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FUSION REACTIONS

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EXOTIC NUCLEI IN DEEP-INELASTIC AND FUSION REACTIONS

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Abstract: A review is given on recent progress in studies of nuclei far from beta stability, with particular emphasis on the use of heavy-ion beams.

1. Introduction

A short review on a rapidly developing research field such as the study of nuclei far from beta stability can only aim at showing a few examples, the selection of which is very much a question of personal taste. Here my bias has led me to select some *recent* results, which either have been presented at the Helsingør conference¹⁾ in 1981 or have appeared more recently, and to concentrate on studies that used *heavy-ion* reactions as the production mechanism. The latter restriction is not particularly justified, as a considerable part of the progress in the field of exotic nuclei is due to experiments with high-energy protons. Moreover, I shall dwell upon properties of ground states and low-lying long-lived isomeric states, rather than on data pertaining to highly excited states of short lifetime and high spin, even though a wealth of interesting nuclear-structure information has been gained there, too.

The term "exotic" in the present context expresses the fact that in general we consider nuclei far from the region of beta stability, and that we have to deal with rare events (down to rates of 1 atom/d against 10^{13} unwanted radioactive atoms/d). It does not mean that the underlying nuclear physics is entirely different from the one of stable nuclei. The motivation for investigating exotic nuclei is rather "learning more about the nucleus from artificial nuclei"²⁾, whose proton and neutron number we can "dial", over wider and wider ranges in the laboratory.

Following an initial description of the properties of heavy-ion reactions with respect to the production of exotic nuclei, examples are given of new radioactive decay modes signaling the approach to and passage of border lines of particle stability. Here special emphasis is put on the recently discovered direct proton decay of ^{147}Tm and ^{151}Lu . Subsequently, new information on shell closures and regions of deformation far from beta stability is given for several cases reaching from the light to the rare-earth nuclei. Finally an attempt is made to summarize recent developments, including some of astrophysical interest and examples from studies of the heaviest known elements.

2. Heavy-ion reactions

2.1 FUSION-EVAPORATION REACTIONS

Fusion-evaporation reactions, representing the classical type of heavy-ion reactions for producing exotic nuclei, are still used extensively: For example, *neutron-rich* projectiles such as ^{54}Cr or ^{58}Fe with energies of 4.7-5.1 MeV/u and ^{209}Bi targets have been applied with particular success in reaching element 107 and 109 through compound-nuclear reactions followed by 1n evaporation; by contrast, availability of beams of *neutron-deficient* isotopes (such as ^{40}Ca or ^{58}Ni) in the same energy range enabled us to produce and study very light isotopes in the element range between tin and lead. By studying fusion-reaction mechanisms close to the interaction barrier of medium-mass nuclei, we have made progress in finding optimum conditions for producing very neutron-deficient isotopes at or beyond the proton drip-line. Here, in contrast to cases of heavy compound-nuclei close to

the beta stability with dominant neutron-evaporation, strong charged-particle emission contributes to driving the evaporation residues towards the beta stability line. We shall return to some particularly interesting evaporation channels such as $1n$, $p2n$, $2p4n$ below when discussing the properties of specific nuclei.

One should keep in mind, however, that fusion-evaporation reactions induced by *light* ions also are a useful tool for reaching out to the limits of stability. E.g. Cable et al.³⁾ recently discovered the first odd-odd member of the $T_z=-2$ series, ^{22}Al , from $^{24}\text{Mg}(^3\text{He}, p4n)$ reactions. Two new proton groups were observed at 7.839 and 8.149 MeV and ascribed to the isospin forbidden proton decay of the lowest $T=2$ state in ^{22}Mg fed by the superallowed β^+ decay of the $T=2$ ground state of ^{22}Al (see fig. 1). Disregarding the interesting discussion³⁾ of ^{22}Al with respect to β -decay, Coulomb displacement energy calculations and the Isobaric Multiplet Mass equation, we note that this nucleus is bound with respect to direct proton emission by only 102 keV; and, that the ground state of ^{22}Al should, comparing it with the mirror nucleus ^{22}F , be its only bound state. Goldanskii⁴⁾ proposed that beta-delayed two-proton emission, a hitherto unobserved nuclear decay mode, might contribute to the 8 MeV "bump" in the proton spectrum observed for the ^{22}Al decay (see fig. 1).

