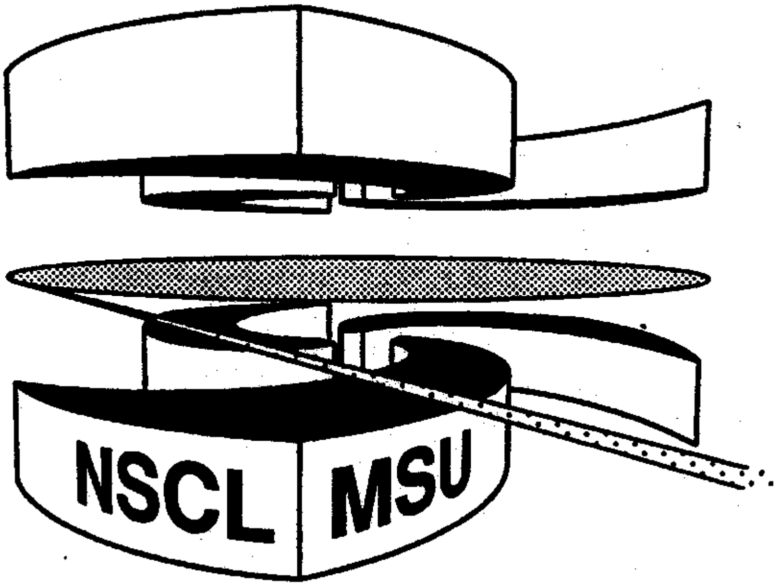
Michigan State University

National Superconducting Cyclotron Laboratory

EXPERIMENTS WITH RADIOACTIVE BEAMS

Paper presented at NN97,
Sixth International Conference on Nucleus-Nucleus Collisions,
Gatlinburg, Tennessee, June 2-6, 1997
To be published in Nuclear Physics A

P.G. HANSEN



MSUCL-1075

JUNE 1997

Experiments With Radioactive Beams

P.G. Hansen
National Superconducting Cyclotron Laboratory
and
Department of Physics and Astronomy
Michigan State University, East Lansing MI 48824-1322

1. INTRODUCTION

Slow radioactive ion beams were produced by on-line mass separation for the **first** time in an experiment in Copenhagen in 1961 [1] and this technique has been in regular use for studies of far-unstable nuclei since the late sixties. The pioneering development 121 of fast mass- and element-separated beams **from** fragmentation reactions of heavy ions at intermediate and high energies has added a second powerful tool for the study of exotic nuclei and has over the past decade stimulated a considerable experimental and theoretical interest in this area. These two techniques are currently at a number of laboratories being supplemented by a third one, the postacceleration of slow radioactive ions, which will allow experiments in the range of **0.5-6 MeV/nucleon,** thus at long last covering the essential region between energies of astrophysical interest and the Coulomb barrier. In this presentation I shall illustrate the way that this field is developing by giving examples of the experimental techniques and of the physics results that have been obtained.

2. BEAMS OF RADIOACTIVE NUCLEI

Techniques for producing beams of radioactive nuclei by on-line isotope separation and by **fragmentation** reactions are discussed in the paper by Geissel et al. [3]. As an example of a second-generation facility based on fragmentation reactions, Fig. 1 shows the central part of the NSCLMSU Coupled Cyclotron upgrade [4], which will increase the intensities. of a number of beams by approximately three orders of magnitude. Estimates show that this installation will allow the neutron drip line to be reached up to $Z=16$ where the current limit is approximately $Z=8$. A number of experiments at the GSI of which some are mentioned in the following demonstrate the value of a storage ring for fast radioactive beams, and the ambitious **RIKEN** Radioactive Ion Factory **Project** incorporates several storage rings and the possibility for studying beam-beam collisions with radioactive ions.

