EXPERIMENTS WITH NEUTRON-GAS TARGETS

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I. Introduction

This paper will deal with our first and crude thoughts concerning the feasibility and advisability of constructing a neutron-gas target to be used in conjunction with a new high-energy, high-intensity facility as well as with present-day high-energy accelerators. The possible use of a neutron-gas target with low-energy ion accelerators as well as with electron accelerators will also be discussed.

High-energy interactions with neutrons are usually studied using deuterons as targets. Secondary neutrons are sometimes used as projectiles, but no $(\bar{p},n)$, (n,n), (π,n), or (K,n) interactions have been studied "directly". Studies of neutron-neutron interaction at $E \simeq 0$ have been proposed by Muehlhause[1] using collisions of two thermal neutrons in a vacuum chamber placed inside a reactor. There has also been some talk about using two H-bombs to investigate neutron-neutron interactions in the Mev region.

Whenever deuterons are used as neutron targets or projectiles, an assumption is made that it is possible to subtract the proton contribution and to correct for the binding energy of the deuteron. The proton in the

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[1] C.O. Muehlhause (NBS), Thermal n-n Scattering, NBSR-8, April 1, 1963

deuteron can be considered as a spectator as long as the wavelength $\lambda\!\!\!^{-}_i$ of the incoming particle obeys:

$$\lambda\!\!\!^{-}_i \ll R_d \,, \qquad (1)$$

a condition which is well satisfied in the Bev/c region. It is, however, never absolutely clear that a bound neutron can be considered as free in a reaction which satisfies Eq. (1), and even if the neutron is considered free it has a relatively large momentum. It is, therefore, of great interest to investigate interactions such as $(\bar{p},n)$, (n,n), (π,n), (K,n), or (e,n) without the presence of a proton. In order to do so a target of neutrons is needed. This involves the construction of a high-neutron-density reactor near an accelerator.

II. Density of a Neutron Gas

The first question concerning the use of a neutron-gas target is the expected interaction rate. The number of detected interactions ν per second, or counting rate, for a steady-state reactor is given by:

$$\nu = nN\sigma\epsilon \qquad (2)$$

where n is the number of target neutrons per cm^2, N is the number of incident particles per second, $\sigma \simeq 4 \times 10^{-26}$ cm^2, for strongly-interacting particles, and ϵ is an efficiency factor which includes detector solid angle, detector efficiency, etc.

n is given by

$$n = \frac{\Phi}{v}\, l \,, \qquad (3)$$

where Φ is the neutron flux, v is the average neutron velocity, and l is the length of the neutron-gas target. The highest thermal flux now expected in a reactor (the 100-Mw HFRI at ORNL) is $\Phi \simeq 2 \times 10^{15}$ neutrons/cm^2 × sec. This flux could be available in a cylinder about 5 cm in diameter and about 100 cm in length, yielding

$$n \simeq \frac{2\times 10^{15}}{2\times 10^{5}} \times 10^{2} = 10^{12} \text{ neutrons/cm}^{2} \; .$$

Let us now consider in some detail several experiments which can be performed if a neutron-gas target of 10^{12} neutrons/cm^2 is available.

III. (p,n) and ($\bar{p}$,n) Interactions in a Storage Ring

If a storage ring is filled with 10 amp of circulating proton beam, $N = 6 \times 10^{19}$ protons/sec. If then the circulating beam is allowed to go through a neutron gas of 10^{12} neutrons/cm^2, the expected counting rate is

$$\nu = 10^{12} \times 6 \times 10^{19} \times 4 \times 10^{-26} \epsilon = 2.4 \times 10^{6} \epsilon \text{ events/sec} \; ,$$

which is a very large rate for any reasonable ϵ. Such an expected rate permits an appreciable decrease in both l and Φ.

If antiprotons are stored in the ring, the number of stored antiprotons is smaller by a factor 5×10^{7}. If $\sigma(\bar{p},n) = \sigma(p,n)$, the expected interaction rate for ($\bar{p}$,n) is about $5 \times 10^{-2} \epsilon$ interactions/sec. By cooling the neutron target to liquid-helium temperature it would be possible to achieve an effective increase of a factor of about 5 in the neutron density, yielding one interaction per four seconds, and still a very small counting rate ν.