Fig. 1 Measured beta-delayed proton spectrum of ^{22}Al and proposed decay scheme. Note the possibility for beta-delayed two-proton emission.

2.2 PRODUCTION OF NEUTRON-RICH ISOTOPES IN QUASI-ELASTIC AND DEEP-INELASTIC TRANSFER REACTIONS

Over the past decade, quasi-elastic and deep-inelastic transfer reactions with heavy ions have been studied in some detail both experimentally and theoretically (see ref. 5 for a review). As far as isotope population is concerned, a strong dependence on the potential energy surface of the double nuclear system has been revealed⁶⁻⁹). As can be seen from fig. 2: for the N=82 projectile ^{136}Xe , one expects some preference for the pick-up of protons from the target nucleus; and, for a ^{238}U projectile, the production of neutron-rich nuclei should profit both from the increased N/Z-ratio and from the increased width of the potential energy surface in the mass coordinate¹⁰). More specific nuclear structure effects, e.g. those enhancing the neutron-rich flow¹¹), also have to be taken into account. Still, in order to optimize the production of extremely neutron-rich isotopes from (the tails of the cross section distributions of) multi-nucleon transfer reactions, more detailed studies of the neutron and proton exchange mechanisms are necessary. The experimental data available so far are scarce and unsystematical in this respect.

More than ten years ago, Artukh et al.⁶) identified a series of new neutron-rich isotopes of elements below argon ($Z=18$) using particle-identification techniques in an investigation of the reactions of 7.25-MeV/u ^{40}Ar ions with thorium targets. Recently, Guerreau et al.¹²) and Breuer et al.¹³) continued to investigate such projectile break-up reactions; but, the only nuclear property determined in these experiments (limited to nuclei with $Z \leq 26$) was that they are bound against particle (i.e. neutron) decay. It was by the application of on-line mass separation, that beta and gamma decay properties were measured by Gurach et al.¹⁴) for ^{41}Cl from 7.25 MeV/u ^{40}Ar +tantalum reactions, and recently by Runte et al.¹⁵) for ^{62}Mn , ^{63}Fe , $^{71-73}\text{Cu}$ from 9-MeV/u ^{76}Ge + tantalum-tungsten reactions. Additionally, the latter group is planning¹⁶) to use ^{82}Se beams for these measurements, and has applied *target break-up* reactions combined with on-line mass separation to investigate the beta and gamma decays of the new isotopes ^{179}Yb and $^{181-183}\text{Lu}$ (refs. 17,18), using 9 and 11 MeV/u ^{136}Xe + tantalum/tungsten reactions (see fig. 2). There are also plans¹⁰) to produce and study neutron-rich actinide isotopes by applying radiochemical methods to reactions such as $^{238}\text{U} + ^{248}\text{Cm}$ (ref. 19).

Again, I would like to emphasize that major contributions have come from studying transfer reactions with "*light*" heavy-ions by magnetic spectrographs and/or $\Delta E-E$ techniques. Bernas et al.²⁰) used e.g. ($^{14}\text{C}, ^{16}\text{O}$) reactions for determining ground-state mass-excess values and excited-state energies in the iron-to-germanium region. Excited states of ^{102}Mo and ^{106}Ru have been studied²¹) by means of ($^{18}\text{O}, ^{16}\text{O}$) reactions and particle-gamma coincidence techniques; similar experiments are planned in the lanthanide region using ^{22}Ne beams. These measurements yield information on excited states complementary to decay studies such as the ones mentioned above, and further, have the advantage of making high-spin (yrast) states accessible. In order to reach very high spin values or large ranges of excitation energies (including the giant dipole resonance) in deep-inelastic reactions, heavy projectiles such as in the 8.5-MeV/u $^{136}\text{Xe} + ^{181}\text{Ta}$ system²² are of advantage.

Another fascinating aspect of heavy-ion reactions with strong energy-damping and high angular-momentum transfer is the question of their time scale. Von Harrach et al.²³) succeeded recently in finding a "direct clock" for these reaction dynamics. In studying the "sequential fission" mechanism, in which the first binary step results in fragments with sufficient excitation and spin to undergo subsequent fission, they determined the scission-to-scission time in 12.5 MeV/u $^{129}\text{Xe} + ^{122}\text{Sn}$ reactions to be 1×10^{-21} s. Furthermore, the energy spectra of positrons emitted in "quasimolecular" uranium-on-uranium collisions might be a sensitive tool to gain information on reaction times and to establish eventually the optimum conditions for formation of giant nuclear systems with $Z \sim 184$ (see e.g. ref. 24). In this context one should remember, that the search for long-lived superheavy elements from ^{238}U on ^{248}Cm reactions has remained unsuccessful so far, yielding a (model dependent) upper cross-section limit of $3 \times 10^{-35} \text{ cm}^2$ or 30 pb ²⁵).