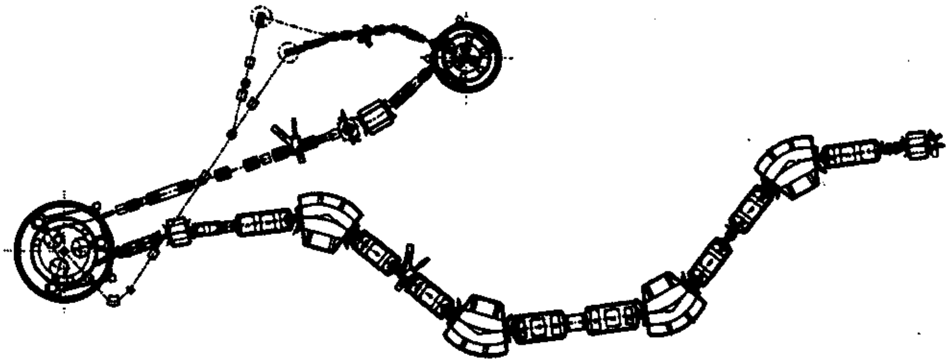


Fig. 1
Schematic layout of the Coupled-cyclotron Facility at MSU [4]. A beam from the ECR ion source is injected into the K500 superconducting cyclotron (top center) and further into the existing K1200 cyclotron (bottom left). The extracted beam is directed to a target at the entrance to the A1900 Fragment Mass Analyzer, which can deliver radioactive beams to all stations in the experimental area (not shown).

For completeness mention should here be made of the recoil mass spectrometers. These are very powerful tools for detecting rare and short-lived proton-rich nuclei from compound-nucleus reactions.

While the major facilities producing beams by fragmentation all are based on roughly equivalent techniques, the facilities based on postacceleration apply a wide variety of technical solutions for the key elements as illustrated in Table 1. Note that the Louvain-la-Neuve Facility, which is used primarily for astrophysical experiments, is the only one to have been in operation for a long time. The Oak Ridge Installation has just entered the operational phase and others will follow from 1998 and on.

3. EXAMPLES OF STUDIES OF MEDIUM-WEIGHT AND HEAVY NUCLEI

Let me mention in passing that two presentations at this Meeting deal with extremely proton-rich systems situated at the very limits of the nuclear chart, both produced by the powerful combination of intense *stable* beams and highly selective recoil spectrometers. The talk by G. Münzenberg [5] deals with the discovery of the heaviest elements and that by C. Davids [6] with the discovery of heavy proton radioactivities. The long alpha decay chains that emerge in both types of experiments provide valuable mass links that serve to constrain the binding energies of far-unstable nuclear systems, a problem that I shall return to in a moment.

The slow beams of high quality from on-line isotope separators are ideally suited for optical experiments, which provide information on nuclear charge radii, spins and moments, see the review by Otten [7]. As an example one may mention the recent experiments on the argon isotopes by R. Neugart and his collaborators (Klein et al [8]), which provide results for the argon isotopes, which in this paper are compared with modern shell-model calculations.

Table 1
Elements of Postacceleration Facilities

Driver (or primary accelerator)	Low-energy proton cyclotron (Louvain-la-Neuve, Oak Ridge, EXYT-Catania) High-energy proton accelerator (ISAC-TRIUMF, REX-ISOLDE (CERN) Light ions (C,O) (SPIRAL-GANIL) Reactor (PIAFFE (Grenoble))
Source of multiply-charged ions	ECR source connected to target (SPIRAL-GANIL, Louvain-la-Neuve) Stripping inside electrostatic tandem accelerator (Oak Ridge, EXYT-Catania) Charge "breeder" based on ion traps operating in pulsed mode (REX-ISOLDE) Acceleration of singly-charged ions (ISAC-TRIUMF)
Secondary accelerator	Cyclotron with axial injection (Louvain-la-Neuve, SPIRAL-GANIL, PIAFFE) Electrostatic tandem accelerator (Oak Ridge, EXYT-Catania) RFQ-Linac combination (REX-ISOLDE. ISAC-TRIUMF)

Another fundamental property is the nuclear mass. Although dedicated mass spectrometers continue to play a role, there are two new techniques that show great promise. One of this is to inject a radioactive beam at high energy into a storage ring and subsequently to cool it by electron cooling so that all ions (representing a multitude of masses and charge states) travel with the same velocity. The small differences in mass-to-charge ratios lead to differences in orbiting time, which can be picked up in a Schottky noise detector. The presence of a large number of species in the beam provides a number of near-lying reference points so that the calibration is similar to that of the classical doublet method in mass spèctroscopy [9]. These experiments are being discussed in the talk by C. Scheidenberger at this conference. The second technique is the use of a pair of Penning ion traps [10] so that the first trap cools the ions and the second, the precision trap, determines the ion mass from a measurement of the cyclotron resonance. In a new development by G. Bollen and his collaborators [11] a third trap has been added so that the ions from an isotope separator can be captured directly into a pre-cooler trap of the Paul type. Both the storage-ring and the trap methods have demonstrated sufficient mass resolution to resolve nuclear isomers, a problem that otherwise would limit the ultimate precision of the method.