The background from the residual gas can be computed as follows: There are 3×10^{7} molecules per cm^3 at a pressure of 10^{-9} mm Hg, so that the number of nucleons in the residual gas can be about 10% of the number of neutrons in the target (for a thermal flux of 2 × 10^{15} neutrons/cm^2 × sec). This sets a limit to the reduction of the size of reactor used. However, by performing the experiment with the reactor on and off, it would be possible to subtract the residual-gas contribution. Cooling the target to liquid-helium temperature increases the neutron density and at the same time decreases the gas density, resulting in an appreciable net gain in the ratio of neutrons to gas nucleons. There is also the problem of background of neutrons, gammas, and electrons, which are present around a reactor. Such a background is not too serious for most high-energy experiments which will be discussed here.

Let us now compare the proposed (p,n) experiments with (n,p) experiments which use hydrogen targets and deuteron-stripped or charge-exchanged neutrons from synchrotrons. As far as intensity is concerned, it is clear that the proposed experiment will have a sufficient rate of interaction. The reason for this is that the loss in target thickness in comparison with a hydrogen target is compensated by the multitraversal of the target by the circulating beam, and by the gain in not having to strip or charge exchange. A big disadvantage, especially for angular-distribution experiments, is the apparent need for elongated targets. It should also be noted that storage-ring experiments are usually very difficult even without the added complication of a reactor. The advantage of the proposed experimental setup is in the good energy definition of both the incident and target nucleons. It also permits a continuous use of the beam in the storage ring without interfering with other experiments at the injector synchrotron or the storage ring.

IV. (p,n) Interactions in a Synchrotron

The AGS intensity is $N \simeq 2.5 \times 10^{11}$ protons/sec. Such an intensity, when extracted, can provide for a counting rate of $\nu \simeq 10^{-2}\epsilon$, which is too small. The ZGS is expected to have about 10 times higher intensity so that $\nu \simeq 10^{-1}\epsilon$.

A synchrotron can be considered as a storage ring by the utilization of the "flattop" concept. If the accelerated beam is allowed to coast around for, say 100 msec at the peak magnetic field, each proton will traverse the target about 10^5 times, thus yielding an effective increase of the interaction rate by this factor.

V. Interaction of Secondary Particles with the Neutron Gas

For secondary particles x, where $x = n, \pi, K$, or $\overline{p}$, the expected counting rate ν_x for the AGS is $\nu_x = 10^{-2} k_x\epsilon$, where k_x is the number of x secondary particles per accelerated proton in acceptable angle and momentum bins. ν_x is very small since k_x is at most 10^{-4}. Some increase in ν_x could be achieved in the ZGS, whereas the proposed MURA FFAG could yield ν_x a factor of 1000 larger than ν_x at the AGS. Cooling the neutron gas can effectively contribute about a factor of 5 with another factor of 5 which might be gained by a future use of reactors with 10^{16} neutrons/sec. The maximum counting rate of such a "brute force" approach for, say, (π,n) interactions is $\nu_\pi = 2.5 \times 10^{-2}\epsilon$.

VI. Pulsed Reactors and Bunched Beams

It is not surprising that the expected counting rates for secondary beams are small, since even with protons it is advisable to enhance the counting rate by the use of the multitraversal concept. Multitraversal of targets by secondary beams is impractical, but an appreciable increase in ν_x can be achieved by the use of properly-matched pulsed reactors and bunched accelerator beams.

If the neutron gas is pulsed to an instantaneous flux Φ' and the incident beam is bunched in such a way that it traverses the neutron gas in a time shorter than the duration of the neutron pulse, then the bunched interaction rate ν' is given by

$$\nu' = \frac{\Phi'}{v'} \, 1 \, N'_{av} \, \sigma \, , \tag{4}$$

and the ratio of the bunched rate to the unbunched rate is

$$\frac{\nu'}{\nu} = \frac{\Phi'}{\Phi} \frac{v}{v'} \frac{N'_{av}}{N} \quad . \tag{5}$$

The average pulsed beam N'_{av} can in some cases be made equal to the unpulsed beam N, and proper time matching can be achieved for instance with one-turn extraction. If $v' \simeq v$, the gain in bunching is Φ'/Φ and for a pulsed reactor with 1 msec pulse and 1 p.p.s., the gain can be by a factor as high as 10^3. (The limit is set by the continuous cooling needed for an average flux Φ, and an acceptable instantaneous temperature rise of all the components of the reactor.)

