1972)
90	Th I	73 Dra (Guthrie 1969b?)
	Th II	HD 25354 (Jaschek & Brandi 1972) 3 Ap stars (Adelman 1972, private communication) HR 465 (private communication of Bidelman quoted by Aller 1972)
92	U II	73 Dra (Guthrie 1969b; Jaschek & Malarada 1970) β Cr B (Brandi & Jaschek 1970; Hardorp & Shore 1972) 4 other Ap stars (Brandi & Jaschek 1970) HD 25354 (Jaschek & Brandi 1972) 20 Ap stars (Adelman 1972, private communication)
94	Pu II	HD 25354 (Jaschek & Brandi 1972)
95	Am	HD 25354 (Jaschek & Brandi 1972)
96	Cm I	HD 25354 (Jaschek & Brandi 1972)

Dworetsky (1969) discovered a large excess of platinum in several peculiar A stars of the Hg group. He reports the identification of Pt II lines in HR 4072 (HD 89822), also in ι CrB, χ Lup, HR 7575, HR 465, τ Cap, φ Phe, 46 Dra, HD 173650. His results seem to imply that the mean atomic mass of Pt in HR 4072 is probably one or two units larger than for a terrestrial sample of platinum. This means that the percentage of isotopes resulting from the r-process should be larger in HR 4072 than on the Earth.

A study, dealing with the Hg II line near 3984 Å, has been performed recently by Guthrie (1971a), who investigated some Ap stars of the Mn group, and compared the results with those for other peculiar A stars (see Table III of his paper). While the mean laboratory wavelength of the Hg II 3984 line is 3983·96 Å (Paschen 1928), the mean wavelength for the Mn stars is higher (3983·98 Å), and that for the other Ap stars—still larger (3984·04 Å). The latter fact could suggest that such Ap stars as χ Lup (with 3984·05 Å) and HD 192913 (with 3984·09 Å) contain abnormally high amounts of the heaviest mercury isotope, ^{204}Hg, that may be produced almost only by the r-process. This confirmed some earlier suggestions of Bidelman (1962), according to whom the higher wavelength of the mercury line in Ap stars points to a higher percentage of isotopes produced by the r-process.

Further studies of the isotope shifts of the Hg II 3984 line has been reported in several papers (Dworetsky, Ross & Aller 1970; Preston 1971a; Guthrie 1971a). The results which point to a different isotopic composition of mercury in each of the investigated stars and on Earth are summarized in Table II, which is adapted from Preston's paper (Preston 1971a). The isotopic composition of Hg follows from an analysis of the Hg II line profile.

TABLE II

Abundances of mercury isotopes in some Ap stars and on Earth (adapted from Preston 1971*a*)

Mass number of the isotope	Abundance (per cent)			
	1 Cr B	HR 4072	HR 5883	Earth
198	6	0	0	10
199				17
200	16	4	0	23
201				13
202	45	37	3	30
204	33	59	97	7

Guthrie (1969b) reported the results of an analysis of three Palomar spectra of the peculiar chromium-europium-strontium star 73 Dra. Two of these spectra were taken near the phases of the maximum line strength for Eu, Sr, Mn, and Ti in the 20-day period, the other near the phase of minimum line strength for these elements. The spectrum is extremely rich in Ti, Cr, Mn and Fe lines; thus it was difficult to find the lines of additional elements. The presence of osmium was reported, with the Os/Fe abundance ratio exceeding by at least 300 times that in the solar system. Other neighbouring elements were sought for. Guthrie reported that 'Th II lines at 4510·53 and 4740·53 Å and the U II lines at 4241·57 and 4543·63 Å are suspected to be present, but need confirmation'. A confirmation was reported independently by Jaschek & Malaroda (1970) who have found five lines belonging to U II in the spectrum of 73 Dra, with the strongest line, λ 3859, clearly visible. In addition, the seven strongest lines of Pt II, 32 lines of Os I, and three lines of Os II were found. There were some indications of the presence of gold.

Some time later, Brandi & Jaschek (1970) reported the results of an analysis of the spectra of 12 late Ap stars. They used Babcock's spectrograms, with dispersion ranging from 2·8 up to 9 Å mm^{-1}. The lines of U II, Os I, Os II, and Pt II were found together in two Ap stars: HD 2453 (of the Eu-Cr-Sr group), and HD 42616 (of the Sr-Cr-Eu group). The λ 3860 line of U II only was found in three other Ap stars, also belonging to the combined subgroups.