At this point it is probably useful to inject a comment on why the problem of nuclear masses continues to hold such a prominent place on the agenda. After all, the problem is not exactly new and many apparently successful theoretical mass calculations exist. However, numerous examples have been brought forward to demonstrate that although the calculations account well for the known masses and their immediate neighbors, any attempt at a long-shot extrapolation to new regions is fraught with uncertainties. As an example consider the tin isotopes, for which beta stability corresponds to mass 118. The heaviest neutron-rich isotope of tin observed, so far, has mass 134. It seems likely that stable isotopes will exist at the doubly-magic combination with mass 176, but the position of the drip line must be considered uncertain by maybe 10 or 20 mass numbers, corresponding to uncertainties in the binding energy of many MeV. To provide experimental fixed points so far from stability is currently out of the question, so the best hope lies in further theoretical progress. In a recent paper B.A. Brown [12] has proposed a new set of Skyrme parameters obtained from a fit to binding energies, charge radii and energies of excited states for a set of doubly-magic nuclei including also exotic species such as ^{34}Si, ^{48}Ca, ^{48}Ni, ^{100}Sn and ^{132}Sn. The agreement is excellent, of the order of ±200 keV for the binding energies and 0.01 fm for the radii. The calculations suggest that the tin isotopes are stable at ^{176}Sn, and maybe even beyond. It will be seen that this approach, even without solving the problem of a general mass formula, at least at the present stage, goes some way towards furnishing a theoretically justified anchor point close to the drip line.

The special role played by the doubly-magic nuclei explains the large effort over the last few years to produce new species of the kind. It is interesting to note that the two mass 48 nuclei mentioned in the previous paragraph actually are mirror nuclei - and members of an isospin nonet - and that the nickel isotope [13] yet has to be observed although experiments are only one unit in mass number away. The only new doubly-magic region away from stability that has been the subject of in-depth studies is that of ^{132}Sn and its single-particle and -hole neighbors, largely due to the efforts of B. Fogelberg and his collaborators [14]. An interesting new result by Stone et al. [15] concerns the magnetic moment of the odd-proton nucleus ^{133}Sb, for which the measured magnetic moment exceeds the Schmidt limit by as much as 1.28 nuclear magnetons. This nucleus furnishes an important check on the contributions from core polarization and meson exchange effects to nuclear magnetism.

An important new development in the spectroscopy of exotic nuclei has been the Coulomb excitation of radioactive beams at GANIL, RIKEN and NSCL-MSU. Since the subject is being covered in a separate talk at this Conference by T. Glasmacher, see also the recent paper [16] and references therein, I shall say no more about this.

