

Recent advances in neutron physics

Along with new techniques, the last decade has seen new studies—such as ultracold neutrons and “neutron bottles,” resonance behavior and doorway states, subthreshold fission, doubly radiative capture and neutron stars.

Herman Feshbach and Eric Sheldon

“At twilight on the sixth day of Creation, so say the Hebrew commentators to the Old Testament, God made for man a number of tools that give him also the gift of creation. If the commentators were alive today, they would write *God made the neutron*.” In these dramatic words the late mathematician and science historian Jacob Bronowski¹ conveyed the importance of the neutron to modern man. Indeed, nuclear physics as we know it may be said to owe its origins to the 1932 discovery of the neutron. We are coming increasingly to appreciate the enormous significance and variety that neutron physics displays throughout the entire realm of the physical sciences and beyond, into such developing areas as therapy, bioanalysis, materials research and astronomy. To survey in any comprehensive fashion the advances achieved over the past decade alone would carry us far beyond the scope of an article such as this.² We therefore will touch only upon some of the salient features on which fresh light is being shed and discuss some of the fields in which neutron physics is being called upon to play a prominent part.

To illustrate the increased sophistication and sensitivity of techniques that have become feasible in recent years, we draw attention right from the outset to the strides that have been made in methods for the production, handling and detection of neutrons. Because of their electrical neutrality and kilosecond mean lifetime in the free state, neutrons do not lend themselves to the routine methods that can be employed with charged, stable particles.

At conventional accelerator facilities,

it has now become possible to produce well-defined, collimated, reasonably intense beams of neutrons in a pulsed and bunched mode. Their time of flight from scatterer to detector can be measured reliably over long stable periods with *subnanosecond* time resolution,³ thereby allowing us to attain finer energy discrimination than could hitherto be accomplished. Quantitatively, accelerator time resolutions of 0.25 nsec (1 part in 2000) are being achieved; the time resolution of 0.7 nsec for 2-MeV neutrons detected at 2.5 m is equivalent to an energy resolution of 1%; that is, discrimination to within 20 keV. Figure 1 shows the fast-neutron time-of-flight system at Argonne National Laboratory.

In a method⁴ first developed in 1958, fairly slow *monoenergetic* neutron beams are produced by causing gamma rays from the high-energy end of a bremsstrahlung spectrum to bring about threshold photoneutron reactions in appropriate target materials. This method has been extensively refined, as has also the utilization of the inverse process,⁵ namely the production of monoenergetic gamma-ray beams at a fission reactor by the (n, γ) capture reaction induced by reactor neutrons, with a broad range of energies, impinging on suitable target nuclei.

The acquisition of monoenergetic neutron beams from the broad energy spectrum associated with reactor neutrons has traditionally been accomplished through the use of velocity-selection “choppers,” illustrated in figure 2. Lately, however, this method has been augmented by the employment of filtered-beam installations. The technique, introduced at the Idaho Materials Testing Reactor Laboratory, has more recently been successfully exploited at several facilities,⁶ notably the National Bureau of Standards and the Brookhaven National

Laboratory. Neutron energy “windows” are determined by the choice of filter: A scandium-titanium filter provides a very clean beam of 2-keV neutrons, while an iron-titanium combination is appropriate for 25-keV neutrons and a silicon filter for 144-keV neutrons. Figure 3 shows an iron filter. New handling and detection techniques, particularly in the field of neutron spectroscopy, were discussed extensively at recent conferences (see references 2 and 6).

Ultracold neutrons

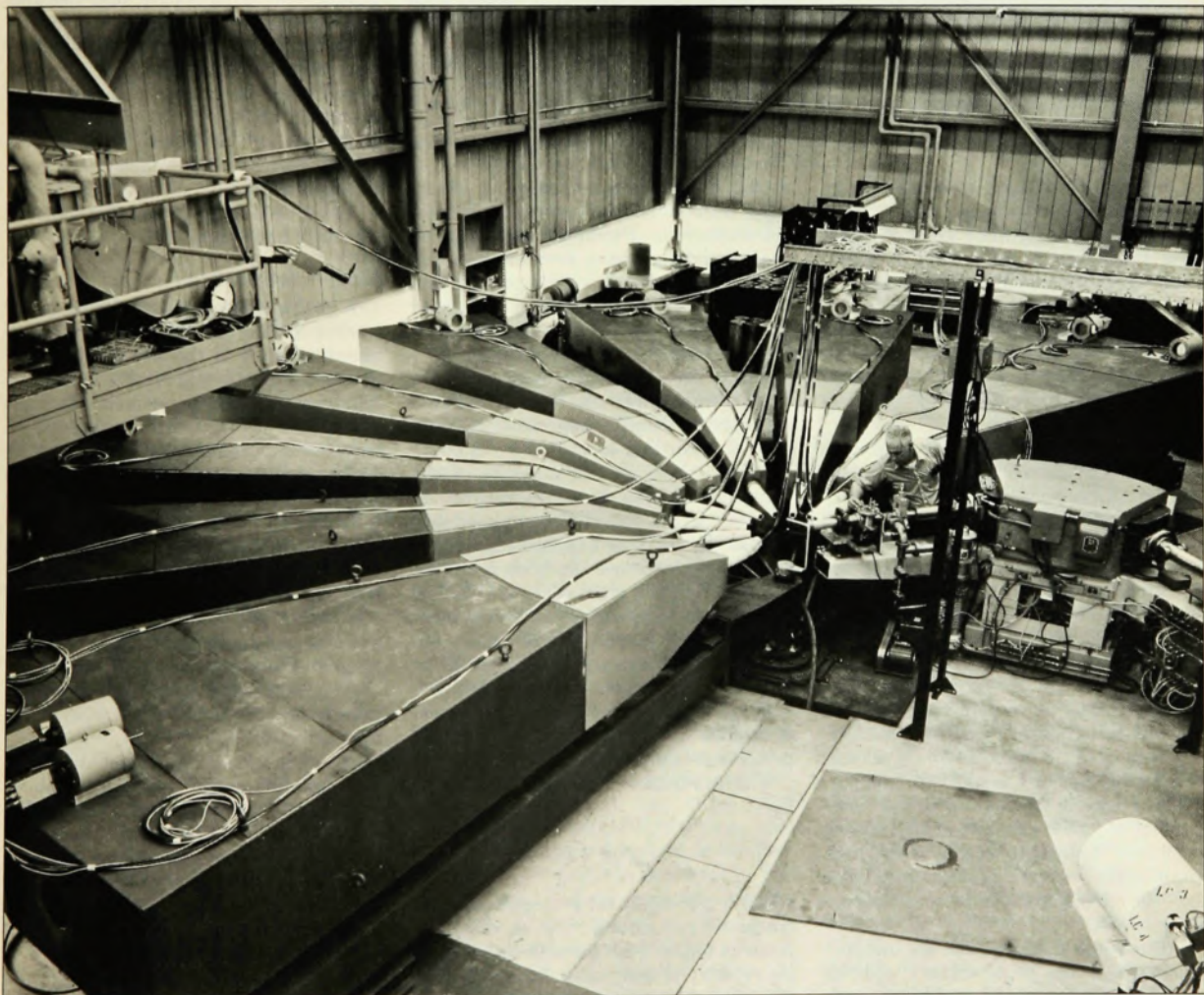
Particularly interesting is the recent work on ultracold neutrons, those with energies of only 10^{-7} eV, corresponding to an effective temperature of 10^{-3} K. Studies of these and very cold neutrons (with energy above 10^{-4} eV and velocity 10–100 m/sec) were initiated in the late 1960's by the late F. L. Shapiro at Dubna and independently by A. Steyerl at Munich, and are now being vigorously pursued in several countries (reviews have been presented by Shapiro⁷ and V. I. Lushchikov⁸).