A detailed analysis of abundances in the Os-Pt-Hg peak has been made recently by Guthrie (1972) for some Ap stars. The results are summarized in Table III which is taken from his paper. The symbol

TABLE III

Abundance data for 74 ⩽ Z ⩽ 83 (*from Guthrie* 1972)

Object	A_{peak}	SA	$N_{\text{pb}}/N_{\text{tot}}$
73 Dra	191 ± 2	unknown	<0·04
HR 4072	201 ± 3	+3	<0·05
Other main-group Ap stars with Pt II lines	199 ± 5	+2 to +4	<0·3 ?
Mn stars	201 ± 2	+1 to +2	unknown
Cosmic rays	193 ± 3	unknown	~0·1
Solar system	195 ± 1	+1	0·44

A_{peak} means here the position of the atomic mass peak (in atomic mass units) while δA denotes the deviation (also in atomic mass units) of the most abundant nuclides from the beta-stability line. Finally the ratio of the abundance N_{pb} of lead to the total abundance N_{tot} of all elements with $74 \leqslant Z \leqslant 83$ is also a characteristic parameter. The deviations between the values for the Ap stars and for the solar system are significant. They point to an enhanced role of the r-process for the abundances observed in Ap stars. Whether these abundances are restricted only to surface layers or are intrinsic characteristics of these stars, will be discussed in the next section.

The most important results concerning the Ap stars seem to be those on the possible presence of transuranium elements (Jaschek & Brandi 1972) and on promethium (Aller & Cowley 1970; Aller 1971). Though it has been suggested earlier that transuranium elements may be found more easily in the peculiar A stars than in other stellar types (Kuchowicz 1970b, c), the discovery by Jaschek & Brandi (1972) may seem to many astronomers to be a surprise. Two of the elements which are known on the Earth to be produced only by artificial methods, americium and curium, have been observed in the spectrograms of HD 25354, a star of the Cr-Eu subgroup. There is also some inconclusive evidence for the presence of plutonium.

These results concerning very heavy elements seem to have nothing in common, at a first glance, with an identification of promethium in the Ap star HR 465 which was reported in 1970 November by Aller & Cowley (1970). Of the total of 44 laboratory lines listed in the tables of Meggers, Scribner & Bozman (1951), 38 were found in the stellar spectrum, three were obscured by Balmer lines so that spectral features could not be distinguished, and three were not found definitely. The analysis was extended further to fainter promethium lines, and the unpublished line-identification list prepared by W.P.Bidelman was used. The results of the search for Pm II lines were summarized by Aller (1971). From a total of 153 laboratory lines of Pm II there were found 110 lines in the stellar spectrum. Many of the remaining 43 lines were also apparent on the tracings. It was stated that only 69·5 (including blends) from the reported 110 identifications would be expected from chance coincidences, and the probability of identifying the 110 lines by chance coincidence in wavelength was estimated to be about one in 10^{10}. This result was questioned by Havnes & van den Heuvel (1972) according to whom the percentage of chance coincidences on the tracings is in excess of 90 per cent. This estimation is questioned, however, in a comment by Aller & Cowley (1972) who do not believe that the number of coincidences between stellar wavelengths and laboratory Pm II lines is insignificant. Though the whole problem is still under discussion, and the promethium abundance needs further confirmation, this result, when taken along with the other ones on the abundances of elements, points to a particular origin of the Ap stars which will be described in the next section.

III. ABUNDANCE ANOMALIES AND THE ORIGIN OF THE AP STARS

It is first important to know whether the abundance anomalies exhibited in the spectra of peculiar A stars are real. This is especially important for a correct analysis of the data in terms of nucleosynthesis processes. This question has been discussed by many authors: a recent summary has been given by Guthrie (1968). In the following we assume, with a majority of authors, that these anomalies are real. If this is the case, it is possible that either of the following situations applies:

(a) The Ap stars have been formed already out of material of abnormal composition; this seems to be in contradiction with the membership of Ap stars in clusters and in visual binaries with normal main sequence members.

(b) The anomalies are restricted only to the surfaces.