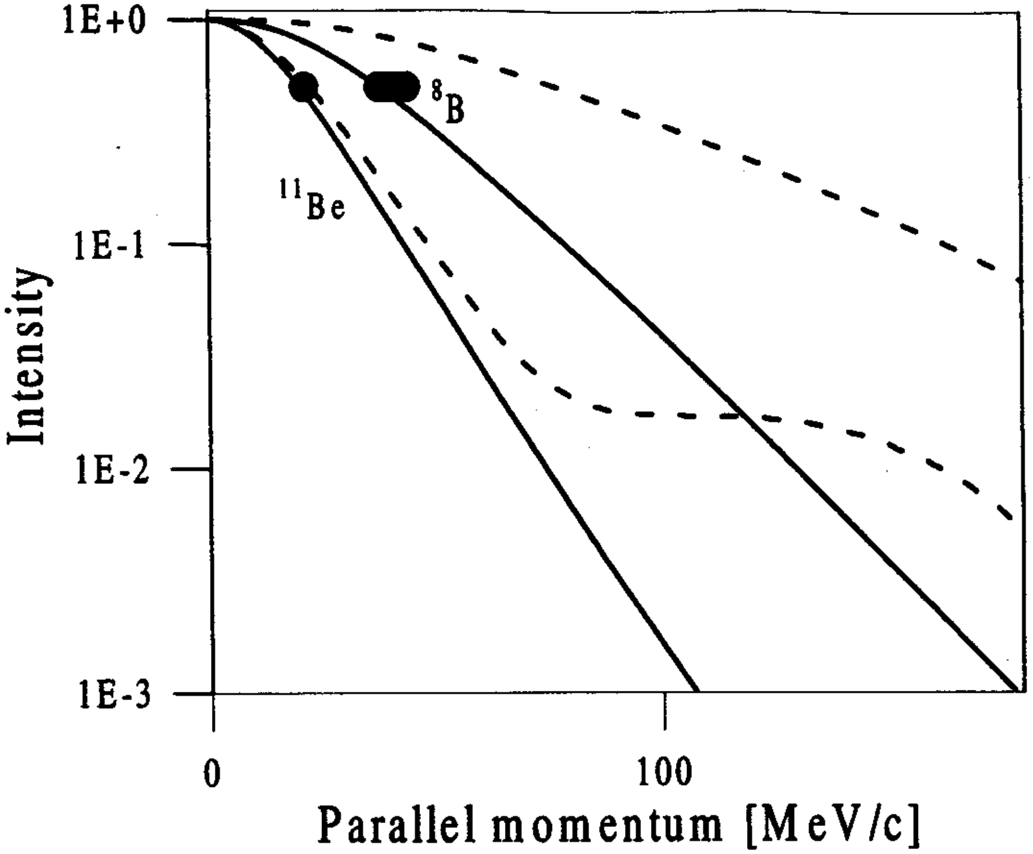


Fig. 2
The parallel momentum distributions of the core fragment from the single-nucleon stripping reactions of ^{11}Be ($s_{1/2}$ ground state) and ^{8}B ($p_{1/2}$ ground state). The dashed lines correspond to the total momentum wave functions and the full-drawn lines to a calculation [22] that takes into account the spatial selection in the reaction. The points are the measured half width at half maximum.

4. STUDIES AT THE NEUTRON DRIP LINE: NUCLEAR HALOS AND THE CONTINUUM PROBLEM

It is clear from the remarks in Section 3 that the neutron drip line is completely out of reach to experiments already in the middle of the nuclear chart. In fact, it seems to have been reached experimentally only up to oxygen. The NSCL Coupled-Cyclotron Upgrade carries with it the promise of making the neutron drip line accessible up to sulfur, but more detailed studies stop short even earlier; most of what we now know concerns helium, lithium and beryllium isotopes and the "frontier" in this respect is in the carbon isotopes. In the following are given examples of experiments on very neutron-rich systems including states that are unbound. Several reviews have covered the subject of light neutron-rich nuclei [17-19].

The measured total interaction cross sections for collisions of nuclei near the neutron drip line states with light targets show [18] an increase compared with what is expected for a normal structure. The indicates the formation of a halo structure, and the size of the halo has been inferred from this increase using a seemingly well-established approach called Glauber theory that effectively amounts to evaluating how much the nucleons in the nucleus screen each other from view of the projectile. In a significant new development that I assume will be discussed in the talk by J.A. Tostevin at this Conference it has been shown [20] that the halos are considerably larger than had been believed previously; thus the ^{11}Li neutron halo has an *rms* radius of about 7 fm instead of the 5 fm that had been believed previously. Their new theory brings an essential refinement of the established theoretical tools for estimating matter distributions of nuclei, and it has the attractive feature that in the limit of small halo size it agrees with the old and empirically well established calculations. The effect comes about essentially because the halo projectile approaches the target nucleus with a velocity that is much larger than the internal velocities of the constituents of the halo system. The outcome of the collision therefore reflects the "frozen" arrangement of the wave function. However, the usual calculation uses the wave function to construct an averaged radial and spherically symmetric density distribution and therefore underestimates the screening and overestimates the reaction probability. The upshot is then that when the size is inferred from a measured cross section, the halo radius is underestimated. This result illustrates how experiments on "exotic" systems can yield new insight into problems that were believed to be well understood from experiments with "ordinary" nuclei.