Fig. 2 Potential energy surfaces of the double-nuclear systems 7.5-MeV/u ^{136}Xe on ^{186}W and 5.4-MeV/u ^{136}Xe on ^{244}Pu . In both cases the area near the injection point is displayed for grazing collisions with 0.5-MeV contour lines. Overlaid are sections of the chart of nuclides showing the most neutron-rich known isotopes below the target nucleus, including the new isotopes 8.1-min ^{179}Yb , 3.5-min ^{181}Lu , 2.0-min ^{182}Lu and 58-s ^{183}Lu identified in ^{136}Xe on tantalum/tungsten reactions. Note the potential energy ridge along the neutron number $N=112$ of the target which reflects the closed neutron-shell $N=82$ of the projectile.

2.3 FRAGMENTATION OF RELATIVISTIC HEAVY-IONS

In recent experiments^{26,27)} with 205-MeV/u ^{40}Ar and 200-220 MeV/u ^{48}Ca beams on beryllium and carbon targets, respectively, it was shown that magnetic A/Z separation, combined with detection in a semi-conductor telescope, represents a powerful tool for identifying new neutron-rich nuclei up to chlorine and for measuring their beta-decay half-lives²⁸⁾ (see fig. 3). It is interesting to notice, how similar the trend of the cross section as a function of mass number is for the reactions induced by different relativistic projectiles (see fig. 3a). So far, the maximum beam intensity has been of the order of 10^7s^{-1} , which, together with the difference in target thickness, means that the presently available production rates from relativistic heavy-ion fragmentation falls short by approximately seven orders-of-magnitude compared to high-energy proton reactions. However, the kinematical advantage of forward focussing of the former reaction, plus the implantation technique, are able to compensate for this large difference (at least partly); and, it is therefore with great interest that one is waiting for further experiments with relativistic projectiles such as ^{48}Ca , especially at higher beam intensities. It is easy to predict their success with respect to identifying new isotopes, whereas determination of decay properties appears to be more difficult.

Fig. 3 (a) Comparison of production cross sections for sodium isotopes produced in $^{48}\text{Ca}+\text{Be}$, $^{40}\text{Ar}+\text{C}$ and $p+^{238}\text{U}$ reactions (the heaviest known isotope of sodium, identified in the latter type of reactions, is ^{35}Na , whose half-life was measured²⁹⁾ to be $1.5 \pm 0.5\text{ ms}$). (b) $Z=13$ particle-identification spectrum obtained in 11.4-GeV $^{40}\text{Ar}+^9\text{Be}$ reactions. The inset shows the data for the ^{32}Al beta-decay half-life measured in this experiment.

3. New radioactive decay modes

The investigation of the limits of particle stability and in particular the search for proton- or neutron-radioactive nuclear states has always been one of the most interesting questions within the "far from stability" field. The term "radioactive" relates to a *long* lifetime of such a state, the time scale being admittedly debatable. We shall discuss new results on the proton-drip line and especially on two cases, where a well-defined (i.e. not a statistical average) nuclear state - presumably the ground state - decays by proton emission with a

half-life of the order of a fraction of a second. Of course, particle emission from *short-lived* excited nuclear states is commonplace for many nuclear-reaction or nuclear-spectroscopy phenomena, when the limits of particle stability within a given nucleus are passed by increasing the excitation energy above the respective separation energies. We have referred to this effect, without mentioning it explicitly, throughout the above discussion of heavy-ion reactions, and it is inherent in the phenomenon of beta-delayed particle emission. Beta-delayed emission of protons and alpha particles has been studied for a large number of nuclei, in particular at Dubna³⁰), CERN³¹) and Chalk River³²); whereas, beta-delayed two-proton emission (mentioned briefly in the above discussion of the ²²Al decay) was searched for unsuccessfully in the case of the ¹¹⁰I decay³³). Beta-delayed neutron emission has been investigated in some detail recently, in particular by Kratz et al.³⁴); it now includes exotic new decay modes such as two-neutron^{35,36}) and three-neutron³⁷) emission, as well as break-up (of ¹⁰Be) into ⁶He and an alpha particle³⁸).