Assuming (b), we may attribute the anomalies either to nuclear processes, or to some other factor, e.g. the diffusion processes considered by Michaud (1970) together with a differentiation of the initial composition by radiation pressure. Various mechanisms of surface nuclear processes have been studied by several authors (Burbidge & Burbidge 1955; Fowler, Burbidge & Burbidge 1955; Fowler *et al.* 1965; Brancazio & Cameron 1967) who tried to explain the observed anomalies with the help of a complicated sequences of events. Fowler *et al.* (1965) interpreted the anomalous abundances in terms of the r-process, surface spallations and shallow mixing, a Si–P–S cycle and a complicated evolutionary history. In their opinion, the peculiarities in the Ap stars can only be formed at a late stage of the stellar evolution, after one or several helium flashes. This theory seems to be at variance with the concepts of stellar evolution (Truran & Cameron 1967; Searle & Sargent 1967); a detailed consideration of arguments against it has been given recently by Kraft (1969).

Another suggestion by Fowler *et al.* (1965), elaborated in detail by van den Heuvel (1967), and modified by Guthrie (1968) seems to be most attractive, and we shall discuss it*. It is the proposal that the present Ap stars are the original secondaries of binary systems in which the original primary was more massive and is now highly evolved. The primary is supposed to have passed through the giant phase, and during which it should have lost mass. Some of the material (which was r-processed or at least s-processed) was lost into space, and partially transferred to the surface of the secondary star, now observed as the peculiar A star. This concept implies immediately that all peculiar A stars have, or at least had, close companions. This question is not simple; the reader is referred to a discussion on the frequency of spectroscopic binaries among Ap stars (Jaschek & Jaschek 1958), to van den Heuvel (1967, 1968) and to Section 5 of the fundamental paper by Guthrie (1968).

In the original formulation of van den Heuvel's theory the abundances anomalies in the Ap and Am stars are related at least in part to the transfer of material processed by nuclear reactions in the surfaces and in the interiors of the primaries. Guthrie (1968) modified this theory by restricting it to the Ap stars. He regarded the primaries as being initially earlier than B 8 type, and exploding later as Type II supernovae. The initial separations between the members of binary systems are assumed to be in the range from 10 to 100 AU. This theory provides a reasonable distinction between the Mn group and other groups of the peculiar A stars. The transfer of material enriched in heavy elements by the explosion changed the composition of the surface of the secondary component. In addition, surface nuclear reactions were possible due to four causes:

(i) gamma rays from the supernova;
(ii) energetic atoms from the transferred material;
(iii) heating-up of the surface by the radiation from the supernova;
(iv) a transfer of magnetic fields.

A detailed explanation of the observed anomalies of heavy and light elements in peculiar A stars was given in four subsequent papers by Guthrie (1969a, 1970, 1971a, 1971b) in the framework of this theoretical model.

Now, provided this supernova-origin theory of the heavy elements holds, some interesting consequences with respect to the observability of the heaviest chemical elements may be drawn from it. Immediately

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*It was also considered by Renson (1963, 1965).

after the identification of uranium by Jaschek & Malaroda (1970), attention was drawn by Kuchowicz (1970b, c) to the question of transuranium elements which may be produced in the r-process together with uranium. Provided the neutron flux is sufficiently high in the primary, all the heavy elements up to $Z = 100$ can be produced in comparable amounts. A majority of them decay quickly after the mass transfer to the secondary occurs, but a temporary accumulation of plutonium is possible, and this can last for as long as 10^6 yr after the explosion. Even after 10^7 yr, the U/Pu ratio is of the order of 8/3 which makes a detection of plutonium in stellar spectra not hopeless. This is due to the long-lived isotope ^{244}Pu($T_{1/2} = 8 \cdot 2 \cdot 10^7$ yr). Similar arguments apply, though to a lesser degree, to neptunium and curium.

Some kind of qualitative arguments in favour of the possible presence of plutonium in 73 Dra may be the absence of lead and the probable existence of gold which were reported by Jaschek & Malaroda (1970). We know that the radiogenic contribution to the Pb abundance from the decay of transbismuth elements is large only after enough time has passed since the end of the r-process in which these elements were produced. The accumulation of lead goes in parallel with the decay of transuranium elements. It may be argued against this suggestion that sufficient amounts of lead may have been produced earlier by the s-process, but it is not necessary for stellar material which has passed through a supernova explosion to have the amount of s-processed nuclides of the same order or larger than the amount of r-processed ones. This refers, of course, only to the composition of matter ejected from such a supernova, and not to average cosmic abundances. Thus it may be concluded that the simultaneous presence of uranium and absence of lead in material which is believed to have been ejected from a supernova is at least an indication of the possible presence of transuranium elements in that matter.