A second method for observing the size of the halo has been to measure the momentum widths in stripping reactions that remove the halo particle(s), the idea being that the large spatial size in the spirit of Heisenberg's uncertainty principle must translate into a narrow momentum width. It has commonly been assumed that the longitudinal momentum distributions of the core fragment in stripping and diffraction dissociation of halo states simply would represent the true momentum distribution of the halo state. The transverse momentum components carry similar information but are more sensitive to diffractive and Coulomb effects. This would imply that experiments on a single-nucleon halo measured the square of the Fourier transform of the total wave function. It has recently been pointed out [21-22] that the information actually obtained is more specific and, in fact, more interesting. The essential point is that the reactions that remove the halo nucleon sample only a region of space at distances larger than the sum of the core and target radii. The core-target collisions at small impact parameters lead to other exit channels, mainly complex fragmentation reactions. When this is taken into account, the calculations agree well with the measured [23,24] momentum widths and cross sections for the reactions (^{11}Be, ^{10}Be) and (^{8}B, ^{7}Be) on light targets as shown in Fig. 2.

The two-neutron halo of ^{11}Li is believed to have a pronounced three-body structure involving two neutrons and the ^{9}Li core, a problem that has attracted considerable experimental and theoretical interest. One of the observables that can throw light on this problem are the relative contributions of $(0p_{1/2})^2$ and $(1s_{1/2})^2$ to the halo wave function. One way to approach this problem is via the beta decay of ^{11}Li [25,26], which seems to indicate sizeable contributions of both. The beta decay also provides information on unique continuum structures in the daughter nucleus ^{11}Be, which have been observed in neutron, gamma-ray and charged-particle experiments. Measurements of ^{4,6}He and Be recoils [26] demonstrate the existence of an intermediate state in ^{11}Be at 18 MeV excitation energy and with a surprising low width, about 1 MeV.

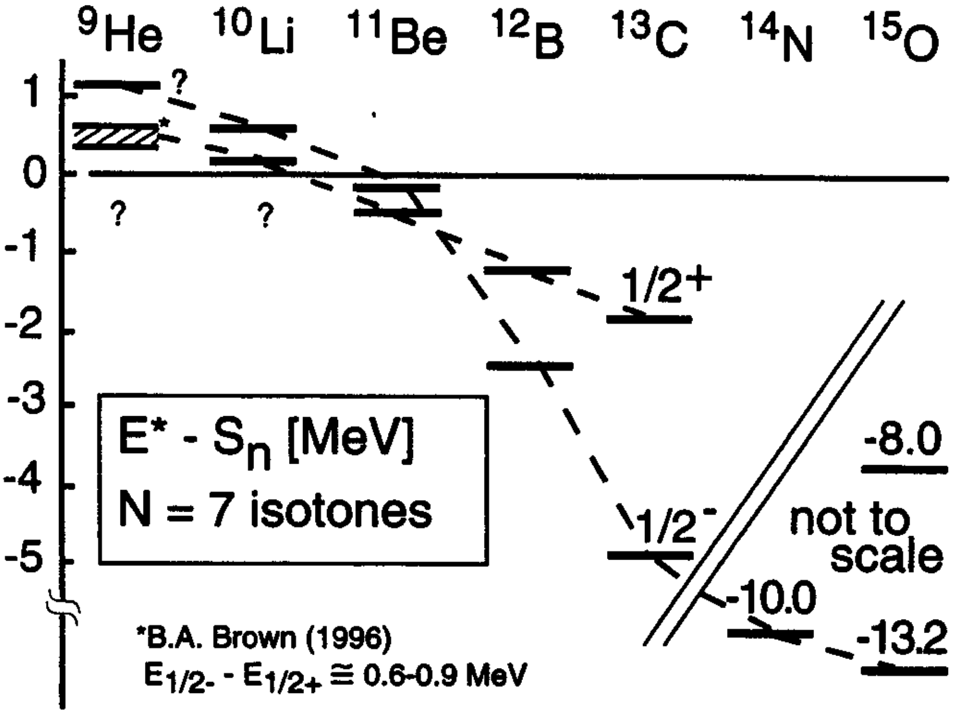


Fig. 3
Systematics of the difference between the excitation energy of the ½± states and the neutron separation energy for the N=7 isotones. Note the inversion for the lightest elements, well established for beryllium, likely for lithium and predicted by theory for helium.

Finally, I would like to mention three problems connected with the structure of continuum states in the region of the neutron drip line. The first concerns the *s* and *p* neutron interactions of a neutron with ^{9}Li to form unbound ^{10}Li are essential for the understanding of the ^{11}Li structure. It is now believed that the *s* intruder state, which forms the ground state of ^{11}Be, also is lowest in the Li and He members of the N=7 isotones, see Fig. 3, and strong final-state interactions in the (^{9}Li+n) channel [27,28] are taken to be experimental evidence in support of this. More work is clearly needed to resolve this problem.