Ultracold neutrons can be detected with proportional counters having a 0.1-mm-thick aluminum window and filled with a gas mixture of 96% argon, 3% carbon dioxide and 1% helium 3. Experimental counting rates are in the region 10^2 – 10^4 neutrons/sec.

The ultracold neutrons can be produced

- ▶ from very cold neutrons by further braking, as through gravitational deceleration in an upright mirror guide tube or
- ▶ through successive reflections from a system of rotating neutron mirrors constituting a “neutron turbine,” or more simply,
- ▶ by diffusion of the neutrons from the core of a reactor via a vacuum guide tube

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In the fast-neutron time-of-flight system at Argonne National Laboratory, monoenergetic neutrons, in nanosecond bursts, hit reaction samples at the foci of ten collimated flight paths 5–6 m long. Fast scintillators (light cylinders) detect the scattered neutrons at ten reaction angles with res-

olutions of about 0.2 nsec/m. The switching magnet that bends the incident ion beam is to the right of the man. This system has been used extensively in fast-neutron studies of scattering and emission, for both basic and applied studies.

Figure 1



The rotor of a neutron-beam "chopper" is being assembled at Brookhaven. Despite its mass of 350 kg, it can rotate continuously at 15 000 rpm suspended by the thin shaft seen in the photo. The device produces a pulsed neutron beam for nuclear-structure studies.

Figure 2

of copper or stainless steel containing three or four bends, the core end of which is closed by a moderator ("converter") of cooled ZrH_2 (or H_2 or D_2 or H_2O). From a reactor having a maxwellian flux of 5×10^{13} thermal neutrons/cm² sec, it is possible to obtain an intensity of about 1000 ultracold neutrons/sec (approximately 10^{-12} of the total neutron flux produced in the reactor), and a density of up to 100 per liter.

Although their wavelength is akin to that of visible light, neutrons in the ultracold region differ from light in one very remarkable property, namely, that all such neutrons must be totally reflected at the surface of any medium, irrespective of the angle of incidence. This is because the de Broglie waves penetrate only a very small way, about 100 Å, into the medium, and hence the probability of neutron loss per collision will be very small. This makes it possible to guide and trap ultracold neutrons in "neutron bottles," typically 1 m³ in volume, which may be made from boron-free glass or from beryllium cooled to liquid-nitrogen temperatures. In the course of their mean lifetime τ of about 10^3 sec, ultracold neutrons might be expected to undergo some 10^3 – 10^5 reflective collisions with the container walls.

A "monochromator" can be incorporated within the guide tubes simply by including vertical "kinks," which can be surmounted only by those ultracold neutrons that possess enough vertical velocity, and hence the energy of the neutrons within the trap can be arranged to be

within 10% of the nominal value. Magnetic traps have been proposed but not yet employed. Ferromagnetic coils, on the other hand, have successfully been used to produce up to 75% polarization when these beams are transmitted through them, with their intensity diminished only by a factor of three.

Once the ultracold neutrons are trapped within a bottle, their intensity is expected to dwindle exponentially with time t , according to the $N = N_0 e^{-t/T}$ relation, where T is a measure of the containment time up to absorption. In practice, T was found to be appreciably smaller than expected, typically about 100 sec, although 400 sec has been achieved. Even so, this falls short of the theoretical expectation by one to two orders of magnitude: The experimental mean absorption coefficient μ for a single collision of a neutron with the container wall, averaged over all angles of incidence, proves to be about 10^{-3} , as against the theoretical prediction of about 10^{-5} .

The prediction is based on the relation

$$\frac{1}{T} = \frac{1}{\tau} + n\mu$$

where n represents the average number of collisions per second that an ultracold neutron makes with the wall (in terms of its velocity v and mean free path $\Lambda = 4V/S$, with V the volume and S the surface area of the bottle, one has $n = v/\Lambda$). A quantitatively satisfactory explanation for this discrepancy is still lacking, as arguments based on surface roughness

and impurity effects or other causes are inadequate to account for this.

Consequently, containment times are yet insufficient to permit the accurate determination of such quantities as the electric dipole moment of the neutron (up to now, established to be less than about 10^{-24} e cm, consistent with the zero value required by time-reversal invariance), or the neutron's mean lifetime τ . If τ and μ in the above equation are treated as free parameters and adjusted to provide a best fit to containment data, one obtains the very rough value, $\tau = 700 \pm 300$ sec, but to arrive at a precise determination of τ it will be necessary to improve conditions until $T \approx 100 \tau \approx 10^6$ sec, instead of the present situation, with $T \lesssim \tau$.

Among other attractive applications of ultracold neutrons that have been proposed, we might instance the opportunities to

- ▶ establish improved limits on a possible neutron electric charge
- ▶ obtain more precise values of the coherent scattering length and neutron-capture cross sections,
- ▶ investigate a wide range of solid-state and surface structures,
- ▶ examine the magnetic properties of materials, and
- ▶ provide for the first time a pure neutron target for atomic and nuclear experimentation.

Thus, ultracold neutrons have opened an entire new field.

Neutron resonances

A problem of great importance to our understanding of nuclear interaction characteristics is the determination of spin assignments and other quantum attributes of neutron resonances. To single out a pair of illustrative examples, we mention the development at the Argonne National Laboratory of a photoneutron polarimeter system which determines the polarization of the emergent photoneutron: As applied to the nuclear reaction $Pb^{208}(\gamma, n)Pb^{207}$ it was possible to show that the resonances at photon energies of 7.56, 7.70, 7.92, 7.98, 8.03 and 8.23 MeV are electric-dipole excitations and not magnetic-dipole, as originally believed.

Also, in a Los Alamos–Oak Ridge collaboration, the spin identification of resonances in $(n + U^{235})$ and $(n + Np^{237})$ experiments is accomplished through a spin-spin interaction analysis: A polarized pulsed neutron beam is arranged to strike a polarized U^{235} target and measurements of the resonance cross sections are made with these polarizations respectively parallel and antiparallel to one another. This has permitted the elucidation of 65 resonances below 60 eV in U^{235} , and yielded commensurately valuable results for Np^{237} . Where it can be applied, this method is more effective than other traditional techniques, such as the observation of de-excitation gamma-radiation or the measurement of both

the total and scattering cross sections.

Thus, intensive recent studies are yielding fresh insights into the electromagnetic-interaction characteristics of photoneutron and neutron-capture resonances and, at the other extreme, into the strong-interaction characteristics of fission resonances. A concomitant of these investigations is the familiar theoretical problem of generally interpreting resonance parameters and deducing their statistical properties. Pier Mello and others² have devoted considerable recent attention to this problem.

Advances in the theory of *spectrum fluctuations* have pointed to the very general character of nuclear-level fluctuations, in particular of spacing distributions, as illustrated by the finding that the same distribution can be observed in the slow-neutron resonance domain, in the fine structure near isoanalog states, in realistic shell-model calculations and, surprisingly, even in the ground-state region of nuclei. This lends further support to the validity of a random-matrix approach in a two-body shell-model version.