With respect to gold, the following argument can be proposed. The only stable isotope of gold, ^{197}Au, lies in the main chain of the s-process. Thus, even if no r-process occurred, some gold nuclei should be present in evolved stellar material. In view of the high neutron capture cross section for gold, however, the gold to platinum abundance ratio in this case cannot exceed the value of 0·01, and should probably be much less. In the other extreme situation, with platinum and gold originating in the r-process only, their final abundance ratio should be of the order Pt/Au $\sim$ 4. It is thus of a fundamental importance to determine the abundance ratio of these two elements in order to be able to decide on the r-process contribution to the gold abundance. A Au/Pt abundance ratio much above 0·01 (but lower, of course, than 0·25) could indicate an intense r-process in which even far transuranium elements could have been built up.

That such a build-up may even yield superheavy nuclei, has been shown recently by Schramm & Fowler (1971), who obtained a total abundance of 0·556 or 0·179 (on the Si = 10^6 scale) for the eight long-lived superheavy nuclei with $T_{1/2} \geqslant 10^3$ yr. The first of these abundances was obtained for a nuclear parameter* $\kappa = 1{\cdot}79$, according to the mass law of Myers & Swiatecki (1966), the second—for $\kappa = 2{\cdot}3$ (Seeger 1967). The real values of κ lie well within these two extreme values. We thus see that the abundances of superheavy elements produced in explosive stellar events are not hopelessly small. We have to take into account also two further factors raising the abundances of these elements in the r-processed matter from supernovae.

(1) The most recent estimates of the total half-lives of these elements (Lukasiak *et al.* 1971) give the largest total half-lives of the order of 10^{10} yr instead of 10^8 yr as was cautiously assumed by Schramm & Fowler (1971); a systematic increase of the half-lives for all isotopes of these elements occurs, and larger amounts of these nuclei survive after the nucleosynthesis.

(2) The abundances obtained by Schramm & Fowler are averaged cosmic abundances; the percentage of superheavy nuclei in the matter ejected by a supernova may be higher by many orders of magnitude. These two factors together may result in quite observable abundances of the superheavy elements on the surfaces of at least some peculiar A stars (those whose exploding companions disposed of sufficiently high neutron fluxes; see details in Schramm & Fowler 1971).

More detailed calculations of the production of superheavy nuclides along the r-process path have been reported recently by Ohnishi (1972) and Schramm & Fiset (1972). Ohnishi (1972) pointed to the possibility of nucleosynthesis of nuclides with $A > 290$ provided the neutron number density N_n (in neutrons per cm^3) is higher than the value $7{\cdot}52 \times 10^{23}\, T_9^{14.62}$, where T_9 is the temperature in units of 10^9 °K. The synthesis may go on, under these conditions, in stellar shells around the core of Type II supernovae, in helium-burning shells of relatively later-stage stars, and in the outer shells of exploding objects.

Schramm & Fiset (1972) pointed to the three types of uncertainties involved in calculations of superheavy element production: I. those connected with the long-lived superheavy island; II. those related to the question of the maximum mass number in the r-process (κ parameter, mass equation, N_n, T_9, r-process path); and III. the ability to reach the 'stability island' from the r-process path (lifetimes for beta decay and for spontaneous fission, the magnitude of the freeze-out neutron flux).

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*The parameter κ is the ratio of the surface symmetry coefficient to the surface term in the empirical mass equation.

It was emphasized at the Dubna conference (Kuchowicz 1971a) that if a trans-astronomy (i.e. an astronomy of transuranium elements) should start, the most suitable objects for scanning for the heaviest elements should be the peculiar A stars. Now, since the first transuranium elements have been reported to be present on the surface layers of one of such stars (Jaschek & Brandi 1972), it seems that a search for heavier, and even for superheavy, elements in such stars is not quite hopeless. Further arguments follow from the promethium abundance in HR 465. This will be discussed in the next section.