The proton-drip line can be localized experimentally either by detecting direct-proton decay of nuclei beyond this line or by determining proton separation energies S_p of isotopes before this line. Results from the latter method, presented in fig. 4, suggest that ¹¹⁰I and ¹¹⁴Cs are the lightest bound isotopes of iodine and cesium. The properties of ¹¹⁴Cs are shown in table 1 together with those of ¹¹Li and ²²Al, representing three weakly bound nuclei (presumably the last bound isotope of the respective elements). Searches for ¹¹³Cs have yielded negative results^{46,47}), perhaps because this isotope has a very short lifetime against proton decay. However, such experiments have been successful for ¹⁴⁷Tm and ¹⁵¹Lu. In addition to the proton energy and the half-life (see fig. 5 and table 1) of these two isotopes (produced via ⁹²Mo(p2n) and ⁹⁶Ru(⁵⁸Ni,p2n) reactions, respectively), the following signatures of this novel radioactivity have been obtained:

- (1) proton identification by means of ΔE -E techniques;
- (2) determination of the mass number (for ¹⁴⁷Tm) by magnetic mass-separation techniques;
- (3) cross-bombardment and excitation-function (for ¹⁵¹Lu) measurements;
- (4) proton-positron and proton X-ray measurements which exclude a beta-delayed emission process;
- (5) measurement of the angular distribution of evaporation residues, used for identifying the deexcitation channel (for ¹⁵¹Lu).

The assignment of direct proton decay to ¹⁴⁷Tm and ¹⁵¹Lu is based on these results as well as on cross-section and separation-energy systematics. Since the branching ratio between direct proton decay and competing (β^+ /EC) decay modes is not determined yet, the measured total half-lives of 560 ms and 85 ms, respectively, can only be considered as lower limits for the partial proton half-life. Nevertheless, it is tempting to compare them with half-lives calculated by analogy with alpha decay: WKB calculations appear to yield a good approximation for s-wave alpha decay widths, leaving for the remaining nuclear structure effect a smooth increasing trend with increasing neutron number between shell closures; this systematical trend is well documented in the region $N=82$ to $N=126$, with experimental data reaching from ¹⁰⁶Te to ²⁵⁶Fm (see fig. 6).

We estimate the partial proton half-life by calculating the decay constant λ_p ,

$$\lambda_p = T_{j\ell} \times f, \quad (1)$$

as the product of the transmission coefficient $T_{j\ell}$ for a proton of total spin j and orbital angular momentum ℓ , and the "frequency factor" f ,

$$f = v_F/2R = 6.8 \times 10^{21} \text{ s}^{-1}, \quad (2)$$

where v_F is the Fermi velocity and R is the nuclear radius. The transmission coefficients were calculated with a WKB method using the real part of the optical

Fig. 4 Proton separation energies for neutron-deficient isotopes of antimony, iodine and cesium, deduced from mass-excess values of neighbouring isotones. Experimental results are from refs. 39-41 (full circles), from the 1977 mass evaluation⁴²⁾ (open circles) and from combining data from the latter reference with recent mass-spectrometric results⁴³⁾ (open squares). Predictions from a droplet⁴⁴⁾ and an inhomogeneous-partial-difference-equation⁴⁵⁾ mass formula are also shown.

Table 1

Compilation of separation energies and decay data for: ^{11}Li , ^{22}Al and ^{114}Cs , which represent nuclei situated directly on the stable side of the particle drip line, and for the known proton-radioactive cases $^{53}\text{Co}^m$, ^{147}Tm , ^{151}Lu .

Nucleus	$T_{1/2}$	Separation energy	Measured decay properties	References
^{11}Li	8.7 ± 0.1 ms	$S_{2n} = 160 \pm 120$ keV	$\beta\gamma$, βn , $\beta n\alpha$, $\beta 2n$, $\beta 3n$	35, 37, 38, 42, 46, 47
^{22}Al	~ 70 ms	$S_p \sim 102$ keV	p	3
^{114}Cs	0.57 ± 0.02 s	$S_p = 290 \pm 200$ keV	α , $\beta\gamma$, βp , $\beta\alpha$	48
$^{53}\text{Co}^m$	247 ± 12 ms	$S_p = -1620 \pm 30$ keV	p	49
^{147}Tm	0.56 ± 0.04 s	$S_p = -1062 \pm 6$ keV	p	50, 51
^{151}Lu	85 ± 10 ms	$S_p = -1239 \pm 3$ keV	p	52