Optical model

It is interesting to note that the growing body of information on nuclear structure has been nurtured not only through direct theoretical findings, but also through the increasing exploitation of links with the more sophisticated theoretical treatments of neutron reactions. Central to these considerations is, of course, the optical model of interactions, which has of late continued to receive further refinement and substantiation. As an instance of this, we might mention the very encouraging results that Claude Mahaux² and others have obtained in microscopic calculations of the real and imaginary *optical parameters* in the Brueckner-Hartree-Fock framework, in which details of nuclear structure exert a dominant influence upon the inherent theoretical constraints.

As a single-particle model description of the neutron-nucleus interaction, the optical model has proved to be extraordinarily useful, but in its traditional form it takes into account only the global aspects of the interaction as expressed in the smooth dependence upon the mass number, atomic number, radius, skin thickness (that is, diffuseness) and nuclear deformation for the real and imaginary part of each term in the optical potential of a given spatial symmetry.

A deviation from this smooth behavior may be indicative of some special structural influence of the nucleus interacting with the neutron. High-quality experimental data indicate the occurrence of such deviations, and these deviations have to be taken into account when the optical-model wave functions are used in the interpretation of other phenomena involving the same nucleus. Such deviations



Some 14.5 pounds of isotopically pure iron 56, worth over \$660 000, go into making this high-energy neutron-beam filter. Here the carefully machined parts are being checked before insertion into the reactor. To exploit the peculiar property this isotope has of being virtually transparent to neutrons near 25 keV in energy, the iron has been enriched to 99.87% Fe⁵⁶ in an electromagnetic mass separator. The filtered beams are for experiments ranging from basic nuclear-structure research to *in-vivo* analysis of heavy elements in body tissues. Figure 3

tions from global values are expected if the target nucleus is easily polarized by an incident neutron. In that case, particularly where collective deformations are concerned, it has proved best to use a coupled-channel description in which the incident channel (neutron plus target in its ground state in the case of elastic scattering) is coupled to one or more excited states of the system.

Such an excited state in a collective, so-called "vibrational," nucleus might, for example, consist of a neutron and the target in a one-phonon state, as illustrated in part a of figure 4. If the shell-model approach appears appropriate, the second stage would then consist of the neutron plus a particle-hole excitation. This configuration, known as a "two-particle, one-hole" or "three-quasiparticle" state, is depicted in the right-hand portion of part b. If only one such excited state is involved, this process is referred to as a *two-step* process. In the coupled-channel description these two steps occur many times coherently with the one-step process; they are symbolized in the first two "boxes" of part c in this figure. The general case of many steps has been reviewed by Taro Tamura.⁸

The concept of the multistep process, especially in the interpretation of charged-particle reactions, is now well established. However, a particularly interesting example has recently been provided by neutron-scattering data on even-mass samarium isotopes.⁹ A two-

stage process, in which the 2⁺ rotational state was excited, was invoked for Sm¹⁵² and Sm¹⁵⁴, whereas the lighter nuclide Sm¹⁴⁸ was taken to have vibrational character, the excited level in the second stage then being a 2⁺ vibration. Both assumptions were tried for the intermediate nucleus Sm¹⁵⁰. Total cross sections for Sm¹⁴⁸, Sm^{150,148}, Sm^{152,148} and Sm^{154,148} were measured for neutron energies of 0.7–15 MeV, as well as differential cross sections at 7.0 MeV.

The calculation of the coupling-matrix elements was macroscopic in nature, expressed in terms of an optical potential $V_{\text{opt}}(R, A, Z, N, \sigma, l)$, where $R = R_0 [1 + \sum_{\lambda\mu} \alpha_{\lambda\mu} Y_{\lambda\mu}(\Omega)]$ for the vibrator and $R = R_0 [1 + \sum_{\lambda\mu} \beta_{\lambda\mu} Y_{\lambda\mu}(\theta)]$ in the body-fixed system for the deformed case.

The potential V_{opt} was obtained by fitting low-energy data on these nuclei and using empirical parameters valid in this range of energy and mass number. These vibration or deformation optical models proved to be capable of furnishing good fits to data for the characteristic vibrator Sm¹⁴⁸ and the characteristic rotators Sm¹⁵² and Sm¹⁵⁴. In the latter two cases, the value of the quadrupole deformation parameter β_2 was determined to within 10%. The interpretation of the Sm¹⁵⁰ data remained unresolved, although a vibrational description was favored pending the availability of improved data.

In this context, though not in others, coupled-channel calculations have em-



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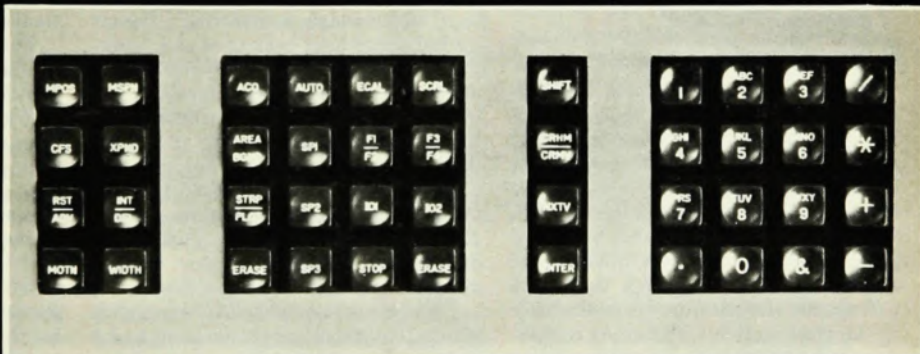
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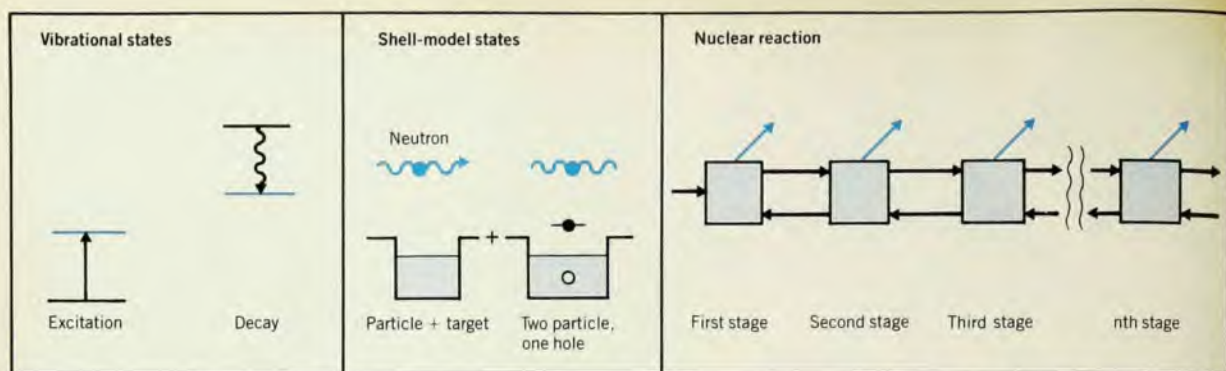
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The stages in a nuclear reaction illustrate the increasing complexity taken into account in generalized statistical theory. The two-step process of excitation followed by decay (diagram at left) may be represented

symbolically as a mixture of two (middle) or more (right) shell-model states. To the incident-particle state is added the two-particle, one-hole state (three quasiparticles) shown. Figure 4

played only the excited states of target nuclei in forming channels. The possibility that the second state involves particle transfers or charge exchange also bears consideration. Such processes could be important whenever the expended energy is not large and if the coupling-matrix elements are comparatively large (as would be the case if the second-stage system resonated at the appropriate energy): An appreciable cross section in the associated reaction would point to the possible involvement of processes of this kind.