IV. PROMETHIUM ABUNDANCE AS A POSSIBLE RESULT OF SPONTANEOUS FISSION OF SUPERHEAVY ELEMENTS

The fact that a number of hitherto unidentified lines in the spectrum of HR 465 can be attributed to promethium is surprising when we take into account that this element has a most long-lived isotope with a half-life of only 17·7 yr, and so is absent from terrestrial samples. It would seem, at a first glance, that the most probable method of synthesizing promethium might be the p-process, since those isotopes of promethium which may be produced in this process have relatively the largest half-lives. Let us consider therefore this possibility.

(a) Promethium could have been produced in the supernova explosion of the primary component (in the van den Heuvel–Guthrie theory) in one of the following reactions: (p, γ) on ^{144}Nd; (p, n) on ^{145}Nd; (α, p) on ^{142}Nd. The seed nuclei could have been produced earlier in the s-process, yet it would seem impossible that observable amounts even of the longest-lived promethium isotope, ^{145}Pm with its half-life of 17·7 yr, could have survived until now from the time of occurrence of the original nucleosynthesis. In addition, we would need to make very artificial assumptions concerning the extremely high initial abundances of the seed nuclei and/or the rather high energies of the bombarding particles (which are necessary due to the high Coulomb barrier for Nd).

(b) We might then imagine that Pm is being produced continually in some kind of surface reactions with, e.g. protons. These might be the same reactions as under point (a). The bombarding particles could be accelerated in areas of high magnetic-field strength, and the whole production model is much the same as that of Burbidge & Burbidge (1955) and of Brancazio & Cameron (1967). Yet there are serious objections against such an *ad hoc* hypothesis: the bombardment by charged particles has an overall effect upon the observed abundances, not only on promethium, and there are troubles with the destructive effect of protons leading to a continuous loss of nucleons by nuclei. This was already recognized by Brancazio & Cameron (1967), and the reader is referred to their paper for details.

As we turn now to neutron capture processes, let us indicate first that the longest-lived Pm isotope that may be produced in them has a half-life of 2·62 yr (^{147}Pm). As it is difficult to imagine some reasonable accumulation of this nuclide (regarded as being produced directly by neutron capture), no direct analogy to the technetium case exists. Unrealistically high neutron fluxes would need to exist in the surface layers to render promethium detectable. A single production event is