Present-day technology unfortunately has not yet reached the stage of $\Phi' = 2 \times 10^{18}$ neutrons/sec $\times$ cm^2 with a repetition rate of 1 p.p.s. It should be emphasized, however, that whenever extracted beams are used, it is the instantaneous flux Φ' rather than the steady-state flux Φ which determines the counting rate if the reactor pulsing matches the beam bunching, so that inexpensive low-power pulsed reactors are equivalent for our experiments to high-power steady-state reactors.

VII. $(e^{\pm},n)$ Interactions

Electron-neutron interaction cross sections are 10^4-10^6 smaller than (p,n) cross section. If a neutron-gas target is used it is essential to use a very high intensity beam. Linear accelerators yield up to 1 ma = 6×10^{15} electrons/sec so that even with pulsed reactors of $\Phi' = 2 \times 10^{18}$ and a repetition rate of 1 p.p.s. the maximum counting rate is

$$\nu \simeq (10^3 \times 10^{12}) \times (6 \times 10^{15}) \times 10^{-31}\epsilon = 0.6\epsilon \text{ events/sec} .$$

If a steady-state reactor is constructed with a storage ring of electrons the maximum counting rate for an expected circulating beam of 50 ma would be:

$$\nu \simeq (10^{12}) \times (3 \times 10^7) \times (10^{-31})\epsilon = 3 \times 10^{-2}\, \epsilon \text{ events/sec} .$$

This number is unfortunately very small and is on the borderline of feasibility. The advantage of (e,n) experiments with storage rings is in the possibility of comparison between (e^+,n) and (e^-,n) interactions, since electron storage rings can be filled with positrons to the same space-charge limit as applies for electrons.

VIII. Low and Medium-Energy Interactions

(e,n) interactions at low energy can probably be best studied with neutrons impinging on atomic electrons. A neutron gas, however, will be very useful for studies of (n,n) interactions. Let us consider a steady-state reactor with $n = 10^{12}$ n/cm^2. An accelerator such as the proposed CW cyclotron at the Naval Radiological Defense Laboratory in San Francisco can yield 10^{15} neutrons/sec resulting in $\nu = 40\epsilon$ events/sec. If, on the other hand, a pulsed reactor is used, it can be matched with a synchrocyclotron resulting probably in a higher ν for lower cost. A more sophisticated system would be the following: a CW cyclotron for, say, deuterons feeds a storage ring which could use the same magnet (at a radius larger than the radius of the dees). The storage ring discharges its beam into a target placed in front of a pulsed reactor with a repetition rate equal to the repetition rate of the pulsed reactor. High interaction rates can thus be achieved. Such a system is obviously complicated and costly, but is probably more useful and less expensive than two H-bombs.

IX. Conclusions

Our discussion has shown that it is useful and feasible to investigate high-energy (p,n) interactions using a steady-state reactor in conjunction with a storage ring or a synchrotron whose magnetic field has a flat top. We also demonstrated that great gains can be achieved by the use of a pulsed reactor and a properly matched synchrotron. Extreme methods, such as highest flux reactors and cooling of the neutrons to liquid-helium temperatures are needed for the investigation of interactions of secondary particles with free neutrons and our feeling is that the usefulness of the neutron-gas target here is questionable. (e,n) interaction rates also are expected to be very small. However, the importance of the comparison of (e^+,n) to (e^-,n) interactions could outweigh the disadvantage of long counting periods which are required for such experiments. (n,n) reactions are of utmost importance since they measure the basic nucleon-nucleon interaction with no coulomb interference. We feel that low and medium-energy (n,n) reactions can be studied with the use of neutron-gas targets and sophisticated bunching techniques.