Inelastic scattering data for protons from ^{11}Li (in inverse kinematics) have been interpreted as indicating [29] the excitation of a state at 1.3 MeV with positive parity and spin 3/2. However, a fully microscopic optical potential formed by folding of the scattering interaction with the nucleon occupancies and single-particle wave functions by Karataglidis et al. [30] fails to reproduce the cross section and angular distribution, although the procedure works well for other nuclei in this region and for elastic proton scattering on ^{9,11}Li. Karataglidis et al. suggest as an alternative explanation for the excitation close to 1.3 MeV that it represents nuclear shakeoff.

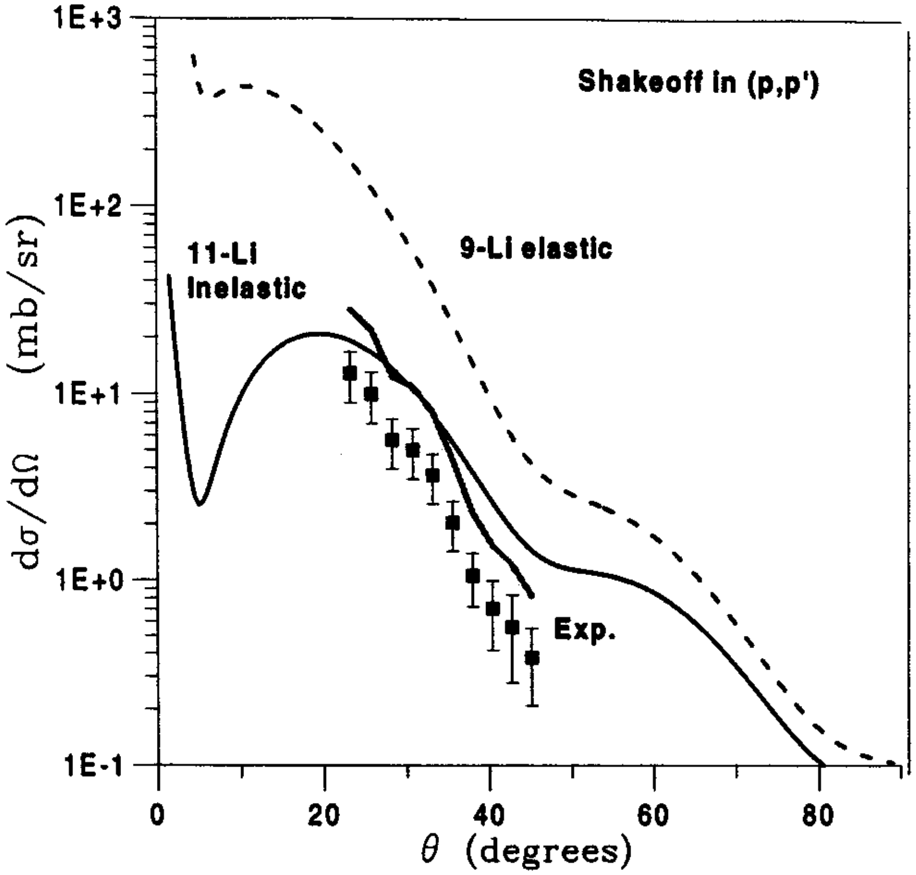


Fig. 4
The calculated [30] angular distributions for elastic proton scattering on ^{9}Li (dashed line) and for ineleastic scattering on ^{11}Li assuming a shakeoff mechanism (full-drawn line). The points are the measured values for the assumed 1.3 MeV excited level and the heavy line the same values rescaled under the assumption that the total obsewrved spectrum at low energy represents shakeoff

The basic process is taken to be elastic scattering of the proton from the ^{9}Li core. The momentum imparted to the halo in the new center-of-mass system entails a certain probability of breakup into the constituents ^{9}Li+n+n with a threshold energy of only 0.3 MeV. Such "shakeoff" processes are commonly encountered in atomic physics; another analogy is the recoilless absorption of photons in the Mössbauer effect, where the probability that the struck system remains in the ground state is referred to as the Debye-Waller factor. Since the ^{11}Li halo has no bound excited states, unity minus the Debye-Waller factor gives the shakeoff probability. (This is equivalent to a non-energy weighted sum rule.) The product of the differential ^{9}Li scattering cross section and the shakeoff probability agrees well with the experiment, see Fig. 4, and also can account for the energy spectrum.