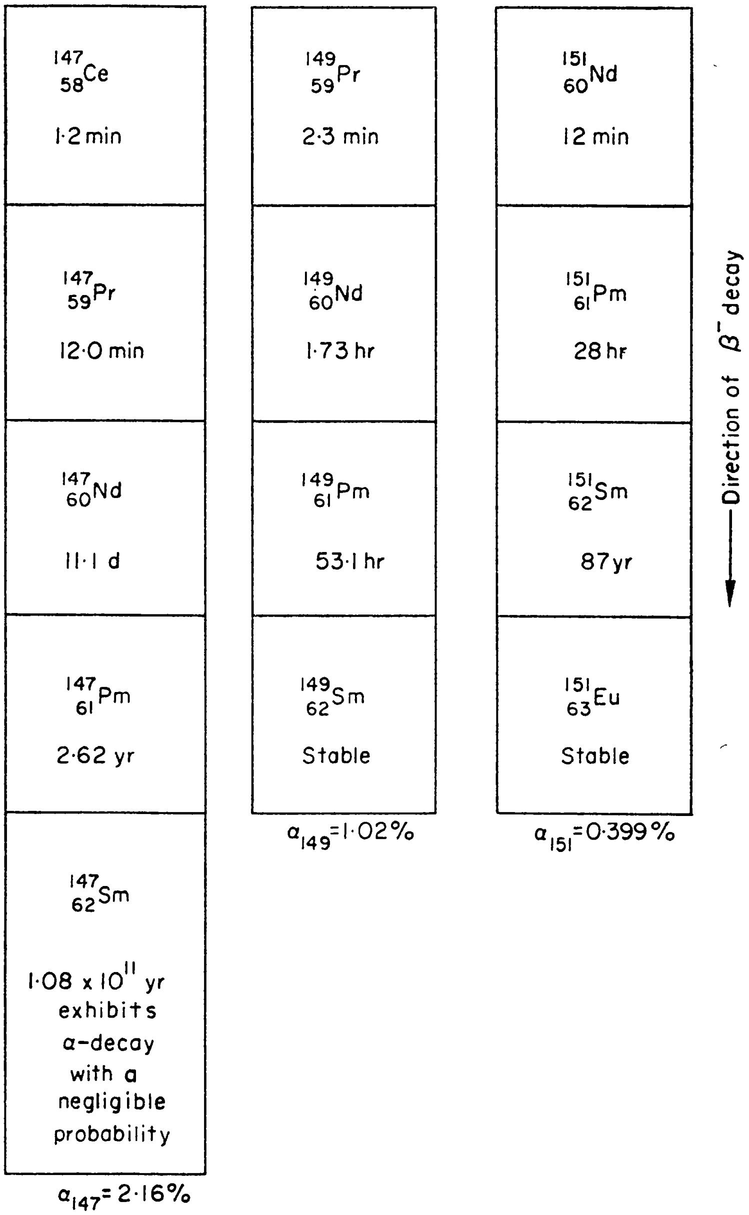

FIG. 1. Three isobaric decay chains of fission fragments involving the isotopes of promethium. Samarium isotopes are the stable end products in two cases. Half-lives of the intermediate radioactive isobars are given. The numbers a_i at the bottom are the isobaric yields for ^{235}U fission with thermal neutrons.

even more hopeless, as the amount of promethium drops by a factor of at least $3\cdot24\cdot10^{12}$ in 100 yr, and by a factor of ~ 10^{+115} in 10^3 yr.

As no direct production mechanisms produce sufficient amounts of Pm, it may be that only nuclear fission of the heaviest chemical elements can be responsible for its origin (Kuchowicz 1971b, c). Promethium is known to be one of the most abundant fission products in nuclear reactors. It is the intermediate product in three isobaric decay chains with mass numbers $A = 147$, 149, and 151 (Fig. 1). The yields for specific chains in the case of the fission of ^{235}U by thermal neutrons are given in Fig. 1; similar values of promethium yield apply to the fission of light transuranium elements. This is due to the effects of the proton and neutron closed shells of the fission fragments, and has been discussed in detail by Wahl (1965).

In the fission of heavier nuclei, the mass distribution of fission fragments changes in the direction of increasing the promethium yield up to 5 per cent. This is caused by shell effects. The heavy mass peak in the fragment distribution remains almost stable, while the light mass peak is shifted towards the former, and the two peaks nearly coincide for fissioning elements of atomic numbers near 110 (Fig. 2). The specific phenomenon of symmetric fission occurs here.

Symmetric fission of superheavy elements has been proposed (Dakowski 1969) as a possible reason for the anomalies in the isotopic composition of Xe and Kr in meteorites. The peculiar role of symmetric fission in explaining abundance anomalies was emphasized

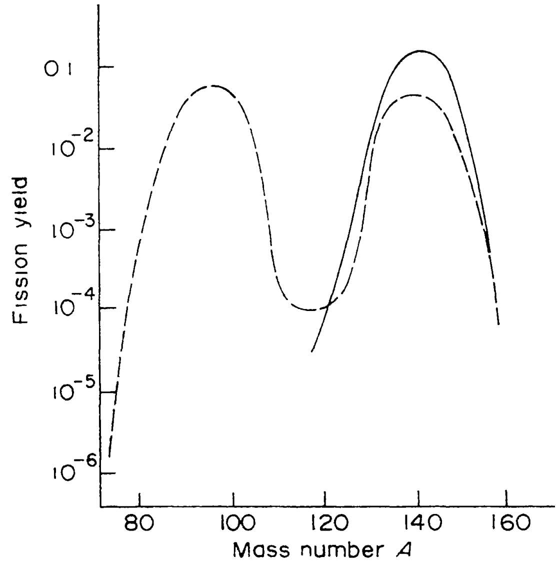

FIG. 2. A schematic presentation of mass yields in the fission of uranium (dashed line) and of super heavy nuclei (continuous line).