Evaporation and direct interaction

One of the dividends of a coupled-channel calculation is the acquisition of the inelastic-scattering cross section as well as the optical-model elastic cross section. Although there is much evidence to indicate that neutron-induced reactions are frequently mediated by a compound-nucleus or statistical-model mechanism, it is clear that the direct process can also contribute substantially to the cross section. The direct component is expected to acquire importance rapidly when the neutron incident energy is increased; statistical theory would still remain applicable to the low-energy part of the emergent particle spectrum.

Whether we use the so-called "evaporation model," in which angular momentum considerations appear only in the level densities, or employ a model that explicitly conserves angular momentum depends very much upon the level density in the residual nucleus: If the levels are sparse, the latter is appropriate. This feature manifests itself quite strongly when the reactions involve the emission of a second particle, as in $(n,2n)$, $(n,n'\alpha)$, $(n,n'\gamma)$ and (n,np) processes. The transitions occur sequentially, so that the first step involves an inelastic excitation, while the second involves the emission of another particle.

If the energy available after emission is small (so that only low-lying levels of the residual nucleus can be excited) angular

momentum can play a significant role. For example, in the case of second-stage alpha-particle emission the use of the simple evaporation model can lead to errors by as much as a factor of 20. This is exemplified by the data for the reaction $\text{Cu}^{63}(n,n\alpha)\text{Co}^{59}$, shown in figure 5 for 12-MeV neutrons. The error is an evident consequence of the sensitivity of alpha-particle transmission to the angular-momentum barrier.

Indeed, order-of-magnitude differences in the cross sections for such reactions as (α,n) with resonances involving different partial waves have been used as a "spin-parity filter" to arrive at spectroscopic assignments to high-lying levels in the intermediate nucleus.¹⁰ These and similar considerations also apply to gamma decay from a nucleus that has been excited to a high-spin state: Even after the evaporation of several neutrons, the nucleus may be left with a high spin, which, of course, strongly favors certain gamma-ray transitions over others.

These remarks emphasize the care with which sequential processes have to be treated. In particular, it is not surprising that the $(n,2n)$ process is not always as simple as was thought when this process was originally considered as simply two sequential evaporations. Figure 6 demonstrates for the $(\text{Nb}^{93} + n)$ system at an incident energy of 14 MeV, the inadequacy of the simple evaporation approach and the need to include a "pre-equilibrium" component. This contribution may still not suffice in other circumstances, as in the $(\text{Fe}^{56} + n)$ system at 14.5 MeV, shown in figure 7, which illustrates the further need to add in a direct-interaction component in addition to the (n,n') , $(n,2n)$, (n,pn) and "pre-compound" admixtures.

Statistical and non-statistical models

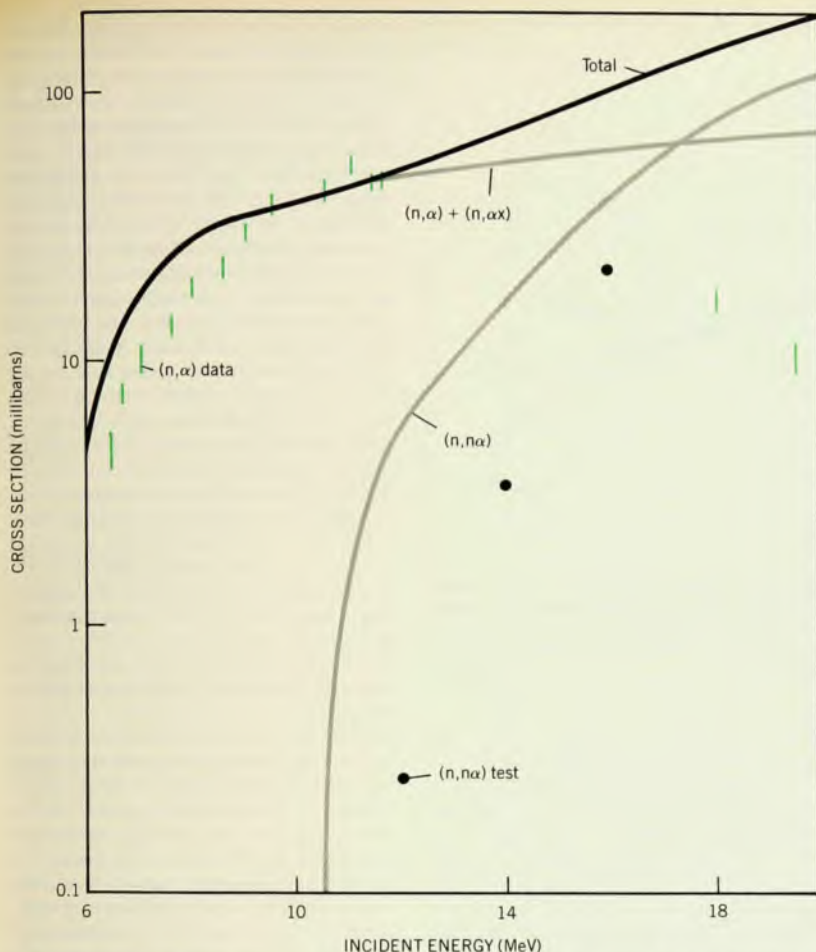
The pre-equilibrium process was first suggested by James Griffin, who made use of some qualitative considerations by Victor F. Weisskopf and Barry Block to build up a formalism that has meanwhile

been subjected to wide-ranging ramifications. Even in its present general form, though highly successful in achieving a semi-quantitative understanding of data in many instances, it still remains essentially a semi-classical theory with a number of *ad hoc* empirical elements. It falls short of yielding quantitative angular distributions and evinces unsatisfactory features in the recipe invoked for multi-particle production. Within these limitations, however, the usefulness of "pre-compound" and "pre-equilibrium" treatments can not be gainsaid.

This does, however, touch upon a very fundamental problem that deserves mention here. The neutron spectrum in, say, an (n,n') scattering reaction has a basic shape with the following interpretation: There are isolated peaks at the high-energy end, corresponding to low excitation energies of the residual nucleus, likely to be dominated by the *direct process*. The rest of the spectrum is dominated by a continuous distribution skewed toward the low-energy end; this is, for the most part, an *evaporation spectrum*. The angular distribution is strongly anisotropic and asymmetric at the high-energy end, whereas it evinces a distinctive symmetric character in the low-energy "evaporation" region.

How, though, is the bumpy region between these extremes to be interpreted, bearing in mind the fact that the evaporation theory is generally not applicable here, and the Bohr independence hypothesis no longer remains valid? Moreover, in the few cases that have been investigated carefully, the angular distribution is symmetric about 90° close to the evaporation region, and markedly asymmetric as one approaches the direct-interaction region, with an intermediate structure that can not be reproduced by statistical theory.

Apart from the immediate goal of predicting the cross section in this important intermediate region, the resolution of the problem has some bearing on two questions of great importance and generality.