It was found a few years ago [31] that polarization of radioactive nuclei may be obtained directly in fragmentation reactions. In a new experiment carried out at 240 MeV/u it has been shown by Chulkov et al. [32] that stripping of ^{6}He to the unbound intermediate nucleus ^{5}He leads to a spin alignment in a plane perpendicular to the ^{5}He momentum vector. The measured angular correlation is illustrated in Fig. 5. The authors point out that this effect seems to offer new possibilities for studying the structure of unbound states formed in the stripping of two-neutron halos and, in particular, for the study of the ^{10}Li problem discussed above.

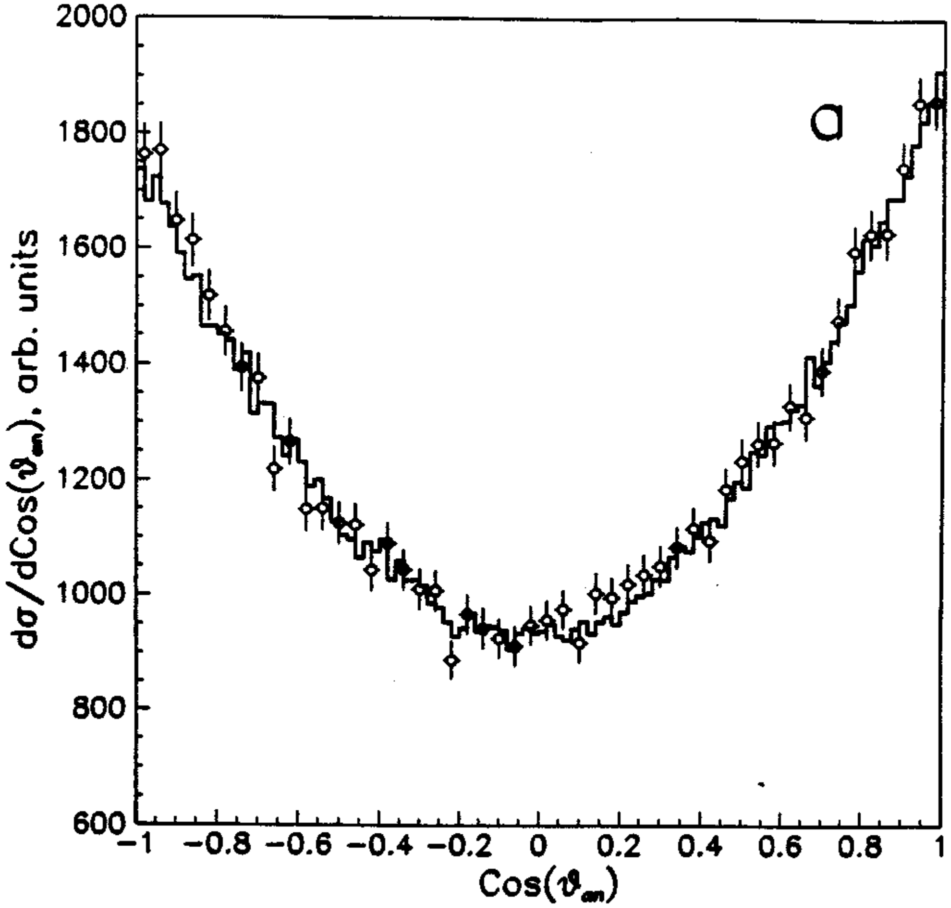


Fig. 5

Intensity of the emitted neutron from ^{5}He as a function of its angle (cm system) with the direction of the ^{5}He. The histogram is a Monte-Carlo calculation incorporating the experimental acceptance and assuming that the distribution in this coordinate system takes the form $1+A\cos^2\vartheta$ with A=1.50.

5. CONCLUDING REMARK

In this presentation I have chosen to concentrate on new physics results, mainly to give an impression of the richness of this field. I have said relatively little about the experimental challenges which, nevertheless, are substantial combining inverse kinematics, low intensities and complex coincidence requirements. The experiments with postaccelerated beams, which have barely begun, will be even harder but should provide information in an energy domain that is central to our understanding of the nucleus. We have an exciting period in front of us.

Acknowledgement. The author is indebted to Drs. G. Bollen, H. Geissel and B. Jonson for help with the choice of examples.