earlier by Selinov (1958); this plays a role in the case of overabundances of certain isotopes of the rare-Earth elements. These overabundances occur almost exclusively for those nuclides which may be the final products of isobaric chains from the spontaneous fission of heavy transuranium elements (Selinov 1964). It is well known that not only promethium but also other rare-Earth elements are high-yield fission products from the heavy-mass peak. This may perhaps be related to the characteristic abundance excesses in peculiar A stars. These excesses were studied in detail by Guthrie (1969a) who concluded that it appears not to be possible to account for them in terms of the s- or r-processes operating on the iron-peak elements. In the case of the main group of Ap stars it was necessary to assume an operation of the (n, γ) reactions on the s-process peak. It seems as though a contribution to the rare-Earth abundances from the fission products would be essential, if Guthrie's supernova model is to account for the peculiar composition of the surfaces of the Ap stars. Schramm & Fowler (1971) have already mentioned the role of the so-called fission-gap nuclei with atomic numbers between those for U and Th and for the superheavy 'island' of stability. They thought only of contributions to the universal abundance curve which may yield an abundance peak around $A \sim 155$. This contribution, together with that from the fission of superheavy elements, appears to be even more important in the case of the surfaces of Ap stars, with their enhanced abundance of the r-process elements.

The sequence of events regarded as responsible for the recent observability of promethium lines in the peculiar A star 465 may be tentatively assumed to be the following one (Kuchowicz 1971b, c). In an exploding stellar event on the primary component of the system to which HR 465 belonged certain amounts of transuranium, or even of superheavy, nuclei were synthesized. After mass transfer occurred, these nuclei continually decayed in the surface layers of HR 465. Since a large proportion of these nuclei (in practice all, when we consider the superheavy 'island of stability') decay to spontaneously fissioning nuclei, a continuous fresh supply of short-lived promethium nuclei is provided. Abundance calculations of superheavy nuclei (Schramm & Fowler 1971) have been applied to a subsequent estimation of the ıbundance of ^{147}Pm for various time intervals after the r-process Kuchowicz 1971c). The final results are given in a graphical form Fig. 3). In deriving the Pm abundances it was assumed that a 'correcion factor' of the order of 10^2 should be applied to the abundances of chramm & Fowler, since these are supposed to be universal and hould be converted into those corresponding to a single r-process vent. This value corresponds roughly to the average abundance excess compiled by Guthrie (1969a). The two curves in Fig. 3 correspond the two values of the nuclear parameter κ (used by Schramm &

Fowler in their calculations). Both the uncertainty in the correction factor and in the half-lives (which might have been underestimated by Schramm & Fowler when compared, e.g. with the results of Lukasiak *et al.* 1971) make it quite probable that the values in Fig. 3 are rather too low even by some orders of magnitude. In spite of this rather serious uncertainty, the general trend of the time dependence remains the same. It would be interesting to try to find the evolution in time of the promethium abundance in those Ap stars for which this element can be observed; even if we cannot manage to produce superheavy elements in the laboratory, this could provide some indication of certain nuclear parameters involved (according to which of the time-dependent curves the abundance should follow). Unfortunately, this would provide results over a large scale of time (at least 10^3 yr).

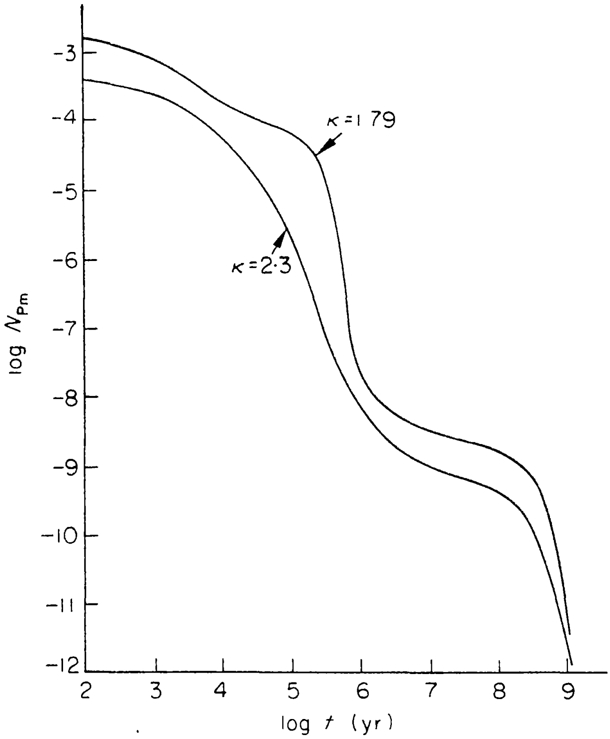

FIG. 3. Abundance of ^{147}Pm in the surface layers of an Ap star (on the Si = 10^6 scale). The two schematic curves refer to two values of the nuclear parameter κ involved in the calculations of Schramm & Fowler (1971).