Helium-production cross section, calculated and measured, for neutrons impinging on a copper-63 target. The experimental data are shown in color, and the black curve denotes the sum of (n, α) , $(n, \alpha x)$ and $(n, n\alpha)$ calculated cross sections (in gray). The dots represent "synthetic" calculations in which the spins of the excited states in the residual nucleus cobalt 59 from the $\text{Cu}^{63}(n, n\alpha)$ reaction are set equal to $1/2$ instead of their correct values of $7/2, 3/2, 5/2, 3/2, 1/2, 9/2, 5/2$ and $7/2$. (Courtesy of C. Y. Fu and F. G. J. Perey, Oak Ridge National Lab).

Figure 5

The first is concerned with the compound nuclear wave function: It is disturbing that, despite our having the Breit-Wigner description of compound nucleus resonances and a diversity of nuclear-reaction theories in our armory, we lack a description of the compound-nuclear wave function even today. The second, as pointed out by D. Agassi and Hans Weidenmüller, is the problem of the non-equilibrium quantum statistical mechanics of relatively small systems—a problem for the investigation of which nuclear reactions offer unique opportunities.

Germane to this discussion is a statistical theory that has been described in part at earlier conferences,¹¹ but up to the present has not been presented in full. To give the gist of this development, begin by assuming that reactions proceed through a series of stages of increasing complexity, as indicated in part c of figure 4. The word "complexity" is defined in terms of the description appropriate to the nuclear system under consideration:

► If, as in Griffin's model, the shell model is used, the complexity is defined in terms of the number of particles and holes; the simplest of the set of states is just the incident one-particle state, the next in order of complexity are the two-particle, one-hole states; the next are the three-particle, two-hole states, and so on.

► If a vibrational model is used, the complexity is defined in terms of the number of phonons.

In either case, the reaction can end at any step in the chain by making a final-state transition.

The second assumption is the chaining hypothesis, which states that a given stage can be connected by the residual Hamiltonian only with its nearest-neighbor stages, those that at most differ from it by unit complexity.

Thirdly, the statistical hypothesis is assumed, one immediate consequence of which is that amplitudes for particles emitted from different stages do not interfere. But, in addition, the statistical assumption is used in two different ways,

according to whether in a given stage there are particles in the continuum or whether all particles are bound. These two non-interfering contributions to the cross section are referred to as *multi-step direct* and *multi-step compound*. The statistical averaging in the second case asserts that states of differing angular momentum (nuclear spin) and parity do not interfere. To this is added the assumption, which can be verified in a given model, that Γ_n , the average width of states in the n th stage, is much greater than D_{n-1} , the average level spacing in the $(n-1)$ st stage. From this we obtain the familiar statistical result that the angular distribution is symmetric about 90° .

The multi-step compound is expected to constitute the major contribution in the region close to the evaporation domain and to become progressively less important as the direct region is approached. The average multi-step compound contribution to the fluctuation cross section for a given spin-parity state is

$$\sigma_{fi}^{\text{fluct}} = \frac{\pi}{k^2} \sum_{n=1}^r \frac{\Gamma_n^f}{\Gamma_n} \left[\prod_{k=1}^{n-1} \frac{\Gamma_k^i}{\Gamma_k} \right] \left(2\pi \frac{\Gamma_i^i}{D_1} \right)$$

The meaning of the factors is fairly obvious: From the initial state, i , the first factor (on the right) measures the probability of the process going with the first stage, the product term gives the attenuation of the incident flux because of emission while en route to the n th stage and the last factor gives the probability of emission into the final state, f . This result is very similar to that obtained in the Griffin model.

The statistical approximation in the case of the multi-step direct component is complementary in its nature to that employed for the multi-step compound. It states that

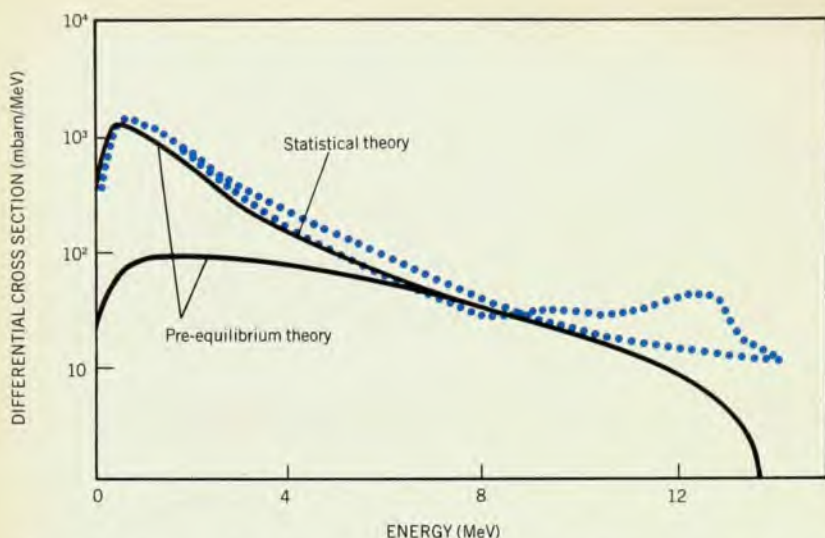
$$\sum_{\alpha} V_{\gamma\alpha}(\mathbf{k}_2, \mathbf{k}_1) V_{\alpha i}(\mathbf{k}_1, \mathbf{k}_2) V_{ia}^*(\mathbf{k}_i, \mathbf{k}_1 \Omega_1') \cdot V_{\alpha\gamma}^*(\mathbf{k}_1 \Omega_1', \mathbf{k}_2') \propto \delta(\Omega_1 - \Omega_1') \quad (1)$$

In this expression, $V_{\gamma\alpha}$ is the matrix element of the residual interaction given by distorted waves between states α of stage 1 and states γ of stage 2; the propagation vectors $\mathbf{k}_1, \mathbf{k}_2, \dots$ give the momenta of the particles in the continuum, and Ω_1 is a unit vector in the $\mathbf{k}_1$ direction.

This random-phase approximation leads to the following expression for the differential cross section:

$$\begin{aligned} \left\langle \frac{d^2\sigma(\mathbf{k}_f, \mathbf{k})}{d\Omega_f dU_f} \right\rangle_i &= \sum_{n,\nu} \frac{(\pi\hbar)^{\nu}}{(2\pi)^{3\nu}} \int d\mathbf{k}_1 \dots d\mathbf{k}_{\nu} \\ &\left[\frac{d^2\omega_{n,\nu}(\mathbf{k}_1, \mathbf{k}_{\nu})}{d\Omega_n dU_f} \right] \left[\frac{d^2\omega_{\nu-1}(\mathbf{k}_{\nu}, \mathbf{k}_{\nu-1})}{d\Omega_{\nu} dU_{\nu}} \right] \dots \\ &\left[\frac{d^2\omega_{2,1}(\mathbf{k}_2, \mathbf{k}_1)}{d\Omega_2 dU_2} \right] \frac{d^2\sigma_{11}(\mathbf{k}_1, \mathbf{k}_i)}{d\Omega_1 dU_1} \quad (2) \end{aligned}$$

The first term on the right gives the differential probability for going from the



Comparison of measured and calculated excitation functions for 14-MeV neutrons impinging on a niobium target. The experimental data (color) can not be fitted by simple evaporation theory alone but require the use of an incoherent admixture of a pre-equilibrium contribution and a direct-interaction component. The dependence of the pre-equilibrium cross section on neutron energy was calculated by D. Hermsdorf, G. Kiessig and D. Seeliger. Figure 6

incident channel to the first stage, in which the residual nucleus has an excitation energy between U_1 and $U_1 + dU_1$. The factor $d^2\omega_{2,1}(\mathbf{k}_2, \mathbf{k}_1)/d\Omega_2 dU_2$ gives the differential probability per unit time for a transition from $\mathbf{k}_1$ to $\mathbf{k}_2$ and the residual nucleus from stage 1 to stage 2. These quantities are essentially direct-reaction transition probabilities for distorted waves, and the cross section follows simply from folding the direct-reaction cross sections over all possible intermediate steps, conserving energy at each step.