6. REFERENCES

1. O. Kofoed-Hansen and K.O. Nielsen, Phys. Rev. **82**, 95 (1951).
2. G. Westfall et al., Phys. Rev. Lett. **43**, 1859 (1979).
3. H. Geissel, G. Münzenberg and K. Riisager, Ann. Revs. Nucl. and Part. Sci., **45**, 163-203 (1995).
4. C.K. Gelbke, Nuclear Physics News **4**, 5 (1994); G.B. Lubkin, Physics Today May 1997, pp. 17-19.
5. G. Münzenberg, this conference; S. Hoffmann et al., Z. Physik A **354**, 229 (1996)
6. C. Davids, this conference; C. Davids et al., Phys Rev. C **55**, 2255 (1997).
7. E. Otten, Nuclear Radii and Moments of Unstable Isotopes, *in* Treatise on Heavy-Ion Science (D. Allan Bromley ed.), Plenum (NY, 1989) pp. 517-638.
8. A. Klein et al., Nucl. Phys. A **607**, 1 (1996)
9. H. Irnich et al., Phys. Rev. Lett. **75**, 4182 (1995).
10. T. Otto et al., Nucl. Phys. A **567**, 281 (1994).
11. G. Bollen, Methods of Atomic Physics: Masses, Spins, Moments and Radii, to be published in International School of Heavy Ion Physics, 4th Course: Exotic Nuclei (in preparation).
12. B.A. Brown, A New Skyrme Interaction for Normal and Exotix Nuclei, to be published.
13. W. Nazarewicz et al., Phys. Rev. C **53**, 740 (1996); B. Blank et al., Phys. Rev. Lett. **77**, 2893 (1996).
14. H. Mach et al., Nucl. Phys. A **588**, 179c (1995).
15. N.J. Stone et al. Phys. Rev. Lett. **78**, 820 (1997).
16. T. Glasmacher et al., Phys. Lett. B **395**, 163 (1997).
17. P.G. Hansen, A.S. Jensen and B. Jonson, Nuclear Halos, Ann. Rev. Nucl. Part. Sci. **45**, 591 (1995).
18. I. Tanihata, Progr. Part. Nucl. Phys. (A. Faessler ed.) **35**, 505-573 (1995)
19. B. Jonson, Nucl. Phys. A **583**, 733c (1995).

20. J.S. Al-Khalili and J.A. Tostevin, Phys. Rev. Lett. **76**, 3903-06 (1996); J.S. Al-Khalili, J.A. Tostevin and I.J. Thompson, Phys. Rev. **C54**, 1843-52 (1996).
21. P.G. Hansen *in* Proc. Int. Conf. Exotic Nuclei and Atomic Masses (ENAM), Arles June 1995, (M. de Saint Simon and O. Sorlin, eds.) Editions Frontieres, Gif-sur-Yvette 1995, p. 175.
22. P.G. Hansen, Phys. Rev. Lett. **77**, 1016 (1996).
23. J.H. Kelley et al., Phys. Rev. Lett. **74**, 30 (1995).
24. W. Schwab et al., Z. Phys. A **350**, 283 (1995).
25. T. Suzuki and T. Otsuka, Progr. Theor. Physics Suppl. No. 124, 155 (1996).
26. M.J.G. Borge et al. Nucl. Phys. A **613**, 199 (1997); Nucl. Phys. A (in press).
27. R.A. Kryger et al., Phys. Rev. C47 (1993) R2439-R2442.
28. M. Zinser et al., Phys. Rev. Lett. **75**, 1719 (1995).
29. A.A. Korsheninnikov et al., Phys. Rev. C **53**, R537 (1996) and Phys. Rev. Lett. **78**, 2317 (1997).
30. S. Karataglidis et al., Is There an Excited State in ^{11}Li at 1.3 MeV?, to be published.
31. K. Asahi et al., Phys. Lett. B **251**, 488 (1990);H. Okuno et al., Phys. Lett. B **335**, 29 (1994).
32. L.V. Chulkov et al., Large Spin Alignment of the Unbound ^{5}He Fragment After Fragmentation of 240 MeV/u ^{6}He, Phys. Rev. Lett. (in press); B. Jonson, Reactions and Beta Decay of Halo States, to be published in International School of Heavy Ion Physics, 4th Course: Exotic Nuclei (in preparation).