Fig. 5 (a) Energy spectrum obtained at mass 147 from investigating $^{58}\text{Ni}+^{92}\text{Mo}$ reactions at the GSI on-line mass separator; the 1055-keV proton line is assigned to the direct decay of 0.56-s ^{147}Tm .
 (b) Energy spectrum obtained from $^{58}\text{Ni}+^{96}\text{Ru}$ reactions at the velocity filter SHIP; the 1231-keV proton line is assigned to the direct decay of 85-ms ^{151}Lu .

Fig. 6 Reduced width W_α for s-wave alpha decay of even nuclei as a function of the neutron number of the emitter. W_α values are obtained according to $W_\alpha \propto \lambda_\alpha / P$, where λ_α is the measured partial transition-probability for alpha decay and P is the calculated⁵³⁾ barrier penetrability for s-wave alpha particles, and normalized to ^{212}Po . The proton number of the emitter is indicated. Experimental data are from ref. 54, but include the more recent refs. 55-60. Note in particular the lightest known alpha emitter, 60- μs ^{106}Te , produced as alpha decay daughter of ^{110}Xe in $^{58}\text{Ni}(^{58}\text{Ni}, 2p4n)$ reactions (ref. 59).

Table 2

Comparison of calculated partial proton-decay half-lives with measured values

Nucleus	$^{53}\text{Co}^m$	^{147}Tm			^{151}Lu		
Experiment	~ 17 s	≥ 0.56 s			≥ 85 ms		
Calculation	$19/2^-$ 60 ns	$s_{1/2}$ 65 μs	$d_{3/2}$ 0.6 ms	$h_{11/2}$ 2.0 s	$s_{1/2}$ 2.3 μs	$d_{3/2}$ 20 μs	$h_{11/2}$ 59 ms
Ref.	49	50, 51			52		

model potential given by Becchetti and Greenless⁶¹). By comparing the calculated partial proton-decay half-lives with the measured limits (see table 2), one can speculate that both the ^{147}Tm and ^{151}Lu decay involve an angular momentum change of $5\hbar$, and represent a transition from a $\pi h_{11/2}$ single-proton state to the 0^+ ground state of the even daughter nuclei ^{146}Er and ^{150}Yb , respectively. Even though the measured half-lives are only limits for the partial proton decay, one can further speculate that the proton decay, at least for ^{151}Lu , occurs from a "good" single-particle state with a spectroscopic factor between 0.1 and 1, and therefore, represents the first observed case of a *one step* (in the sense of perturbation theory) direct proton decay⁵²). This contrasts drastically with the $^{53}\text{Co}^m$ decay which has a very large hindrance factor of about eight orders of magnitude, apparently due to a complex rearrangement process involving the detailed many-particle structure of the parent state (see ref. 62, and also calculations cited in ref. 63).

I would like to emphasize that there is some ambiguity left in the assignment of the proton radioactivity to ^{147}Tm and ^{151}Lu , in particular with respect to the Z-assignment and/or the occurrence of isomers: It is worth performing additional experiments, which might shed light on these points as well as on the spin assignment; and, to search for other cases of direct proton radioactivity. In parallel, there are attempts underway to do more refined calculations of the proton decay constants of ^{147}Tm and ^{151}Lu (refs. 64,65).

4. Magic and quasi-magic nuclei far from beta stability

In studying nuclear properties far from stability, the magic nucleon configurations 20, 28, 50 and 82 have particular interest recently: E.g. excited states of doubly-magic ^{132}Sn were investigated⁶⁶) by beta-gamma measurements to quite some detail; and the onset of a new region of deformation has been found for neutron-rich isotopes of sodium⁶⁷) and magnesium⁶⁸) around the $N=20$ neutron shell closure. Exciting new results have been obtained in the regions around *quasi-magic* nuclei such as $^{68}_{28}\text{Ni}_{40}$, $^{90}_{40}\text{Zr}_{50}$, and $^{146}_{64}\text{Gd}_{82}$. These nuclei are characterized by having both magic and quasi-magic nucleon number. I shall try in the following to very briefly cover measurements of ground-state masses and excited-state properties for these three cases, describe the status of the experimental approaches towards doubly-magic $^{100}_{50}\text{Sn}$, and include as an example also results on mean-square radii obtained from collinear laser spectroscopy measurements in the transitional region above $N=82$.