This expression is exactly what one would expect in the classical kinetic-theory discussion of the passage of a particle through a Fermi-gas model of the nucleus (although, of course, it applies more broadly). It thus connects directly with the Bertini cascade theory. More importantly, it also establishes a connection with multiple-scattering theory applicable at higher energies. Indeed, as the energy increases, the contribution of the multi-step compound process will correspondingly decrease.

Let us look at two applications of the multi-step compound process. Steven Grimes and his co-workers¹² compared experiment and theory (the latter distinguishing between the pre-compound and evaporation contributions to the differential cross section) for the neutron spectra obtained from the reaction $V^{51}(p,n)Cr^{51}$. The angular distributions of the neutrons at the low-energy end of the spectrum are isotropic, while those nearby are symmetric about 90°. The measured data can be well fitted by the multi-step compound contribution in the above theory with just two constants. They are g , a measure of the level density

in the residual nucleus, and v , the strength of the residual interaction.

A second application is concerned with the (γ, α) reaction which, while strictly not within the purview of an article on neutron physics, nevertheless bears discussion here because of the insight that it provides into the question of how the conservation of isospin affects neutron interactions. Of the two reactions in the region of the giant dipole resonance $Si^{28}(\gamma, \alpha)Mg^{24}$ and $Si^{30}(\gamma, \alpha)Mg^{26}$, the former is isospin-forbidden while the latter is isospin-allowed. Yet the cross section of the former is larger than that of the latter!

By adapting the multi-step compound analysis discussed above, R. Leon Feinstein¹³ was able to show that isospin was not conserved, primarily because of the many steps involved in building the alpha particle. However, isospin conservation should hold for such one-step processes as (γ, n) or (γ, p) . The important conclusion is that isospin conservation will generally *not* hold for multi-step compound nuclear processes—a point that may have great relevance for (n, α) and kindred reactions.

Doorway states

It is often the case, as it was for the (p, n) reactions discussed above, that only a few steps contribute to the pre-equilibrium component. If only one step beyond the incident channel is important, the multi-step compound reaction then reduces to the statistical theory of "doorway states," and this model is able to provide a good fit to measured data, yielding values for the average doorway-state width and spacing.

The concept¹⁴ of doorway states origi-

nated in an attempt to explain the features of the S-state strength function with statistical theory, and in particular to reproduce the deep minimum around mass number $A = 110$, a trough also evinced by the subsequent data on P- and D-wave strength functions (albeit in a different range of A). This has led to a spate of theoretical attempts to improve the fit, particular attention being devoted to the 3S and 4S resonance regions. The latter is noteworthy in manifesting a strong odd-even effect in that the strength function for even- Z , odd- N nuclei lies about a factor of two above that for the even- Z , even- N nuclei over the mass range 142–160, as shown in figure 8.

The new formulations differ from the original treatment in that

- ▶ the original multipole expansion is replaced by the introduction of a spin cut-off factor, which reduces the empirical parameters from three to just one;
- ▶ an explicit A -dependence of the average escape width, $1/A^3$, is introduced, and
- ▶ a Fermi-gas treatment is employed to estimate the density of three-quasiparticle states.

This simplified treatment yields satisfactory results, as demonstrated in figure 9 for the S-wave neutron strength function in the 4S resonance region for A between 143 and 158; similar agreement ensues for the 3S region. However, the method fails between these two regions, where one has to revert to the more complicated original model. It is noteworthy that the $1/A^3$ dependence of the escape width is also obtained in studies of pre-equilibrium reactions; it would appear irrefutable that the dependence on doorway-state density is established empirically. These tantalizing results clearly call for further theoretical investigation.

The identification of individual isolated doorway states has proved difficult except in cases where symmetry effects or a dynamical mechanism operates: The former situation is exemplified by the isanalog states, and the latter by the giant multipole resonances or by subthreshold fission. Experimental data bear out the theoretical indication that isolated doorways for the interaction of neutrons with nuclei exist in the vicinity of the closed-shell nuclei.

The most thorough examination of neutron reactions for the identification of doorway-state effects has been performed by the nuclear group at Duke University and their collaborators, as reviewed at the 1971 Albany Conference.¹⁵ Based upon experimental studies at extremely high resolution, evidence for doorway structure was found for a number of target nuclei ranging from Si^{28} to Pb^{209} . Theoretical calculations based on either the two-particle, one-hole description of doorways or the particle-vibrator model substantiated these identifications. The small value for the strength function for Ca^{48} at

energies ranging up to 1.4 MeV, for example, was shown to be a consequence of the absence of any doorway state in that region.

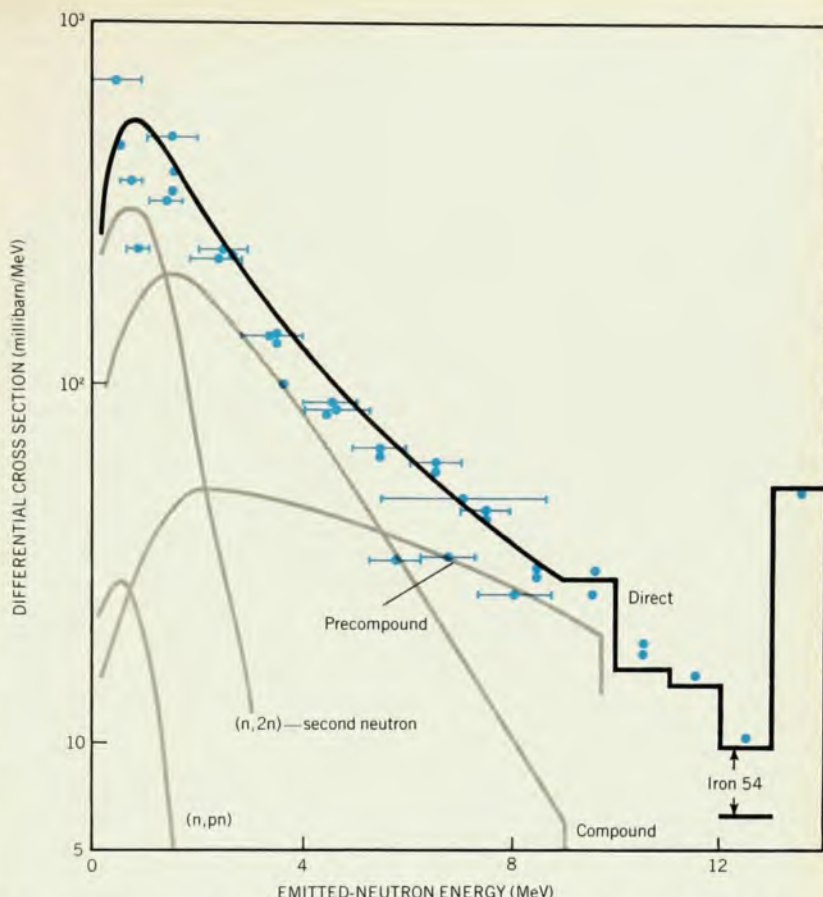
Further evidence for the P-wave doorway state in Si^{28} has meanwhile been adduced from the reaction $\text{Si}^{29}(\gamma, n)\text{Si}^{28}$ and other sources; however, similar investigations of the $\text{Pb}^{206}(n, \gamma)\text{Pb}^{207}$ radiative-capture reaction fail to corroborate the doorway state in the $(\text{Pb}^{206} + n)$ system. This does not necessarily mean that this doorway does not exist: An explanation could be that the structure of the state is such as to make gamma-transitions unfavored. One result, in agreement with several calculations, is that the width of the doorways as one proceeds away from closed-shell nuclei increases rapidly, and they become impossible to observe if, indeed, they can be said to exist at all.