V. PROBLEMS AND PROSPECTS

The results of element observations in Ap stars are enlightening both for the theory of stellar evolution and for the theory of nucleosynthesis. Recent discoveries of transuranium elements and of promethium may be compared with Merrill's announcement (Merrill 1952) of the detection of technetium. They appear to give the r-process a final, direct confirmation in the stellar spectra that is as convincing as for the s-process. Besides, some recent concepts of nuclear structure and stability, which cannot be proved experimentally in laboratories, might be tested by an inquiry in stellar spectra. It may be that superheavy elements which still cannot be produced or found on Earth may exist quite naturally in at least some peculiar A stars.

It is satisfactory that the Pm abundance in HR 465 correlates with such heavy nuclides as Pt, Hg, Th (Aller 1972; Cowley & Aller 1971). It would be worth while to seek further promethium lines in those Ap stars in which uranium has already been identified, or in which evidence for the presence of r-process products from isotope shifts in optical spectra has been obtained. It is, of course, useful to extend the examination to lines of the transuranium elements. All this might together provide a consistent picture of the way in which synthesis has occurred in the r-process.

It would be extremely useful if nucleosynthesis models could determine the isotope shifts of those elements which have at least one isotope produced in the r-process. This line of investigation should be assisted by precise laboratory measurements of wavelengths for separated isotopes. It might be useful to try to determine in laboratory the exact wavelengths for various promethium isotopes, and to compare these values with the stellar ones in order to rule out any possible contribution from the longest-lived isotope (^{145}Pm) which has nothing in common with the r-process.

Systematic studies of the spectra of peculiar A stars should be also made with respect to those elements which may be the products of spontaneous fission both of the superheavy nuclei and of the nuclei of the 'fission gap'. The results could indicate to us whether the explanation proposed to account for promethium (Kuchowicz 1971b, c) is wrong or inaccurate in some respects. One of the stars which appear to be promising with respect to such studies may be Przybylski's star, HD 101065, with its high holmium and dysprosium abundances (Przybylski 1966).

With respect to the question of a possible existence of superheavy nuclei, it is to be hoped that the words with which my Dubna conference talk concluded (Kuchowicz 1971a) should apply: 'It will be, surely, not easy, to find at some time atomic lines of the superheavy elements in some kind of stars. But if they can be found in some place, they should be found first of all in the peculiar A stars'.

Interesting developments are currently under way in the theory of the Ap stars (see the surveys by Cameron 1971; Pikel'ner & Khokhlova 1971; Kraft 1969; these cover aspects not mentioned here). Even if one assumes that abundance anomalies in these stars are real and restricted only to the surface layers, it is still possible to speculate on the origin of these anomalies.

(a) There may be some nuclear reactions in the interior which combine with surface spallation (Fowler *et al.* 1965). Several arguments exist against such an explanation, and, even if it is true, it has not too much value for our study of the heaviest elements.

(b) Surface nuclear reactions (e.g. Brancazio & Cameron 1967) do not have much application to the abundances of the heaviest elements.

(c) Michaud's (1970) diffusion theory may account for some observational peculiarities, and it might be combined with another mechanism (Sargent & Burbidge 1970).

(d) Abundance anomalies may result from accretion of material from: I. the interstellar medium (Havnes & Conti 1971); II. a nearby highly evolved companion (from a possible binary system), which might have lost matter either by a single supernova explosion or in some other way (giant stage, etc.). This latter theory has been considered in the preceding sections, and it seems to be relatively well justified (Renson 1965; all papers by Guthrie).

We have not considered here such characteristics of the peculiar A stars as their magnetic fields, rotation, etc. (Strittmatter & Norris 1971; Durrant 1970; Preston 1971b), for it was our aim to emphasize the role of the Ap stars in nucleosynthesis. Due to the supposed peculiarities of their evolution they appear to give much more evidence for the r-process than other types of stars. A combination of various recent models may lead to a reasonable theory of these objects and to a deeper insight into the r-process at the same time. Let us await further discoveries—of hitherto unexpected elements and in overabundant quantities. This should lead us towards a possibly more certain explanation of the surface abundances, perhaps in terms of all the mechanisms above—in reasonable proportions.

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