Bernas et al.²⁰) succeeded recently in determining the ground-state mass-excess as well as the 0^+ and (tentatively) 2^+ excited states of ^{68}Ni , using $^{70}\text{Zn}(^{14}\text{C},^{16}\text{O})$ reactions. The mass-excess data available in this area do not allow a detailed discussion of the mass surface, e.g. a systematics of two-neutron separation energies along $Z=28$. However, as can be seen from fig. 7, the inversion of the 2^+ and 0^+ states, has a striking similarity with ^{90}Zr (ref. 55) - these exciting levels agreeing for the two nuclei within a few keV: In both cases, the $1f-2p$ shell is being closed for $N(\text{or } Z)=40$, increasing the sphericity of those nuclei. In order to further investigate the quasi-magic properties of ^{68}Ni , more data on masses and excited states of nuclei in this area are needed. As was mentioned already in chapter 1.2., besides $(^{14}\text{C},^{16}\text{O})$ reactions the break-up of ^{76}Ge or ^{82}Se projectiles appears to be promising means for producing such nuclei. In fig. 7, the new neutron-rich isotopes, whose properties were studied recently using ^{76}Ge on tantalum/tungsten reactions, are shown (heavily outlined squares) together with stable nuclei (hatched squares) and other isotopes with known decay properties (squares): Note that the beta decay half-life and other decay properties of ^{68}Ni are not yet known. Finally, it is tempting to investigate the experimental possibilities of reaching out to ^{67}Fe (marked by "m" in fig. 7), where a high-spin ($19/2^+$) isomeric configuration $[(\pi f_{7/2})^{-2}]_{6+} \cdot (\nu g_{9/2})^1$ might occur at high excitation energies and might decay by direct neutron emission.

The double-shell closure expected for ^{100}Sn has not been reached yet due to the very small cross sections for its production in fusion-evaporation reactions. Nevertheless, some progress has been made recently in approaching ^{100}Sn , e.g. by

Fig. 7 Comparison of the quasi-magic nuclei ^{58}Ni and ^{90}Zr (see text).

identifying the beta-delayed proton precursors ^{100}In (ref. 69) and ^{103}Sn (ref. 70) as well as the $^{106}\text{Te} \rightarrow ^{102}\text{Sn}$ alpha decay⁵⁹); and we are able to deduce quantitative information on the $Z=N=50$ double shell-closure from the following sources (see fig. 8):

- (1) The occurrence of an island of alpha decay⁵⁹) in the region of light tellurium-to-cesium is already a qualitative hint for the tin shell closure; besides the discussion of alpha decay widths (see section 3), qualitative conclusions with respect to the $Z=50$ proton shell strength⁴¹) can be drawn from alpha decay Q -values combined with additional Q -values and mass data.
- (2) From a fluctuation analysis of beta-delayed proton spectra, a very low value of the level density parameter α was found⁷¹) for ^{99}Ag , indicating the strong influence of the double shell closure $N=Z=50$ on the level density.
- (3) The 2^+ , 4^+ , 6^+ , 8^+ yrast states, observed⁶⁹) in ^{96}Pd , can be described within a shell model, assuming a ^{100}Sn core and proton holes in the $2p_{1/2}$ - $1g_{9/2}$ sub-shell to yield $[(p_{1/2}, g_{9/2})^{-2}]_0^+ [(g_{9/2})^{-2}]_1^+$ configurations.

It is worth noting again the occurrence of high-spin isomers (marked by "m" in fig. 8): Using $^{58}\text{Ni}(^{40}\text{Ca}, 2pn)$ reactions, Nolte and Hick^{72,73}) identified a long-lived $21/2^+$ isomeric state in ^{95}Pd and interpreted it as a spin-gap⁷⁴) isomer; a similar $23/2^+$ isomer, predicted⁷⁴) in the isobaring neighbouring nucleus ^{95}Ag to have a half-life of the order of 1s with respect to a M3 deexcitation, might possibly decay by direct proton emission.