The fission barrier

The phenomenon of intermediate structure in sub-threshold fission was discovered in the neutron bombardment of Pu^{240} some eight years ago, and other examples have meanwhile been brought to light, as reviewed by André Michaudon.² Central to the explanation of this finding is the postulate of a double-humped, or multiply humped, fission barrier, first introduced by Victor Strinsky.

From the point of view of a reaction picture, this situation may be regarded as an example of an *exit doorway*, a viewpoint consistent with the observation of electromagnetic transitions in the region between the double hump. Rotational levels built upon these vibration levels have been postulated to exist: These rotational levels appear to have been observed in neutron-induced fission of Th^{232} . From these data the moment of inertia associated with the second region can be determined. A similar result has been surmised for U^{238} by an Oak Ridge group and reported at the International Conference on the Interactions of Neutrons with Nuclei,² and the 1975 Nuclear Cross Sections and Technology Conference,⁶ prompted by the finding of a number of fission clusters with average spacings clearly too small for vibrational clusters. Furthermore, an *entrance-channel doorway* appears to have been observed in the radiative neutron-capture reaction $\text{U}^{238}(n, \gamma)\text{U}^{239}$.

The doorway state can often decay into several exit channels. If the branching ratios for several of these outgoing channels are all compatibly substantial, the channels may be deemed to have a *common doorway*, a phrase coined by Tony Lane, who employed it in connection with radiative neutron capture and its inverse, the threshold photoneutron reaction, where the doorway is common both to the neutron and gamma-ray channels. Consequently there can be a strong correlation between the partial neutron



For an iron target bombarded by 14-MeV neutrons, the pre-equilibrium theory due to M. Blann (Nucl. Phys. 213, 570; 1973) was combined with conventional statistical Hauser-Feshbach theory. The direct contribution was added after adjustment of the pre-compound cross section to fit the high-energy end of the spectrum for $n + \text{Fe}^{56}$. (From C. Y. Fu, ref. 6.) Figure 7

width and the partial gamma-ray width as well as with the (d, p) spectroscopic factor.

Thus, experiments on $\text{Mo}^{98}(n, \gamma)\text{Mo}^{99}$ have shown that the correlation is strong when the ground state of the residual nucleus, Mo^{99} , has a strong single-particle character and the resonant state in the $(\text{Mo}^{98} + n)$ system can be excited by absorption of a gamma-ray photon. Such a transition picks out the single-particle component of the resonant state, which suggests the use of a valence model to explain these correlated transitions, such as has been developed by Lane and Eric Lynn over the past decade.

Microscopic theory

The understanding of neutron resonances and strength functions was greatly advanced of late by semi-microscopic calculations. The work pursued by Vadim Soloviev² and others indicates that the experimental information on neutron resonances embraces only the few-quasi-particle components, and that these may make up only about 10^{-3} – 10^{-6} of the normalization of the total wave functions describing nuclear states. The many-

quasiparticle components are accessible to experimental study only in instances that have not yet been adequately explored. A good candidate for such investigations would be the $(n, \gamma\alpha)$ reaction, in which the intensities of gamma transitions between neutron resonance states and highly-excited levels some 1–2 MeV lower in energy are analyzed.

Valuable progress has been made toward comprehending the fragmentation of nuclear states at high and intermediate excitation, in determining the distribution of the strengths of single-particle and many-particle states over many nuclear levels. This betokens a consolidation of the combined independent-particle and quasi-particle models (in which the single-particle strength is concentrated in a single level) with the extreme statistical model, in which it is randomly distributed over all nuclear levels. Results for deformed nuclei, such as gadolinium, indicate that the fragmentation of single-particle states is indeed non-gaussian, and that the strength of states remote from the Fermi level is distributed over a wide energy interval. The application of this theoretical approach to the evaluation of

S-, P-, and D-wave neutron strength functions has met with conspicuous success.

Furthermore, it is now being explored in the calculation of partial radiative widths. These studies may shed fresh light also on the influence of the giant dipole resonance and other multipole resonances upon radiative strength functions, and offer new insights into electromagnetic aspects of neutron-associated interactions.

Electromagnetic interactions

The obvious vehicles for the examination of electromagnetic interactions in neutron physics are neutron photoproduction (γ, n) and radiative capture (n, γ). An extension into this realm has been the measurement and calculation of cross sections for the doubly radiative capture of thermal neutrons, the ($n, 2\gamma$) process.

The Chalk River group has now acquired some exciting evidence for the two-photon process with H^1 , H^2 and O^{16} targets, on which they directed a 9-meV flux of Bragg-scattered neutrons from a reactor. Their results, although still beset with large error limits (-3 ± 8 , 8 ± 15 and 3 ± 19 microbarns, respectively), are compatible with the values (0.118 microbarns, 0.026 microbarns and 0.048 microbarns, respectively) calculated from a coherent combination of single-particle and collective (excited-core) theory, and refinements of these investigations are currently envisaged.

The large calculated cross section for the $He^3(n, 2\gamma)He^4$ reaction of 1.180 microbarns offers encouragement, but this may be offset by the presence of the competing $He^3(n, p)H^3$ reaction, with its cross section of 5327 barns. Results for the $H(n, 2\gamma)D$ reaction, also recently investigated by various groups, are currently under scrutiny.

Of course, the companion study of two-photon emission processes in $0^+ \rightarrow 0^+$ gamma transitions in such nuclei as O^{16} , Ca^{40} and Zr^{90} has long been underway, but the complicated structure of excited 0^+ states has occasioned problems in the extraction of definitive information. The prospects are considerably more encouraging, on balance, for an elucidation of electromagnetic-interaction effects at this higher order of interaction complexity from data on doubly radiative neutron capture.

Strong interactions

An outstanding fundamental problem, which even the progress of the past decade in neutron physics has not resolved entirely, is the detailed quantitative representation of the neutron-neutron force. Until now we have been obliged in general to use a "difference" approach to glean information by subtracting protonic effects from observed deuteron effects, direct primary exploration having been tantalizingly unattainable. Now at last, two lines of investigation, concerned with neutron bottles and neutron stars, may offer the wherewithal to tackle significant aspects of this problem.

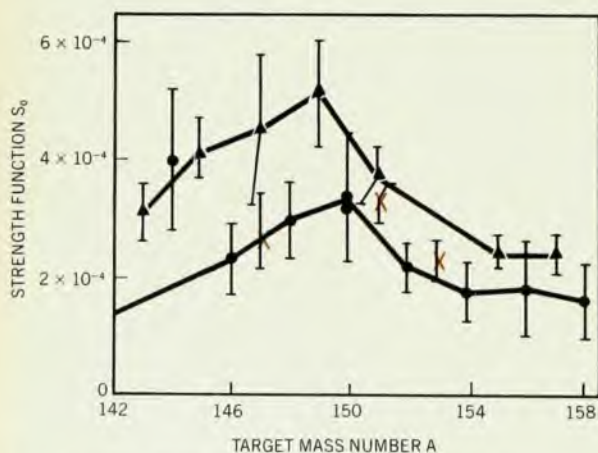
In our discussion of ultracold neutrons we indicated that they could be polarized and trapped, so that they constitute a polarized neutron target for bombardment by the polarized neutron beams produced from nuclear reactions such as (p, n) or (d, n). This would offer a direct means of studying the spin-spin interaction between neutrons. Questions of intensity and durability pose the major difficulties: Even if the target dimensions can be reduced to acquire an improvement in the available neutron density, the intensity may still be far from adequate to satisfy experimental requirements, and the mysteriously short

containment time may drastically impede or even rule out protracted measurement runs.

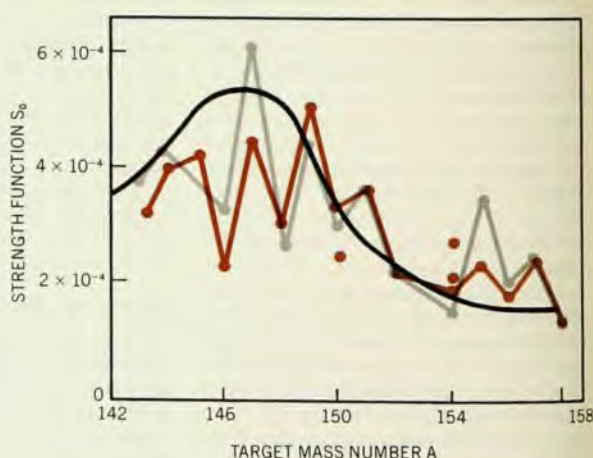
A domain in which, at any rate, densities and containment times of neutrons are far from meager is that of *neutron stars*. If a star of mass greater than the Chandrasekhar limit of 1.4 solar masses reaches the stage in its stellar evolution at which a supernova explosion occurs, the core that remains (some 10% of the original material) becomes so densely compressed that electrons are effectively "squeezed" onto protons. The residual matter is therefore essentially made up of neutrons in a high state of compression, constituting a stellar remnant typically about 15 km in radius. Of this inner crust, extending radially 9-14 km from the center, comprises a lattice of nuclei surrounded by neutron fluid and an electron gas, because at densities in the vicinity of 4.3×10^{11} gm/cm³ it becomes energetically favorable for the neutrons formed by ($p + e$) intercompression to "drip" out of the nuclei. The boundary of this region, at a radial distance of about 9 km, where the density has risen to approximately 2×10^{14} gm/cm³ (that is, to that of nuclear matter) is marked by the disappearance of the nuclear lattice and the homogenization into a pure neutron liquid. (The possible existence of a core made up of a π^- condensate or a π^0 solid is still being disputed.)

Applications of neutron physics

To explain the presumed properties of the neutron liquid spanning some three orders of magnitude in density about that of nuclear matter, a *tensor-interaction model*, based upon the 1974 work of A. M. Green and P. Haapakoski, which takes nucleon-isobar formation into account, has been constructed. Thereby new lines of enquiry have been opened into the



S-wave neutron strength functions in the first peak of the 4S resonance illustrate the odd-even fluctuations to which George Kirouac (reference 6, page 338) has drawn attention. The graphs on the left indicate that the strength functions for even-Z, odd-N nuclei (triangles) lie, by almost a factor of two, above those for even-Z, even-N nuclei (circles). Also



shown (colored crosses) are three odd-Z isotopes. This odd-even effect is well rendered by calculations in which cognizance is taken of fluctuations in the doorway-state density, shown on the right (in gray; experimental values in color), but not by the statistical calculation based on the conventional optical model (in black).

Figure 8

characteristics of the neutron-neutron force.

Complementary to the achievement of the last few years in bringing us to the threshold of producing a pure neutron target in the laboratory is the attainment of *high-flux neutron beams* as bombardment sources. The Grenoble high-flux reactor source has, through a German-French-British collaboration at the Institut Laue-Langevin, been operational since 1971. New designs of accelerator facilities for neutron production encourage the hope of achieving still higher fluxes, over 10^{16} neutrons/cm² sec.

Principal among the current generation of accelerator sources of neutrons are the isochronous cyclotrons at Karlsruhe and the nearly completed one at Kiev which are intended for prime use in the MeV energy region; the Columbia and Harwell synchrocyclotrons, designed to operate over a broader and slightly lower energy range, and the Oak Ridge electron linear accelerator ORELA, having the most flexible performance over a wide region from eV to MeV. Currently approaching completion is the Los Alamos WNR facility, with a peak instantaneous neutron intensity of 2×10^{19} sec⁻¹, and an average intensity of 10^{15} sec⁻¹.

Several accelerator sources of fast neutrons for neutron therapy and biomedical applications are in planning or operational status, including the Livermore Rotating Target Neutron Source and the Karlsruhe Ring Ion-source Neutron Generator; surveys of these have been presented by Heinz Barschall,⁷ Siegfried Cierjacks,² Lawrence Cranberg,² D. Bewley⁶ and K. E. Scheer.² Renewed recognition of the value of neutrons for medical irradiation has arisen through recent clinical trials in Hammersmith, Heidelberg and Hamburg, in which malignant tumors were successfully treated with newly modified neutron-dosimetry procedures that avoided deleterious radiation effects and exploited the advantageously high relative biological effectiveness and low oxygen-enhancement ratio of neutrons for tissue. Figure 9 shows a neutron-irradiation facility in a medical setting.

Still in the developmental stage are advanced neutron accelerator sources for studies of condensed matter, such as the Argonne Intense Pulsed Neutron Source, in which it is intended to produce neutrons via (p,n) reactions on heavy-metal targets in a high-intensity 800-MeV proton synchrotron. The aim is to achieve fluxes of 1×10^{16} thermal neutrons/cm² sec and 2×10^{16} epithermal (1-eV) neutrons/cm² sec, as well as intense cold-neutron and fast-neutron fluxes (the latter in the vicinity of 3×10^{14} neutrons/cm² sec, time-averaged, for radiation-effect studies).

Ongoing investigations into the detailed behavior of neutrons in fission processes include the accurate determi-



Cyclotron-based neutron-therapy unit, built by the Cyclotron Corporation in Berkeley. Neutron irradiation has been successful in the treatment of malignant tumors. Figure 9

nation of the number of neutrons emitted per neutron absorbed in fission devices (crucial to the operation of fast-neutron breeder reactors), as well as other decisive parameters. An increased awareness of the important role played by neutrons in energy transport within fusion devices has prompted new lines of enquiry that are still being consolidated.

Too numerous and varied for discussion here have been the manifold new developments in the application of neutrons to solid-state and complex-molecule research. An extensive review of the former has been provided by Walter Gläser² and of the latter by Benno P. Schoenborn,² conjoined with a survey of the technological and industrial utilization of neutrons by Claus Weitkamp.²

Thanks to advances in neutron detection and flux normalization, the techniques for the acquisition of reliable data have now become essentially as straightforward as those for the counting of charged particles, and neutron physics has entered an era of diversity, challenge and potential that carries immense promise.

* * *

This article is based on the opening address, by Herman Feshbach, to the International Conference on the Interactions of Neutrons with Nuclei, held 6-9 July 1976 at The University of Lowell.

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