Another quasi-magic nucleus far from beta-stability is ^{146}Gd . Measurements of masses in this area are partly contradictory and do not form a consistent basis for, e.g., two-proton separation energy systematics. On the other hand, results from extensive spectroscopic studies of nuclei around ^{146}Gd by many groups and in particular by Kleinheinz et al.⁷⁵) are in accord with a ~ 3.5 MeV single-particle energy gap at $Z=64$, which makes ^{146}Gd suitable as a shell-model core similar to ^{90}Zr . Current experiments^{76,77}) extend e.g. the systematics of $N=82$ even-parity yrast states in $Z=66, 68$, etc. with particular emphasis on the 10^+ seniority isomers⁷⁸), in which only $h_{11/2}$ orbitals contribute. (Note the correspondence with the $[(p_{1/2}, g_{9/2})^{-2}]_0^+ [(g_{9/2})^{-2}]_8^+$ state in ^{96}Pd and with above discussion of high-spin isomers in the area around ^{100}Sn : the $N=82$ 10^+ isomers might become unbound for $Z \geq 70$.) Another interesting result is the unusually high amount of structure observed⁵⁰) in the proton spectrum from the decay $^{147}\text{Dym} \xrightarrow{\beta^+/\text{EC}} ^{147}\text{Tb}^* \rightarrow ^{146}\text{Gd}$: An analysis analogous to the one made in above-mentioned case of ^{99}Ag might yield a low level density as expected for a single proton nucleus ^{147}Tb .

Quasimagic nucleon numbers are of course less stable than magic ones; moving away from the magic particle number of a quasi-magic nucleus, e.g. from $N=82$ in the case of ^{146}Gd , its quasi closed-shell properties such as sphericity disappear more rapidly than for doubly-magic nuclei. In this context, the results on mean-square charge radii are relevant, which were obtained⁷⁹) recently by fast-beam laser spectroscopy for long chains of isotopes of dysprosium ($Z=66$), erbium ($Z=68$) and ytterbium ($Z=70$): As can be seen from figs. 9 and 10, there is a sharp increase of the mean square charge radii between $N=88$ and $N=90$, corresponding to an abrupt onset of nuclear deformation, for dysprosium ($Z=66$); this sudden "jump", which is also known⁸⁰) for the stable even nuclei between neodymium ($Z=60$) and gadolinium, disappears gradually for the higher- Z elements erbium and ytterbium as well as for the lower- Z element barium ($Z=56$). This effect of stabilizing spherical nuclear shape by the proton subshell closure at $Z=64$ leads to equi-deformation curves which are almost parallel to the Z axis on the high- N side of ^{146}Gd . These conclusions are in agreement with a recent analysis of the energies of 2^+ and 4^+ states in the ground-state vibrational/rotational bands⁸²).

Considering the direct proton emission observed for ^{147}Tm and ^{151}Lu , and the assumption of a $(\pi h_{11/2})$ single-particle configuration as decaying state, there is considerable interest in extending both gamma- and laser-spectroscopic studies towards these nuclei. This corresponds, however to a giant increase in sensitivity necessary e.g. for the collinear laser method: So far, the measurements on mass-separated beams of rare-earth isotopes were restricted to intensities above approximately 10^7 atoms/s, whereas the corresponding rate of ^{147}Tm is of the order of 1 atom/s at present!

Fig. 8 Approaches towards the structure of the doubly-closed shell nucleus $^{100}_{50}\text{Sn}$, using (a) alpha decay data, (b) fluctuation analysis of beta-delayed proton spectra and (c) interpretation of positive parity states in even N=50 nuclei within a shell model. In the plot (b), the parameter α of the Fermi-gas level density formula is shown as deduced from fluctuation analyses (full points), from neutron resonance data (open points) and from semi-empirical models (see ref. 71 for details).

Fig. 9 Brix-Kopfermann diagram⁸⁰⁾ for the differences of mean-square charge radii between isotopes $N - 2$ and N . The horizontal dashed line corresponds to the spherical droplet model⁸¹⁾.

Fig. 10 Integral change of mean-square charge radii, with respect to the isotopes with $N = 82$. The slope of the equi-deformation lines is given by the droplet model⁸¹⁾.

5. Concluding remarks

In this short review I have tried to give a few examples of recent studies of exotic nuclei and to additionally include some remarks on future developments. The properties of exotic nuclei are of interest not only for nuclear physics, but also for astrophysics, and I would like to mention a few points related to results discussed above. Firstly, β decay half-lives and Q-values play an important role in calculating reaction rates of the nucleosynthesis⁸³⁾ in general, the mass 20-60 region attracting particular interest recently (see e.g. ref. 84). Furthermore, from estimates of the β^- -decay branches for $^{180}\text{Lu} \rightarrow ^{180}\text{Hf}^m \rightarrow ^{180}\text{Ta}^m$ ($T_{1/2} \geq 10^{13}\text{y}$) and measurements of the $^{179}\text{Hf}(n,\gamma)^{180}\text{Hf}^m$ production, one may speculate that the very low solar abundance of $^{180}\text{Ta}^m$ is predominantly due to r-process formation⁸⁵⁾; β - γ spectroscopy of mass-separated ^{180}Lu and ^{180}Hf sources may allow us to measure these branching ratios and to eventually use the $^{180}\text{Ta}^m$ abundance as a probe for the post r-process temperature of the supernovae explosion. Finally, our knowledge on heavy-ion reactions can be applied for producing radioactive ion beams⁸⁶⁾ and measuring small cross sections of astrophysical interest, e.g. those being critical in calculations of the solar neutrino rate.

Secondary beams of radioactive ions or in-situ production of secondary radioactive targets are objects of most interesting speculations (see e.g. ref. 87) not only in astrophysics, but also in nuclear physics. The presently-available secondary beams are, on the one hand side, nuclei in a wide Z- and N-range from high-energy proton reactions with intensities of separated isotopes up to 10^{11} s^{-1} at the ISOLDE facility⁸⁸⁾ at CERN. Post-acceleration of these beams⁸⁹⁾ would enable a variety of exciting possibilities: studies of transfer and fusion reactions; in-beam gamma spectroscopy of far unstable nuclei; production of exotic nuclei including very heavy and superheavy elements; deep implantation of radioactive ions for applied purposes. An alternative to post-acceleration is to use secondary beams from fragmentation of relativistic heavy ions. Anyway, one ought to look into these possibilities around the new generation of heavy-ion accelerators, and this is actually being done in the case of the SIS proposal⁹⁰⁾ at GSI.

I would like to conclude with a few remarks on the synthesis of the heaviest elements. In the Z_1 - Z_2 plane, shown as fig. 11, there appears to be a limiting "belt" region, to the high (Z_1+Z_2) side of which fusion is excluded; this limit was recently interpreted, within the "new dynamics" of the liquid drop model as being due to an increase of (or an "extra-push" over) the fusion barrier⁹¹⁾. Accordingly, current attempts to produce superheavy elements, being planned by a LBL-GSI collaboration, aim a formation of *cold* compound nuclei $^{48}\text{Ca}+^{248}\text{Cm}$ reactions with beam energies *below* the ones of earlier measurements. Cold fusion was also applied for unambiguously identifying element 107: Münzenberg et al.⁹²⁾ investigated evaporation residues from $^{54}\text{Cr}+^{209}\text{Bi}$ reactions, after in-flight separation by the velocity filter SHIP and implantation into a detector, by an ingenious measurement of time-of-flight, energies, positions and time differences for the evaporation residues as well as their alpha decay products. Six events were detected and assigned to the 10.376 MeV alpha decay of 4.7-ms $^{262}107$; fig. 12 shows one of the most significant events. It is only four weeks ago, that Münzenberg et al.⁹³⁾ succeeded with 5.15 MeV/u $^{58}\text{Fe}+^{209}\text{Bi}$ reactions to detect *one* event, which comprises two correlated alpha decays and a subsequent spontaneous fission process; this is preliminarily interpreted as evidence for the identification of $^{266}109$ - the heaviest isotope ever made. And with the message, that there is indeed multi-fold coincidence spectroscopy feasible now for elements at the very end of the periodic table and for production cross sections of the order of picobarn, I would like to close this survey on heavy-ion born exotic nuclei.

Fig. 11 Compilation of the fusion-reaction studies: Full points mark cases where evaporation residues were detected (at GSI), crosses stand for non-observation of fusion (in different laboratories). The hatched area corresponds to an X_{eff} value of 0.80, X_{eff} being the ratio of attractive nuclear forces and repulsive Coulomb forces in a configuration of two touching spheres (see ref. 91 for details).

Fig. 12 Identification of the isotope $^{262}_{107}$ from $^{209}\text{Bi}(^{54}\text{Cr}, n)$ reactions by establishing position- and time-correlated alpha decay links to known isotopes.

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